Smart Innovation, Systems and Technologies 263

John R. Littlewood
Robert J. Howlett
Lakhmi C. Jain *Editors*

# Sustainability in Energy and Buildings 2021

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# Preface

The 13th International Conference on Sustainability and Energy in Buildings 2021 (SEB-21) is a major international conference organized by a partnership made up of KES International and The Sustainable and Resilient Built Environment group, Cardiff Metropolitan University.

SEB-21 invited contributions on a range of topics related to sustainable buildings and renewable energy and explored innovative themes regarding building adaptation responding to climate change.

The aim of the conference was to bring together university researchers, government and scientific experts and industry professionals to discuss the minimization of energy use and associated carbon emissions in buildings, neighbourhoods and cities, from a theoretical, practical, implementation and simulation perspective. The conference formed an exciting chance to present, interact and learn about the latest research and practical developments on the subject. This is the second time that SEB-21 had held virtually, and this has been made necessary because of the ongoing COVID-19 pandemic which has swept the world.

The conference featured two general tracks chaired by experts in the fields:

- Sustainable and Resilient Buildings
- Sustainable Energy Technologies.

In addition, there were seventeen Invited sessions proposed and organised by prominent researchers.

It is important that a conference provides high-quality talks from leading-edge presenters. SEB-21 featured two keynote speakers: Dr. Clayton Miller, National University of Singapore, Singapore, and Prof. Liz Varga, University College London (UCL), UK.

The conference attracted submissions from around the world. Submissions for the full-paper track were subjected to a two-stage blind peer review process. With the objective of producing a high-quality conference, only the best of these were selected for presentation at the conference and publication in Springer as chapters. Submissions for the short paper track were subjected to a 'lighter-touch' review and published in an online medium, but not in Springer book.

Thanks are due to the very many people who have given their time and goodwill freely to make SEB-21 a success. We would like to thank the members of the International Programme Committee who were essential in providing their reviews of the conference papers, ensuring appropriate quality. We thank the high-profile keynote speakers for providing interesting talks to inform delegates and provoke discussion. Important contributors to the conference were made by the authors, presenters and delegates without whom the conference could not have taken place, so we offer them our thanks. Finally, we would like to thank the administrative staff of KES International.

It is hoped that you find the conference an interesting, informative and useful experience and remain connected through the KES International Virtual Conference Experience.

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# About the Editors

**Dr. John R. Littlewood** graduated in Building Surveying, holds a Ph.D. in Building Performance Assessment of Zero Heating Housing and is a Chartered Building Engineer. He is Head of the Sustainable and Resilient Built Environment Research group in Cardiff School of Art & Design and the Human Centred Design Global Academy, at Cardiff Metropolitan University (UK). He coordinates three Professional Doctorates in Art and Design, Engineering and Sustainable Built Environment, and has supervised and examined to completion 11 and 18 doctorates. His research is industry focussed, investigating methods to optimize the fire, production and thermal performance for existing and new dwellings during the design, manufacture, construction, operation or during and after retrofit stages. His current research includes working with Wales' largest offsite manufacturer of timber frame construction systems to increase the use of natural materials and recycling to embrace the circular economy. The outcomes of his research enhance occupant quality of life and increase the environmental sustainability and resilience of the built environment. He has authored, co-authored and co-edited 155 academic peer-reviewed publications and supported the SEB international conference series since 2010.

**Dr. Robert J. Howlett** is Executive Chair of KES International, a non-profit organization that facilitates knowledge transfer and the dissemination of research results in areas including intelligent systems, sustainability and knowledge transfer. He is Visiting Professor at Bournemouth University in the UK. His technical expertise is in the use of intelligent systems to solve industrial problems. He has been successful in applying artificial intelligence, machine learning and related technologies to sustainability and renewable energy systems; condition monitoring, diagnostic tools and systems; and automotive electronics and engine management systems. His current research work is focussed on the use of smart microgrids to achieve reduced energy costs and lower carbon emissions in areas such as housing and protected horticulture.

**Dr. Lakhmi C. Jain** Ph.D., M.E., B.E. (Hons), Fellow (Engineers Australia), was with the University of Technology Sydney, Australia, and presently serving the Liverpool Hope University, UK. He founded the KES International for providing a professional community the opportunities for publications, knowledge exchange, cooperation and teaming. Involving around 5000 researchers drawn from universities and companies worldwide, KES facilitates international cooperation and generate synergy in teaching and research. KES regularly provides networking opportunities for professional community through one of the largest conferences of its kind in the area of KES.

# Examining the Deviation in Energy Saving Estimations Due to the Use of the Degree Days Method

**Ahmed Mokhtar**

**Abstract** Energy performance contracts are commonly used to retrofit buildings and reduce their energy consumption. The financial agreement in the contracts typically depends on calculating the amount of energy saved every year. This is difficult to calculate as many aspects that impact a building's energy consumption continuously change, including the weather. The Degree Days method is commonly used to help estimate the energy saving while the weather is changing. The Degree Days can be calculated with a variety of base temperatures resulting in different values. This paper is a first step in examining the significance of the deviation in energy saving calculations when using this method. It also investigates if there is a more appropriate base temperature to use for that purpose. Energy simulation with actual annual weather data is used to make the investigation. Two different building types and three different energy conservation measures are used. The results of this preliminary investigation show that the deviation can be significant in some cases. They also show the possibility that a particular base temperature for calculating the degree days can give more accurate savings estimations. These can be very important results for users of energy performance contracts.

## 1 Introduction

With the signing of the Paris Agreement on climate change, several countries initiated programs to retrofit old buildings to reduce their energy consumption. In addition, many owners see a financial benefit in improving the energy performance of their buildings by reducing their energy bill. As a result, energy service companies (ESCO) are offering various services to accommodate this market demand. An important part of these services is the energy performance contract [1]. These are contracts that aim to finance the retrofitting cost by using the savings in the energy consumption cost. There are basically two common types of energy performance contracts between

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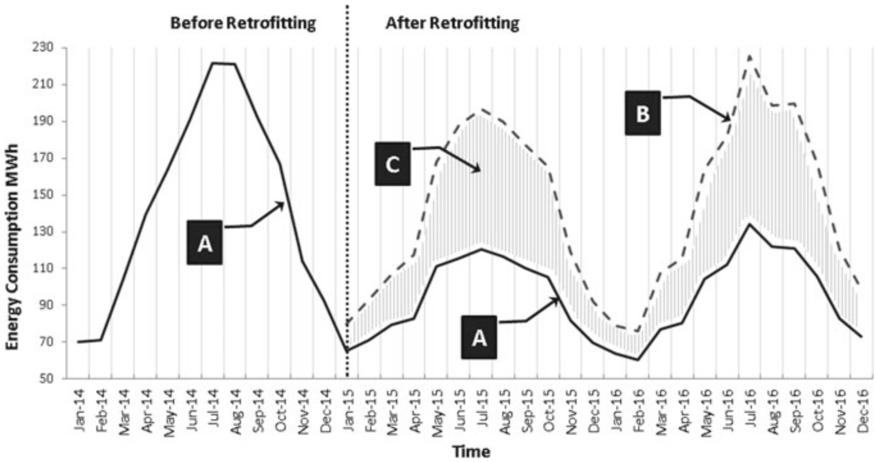



**Fig. 1** Building energy consumption before and after retrofitting. **a** is actual consumption. **b** is estimated consumption if there was no retrofitting. **c** is the estimated saving in energy consumption

an owner and an ESCO. These are the Guaranteed Savings contract and the Shared Savings contract. In a simplified way, the main difference between these two types of contracts is in the financing of the retrofitting cost and in the calculations of the savings. In a Guaranteed Savings contract, the owner finances the retrofitting cost and pays the ESCO for their technical service. However, the payment is due only when a certain level of energy consumption saving is achieved from the retrofitting. In a Shared Savings contract, the ESCO finances the retrofitting costs in return for a percentage of the saving in the consumption cost. In both types of contracts, the saving in energy needs to be determined to process the payments according to the contract.

The problem is that energy savings is not a measurable quantity. Rather, it is an estimated one. Figure 1 illustrates this problem. What can be measured is the energy consumption because it is metered. We can measure it before retrofitting and after retrofitting. Line (A) shows this metered energy consumption. It is certainly easy to assume that—if the retrofitting is not done—the building would have consumed the same energy that we measured before its retrofitting. Hence, the difference between what we measure before retrofitting (the part of line A before retrofitting) and what we measure after retrofitting (the part of line A after retrofitting) is what is being saved. Yet, this is not correct. Several factors affect the building which results in a variation in energy consumption every year. These include changes in the schedule of the building use or in the number of its occupants among many other factors. Therefore, we need to establish an estimation of what would have been the building's energy consumption if it was not retrofitted. Line (B) in Fig. 1 shows an example of this estimation. Using estimated energy consumption (B), and the metered energy consumption (A), we can establish a more accurate estimation of the energy saving due to the retrofitting. This will be the difference between (B) and (A) as represented by the area (C) in

Fig. 1. As mentioned above, the estimation in savings has contractual and financial implications for both parties involved in the energy performance contracts. The more accurate the actual saving calculation is, the clearer are the contractual obligations and the fairer is the distribution of saved money.

The challenge now is in estimating line (B) for a particular building reasonably accurately. Several methods exist to make such estimation as defined by the International Performance Measurement and Verification Protocol (IPMVP) [2]. The amount of data needed and the effort and money put in collecting different data varies between these methods. Depending on the nature of the building and the extent of the retrofit, a simple or more complex method is selected to help estimate the saving in energy consumption (C) in Fig. 1.

One of the most important factors that affect the variation in a building's energy consumption is the annual change in the weather conditions. In most buildings, this change has a direct impact on the energy consumption by the HVAC systems. Depending on the building type and its surrounding climate, these systems can be by far the biggest consumer of energy in a building. Hence, fluctuation in weather conditions means fluctuations in the building's annual energy consumption. To estimate the impact of weather in creating line (B) in Fig. 1, the "Degree Days" method is commonly used [3]. The method uses numbers that can be generated from weather data. These numbers change as the weather changes. A simple equation can be used then to estimate line (B) in Fig. 1 from the section of line (A) that is before retrofitting. For example, and following the timeline in Fig. 1, to estimate the energy that the building would have consumed if it were not retrofitted in the year 2015 ($E_{Est}$), get the energy actually used by the building before retrofitting in year 2014 ($E_{Base}$) which is considered the base (or reference) year, get the cooling degree days for 2015 ($CDD_{Est}$) and the cooling degree days for 2014 ($CDD_{Base}$) and use these in Eq. (1).

$$(E_{Est}) = (E_{Base}) * \frac{CDD_{Est}}{CDD_{Base}} \tag{1}$$

The question now is how to calculate the values for the CDD in the needed years. According to Bromley [4], "*Degree days are a measure of how much (in degrees), and for how long (in days), the outside air temperature was below [above] a certain level*". In case of Heating Degree Days (HDD), we measure "below" a certain base temperature while in the case of Cooling Degree Days (CDD), we measure "above" a certain base temperature. HDD are used when we want to estimate the energy needed to heat a building while CDD are used when we want to estimate the energy needed to cool a building. The bigger the number, the more energy is expected to be used by the HVAC system to achieve human thermal comfort. In this article, we focus on using the CDD.

Calculating the CDD requires a base temperature. This is the temperature above which we assume the building requires cooling. The standard base temperature used in ASHRAE is 18.3 °C (65 °F). However, others use different base temperatures. Azevedo et al. [5] provides a list of base temperatures used in different countries as they appear in the literature. The list shows a variation from 18 to 28 °C and it reflects the assumptions made by the different researchers on the temperature beyond which a building needs to be cooled mechanically. This certainly depends on the type of building and its climatic region.

Once the base temperature is determined, calculating the CDD for a particular period (e.g. month or year) is simple. Using the hourly weather data, a value "$X_i$" is calculated for each day using Eq. (2). All the positive values for "$X_i$"—for the number of hours "h" that are in the calculated period—are summed to be the CDD for the needed period as shown in Eq. (3).

$$X_i = \frac{\left(T_{Daily\ Max} - T_{Daily\ Min}\right)}{2} - T_{Base\ Temperature} \tag{2}$$

$$CDD = \sum_{i=1}^{h} \mathrm{X}_i \ (\text{where } \mathrm{X}_i > 0) \tag{3}$$

Clearly, the selection of the base temperature impacts the calculated CDD. Hence, the ratio $CDD_{Est}/CDD_{Base}$ that is used in Eq. (1) will vary accordingly. Consequently, the estimated energy consumption $E_{Est}$ that represents line (B) in Fig. 1 will also vary. Therefore, the estimated saving due to the retrofitting, (C) in Fig. 1, will be different each time we change the base temperature for calculating the CDD. This may affect the amount of money to be paid to the ESCO in the case of a shared savings contract. It may also result in non-payment in the case of a guaranteed savings contract.

This paper is a step towards answering two questions. The first is how big the deviation is in estimating the saving in energy consumption when the CDD method is used. The second is whether there is an optimal base temperature that minimizes the deviation. The paper starts by explaining the methodology used to answer the two questions and it then shows the results and the conclusion of the study.

## 2 Methodology

Energy saving can never be measured in reality. Therefore, the researcher approach to answering the two questions is to use energy simulation software. With simulation, it is possible to keep all the parameters that impact a building's energy consumption constant, with the exception of the parameters being tested. This allows us to isolate some parameters and hence evaluate the impact of their changes on the building's energy consumption. In our case, we need to do so to create lines (A) and (B) of Fig. 1.

A building is modeled in the energy modeling software IESVE [6]. The following series of simulations are run using the weather data for the city of Sharjah in the United Arab Emirates (ASHRAE Climate Zone 1B Very Hot–Dry):

1 A simulation is done using actual hourly weather data for a base year (e.g. 2014). This creates the part of line (A) that exists before retrofitting as shown

in Fig. 1. The sum of the calculated monthly energy consumption represents the base consumption value $E_{Base}$ of Eq. (1). No particular reason for selecting 2014 as the base year. The author just wants to have four years of performance after retrofitting as a reasonable time for testing the possible deviation in results. Further studies should test different base years and more years after retrofitting.

2 A simulation is done using actual hourly weather data for the consecutive years. (e.g. 2015, 2016, 2017, 2018). This creates line (B) as shown in Fig. 1 based on simulation results.

3 Some Energy Conservation Measures (ECMs) are applied to the simulated building to represent a retrofit work done on the building. The simulation is run using the actual hourly weather data for the consecutive years. (e.g. 2015, 2016, 2017, 2018). This creates the part of line (A) that exists after retrofitting as shown in Fig. 1.

Using Eqs. (2) and (3), several CDD calculations are done using a spreadsheet macro developed by the researcher. The macro uses actual hourly weather data and a base temperature—defined by the user—to make the CDD calculations. The following CDD calculations are done using the weather data for the city of Sharjah in the United Arab Emirates:

1 CDD for the base year (e.g. 2014) and for a range of base temperatures from 15 to 25 °C. For each base temperature, this is the value needed for $CDD_{Base}$ in Eq. (1). Table 1 shows the results.

2 CDD for the consecutive years (e.g. 2015, 2016, 2017, 2018) and for a range of base temperatures from 15 °C to 25 °C. For each base temperature, this is the value needed for $CDD_{Est}$ in Eq. (1). Table 1 shows the results.

For each base temperature, and for each of the consecutive years, we calculate the ratio $CDD_{Est}/CDD_{Base}$ of Eq. (1). We then use Eq. (1) to estimate the energy consumption if the building is not retrofitted. This will be line (B) in Fig. 1 based on the CDD method.

To compare the difference between generating line (B) of Fig. 1 by using the two methods, Fig. 2 shows line (B) as (Bs) in case it is generated by the simulation and as (Bc) in case it is generated by the CDD method. The line (Bc) will be different for each base temperature.

**Table 1** Calculated CDD for different base temperatures

| Base temp. °C | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *2014* | *4792* | *4439* | *4087* | *3743* | *3413* | *3100* | *2804* | *2528* | *2271* | *2023* | *1791* |
| 2015 | 4825 | 4473 | 4123 | 3777 | 3443 | 3123 | 2824 | 2540 | 2265 | 2002 | 1754 |
| 2016 | 4720 | 4367 | 4015 | 3667 | 3330 | 3012 | 2711 | 2423 | 2147 | 1892 | 1657 |
| 2017 | 4859 | 4509 | 4160 | 3814 | 3472 | 3148 | 2841 | 2551 | 2279 | 2026 | 1789 |
| 2018 | 4824 | 4471 | 4119 | 3776 | 3446 | 3130 | 2830 | 2544 | 2272 | 2017 | 1774 |

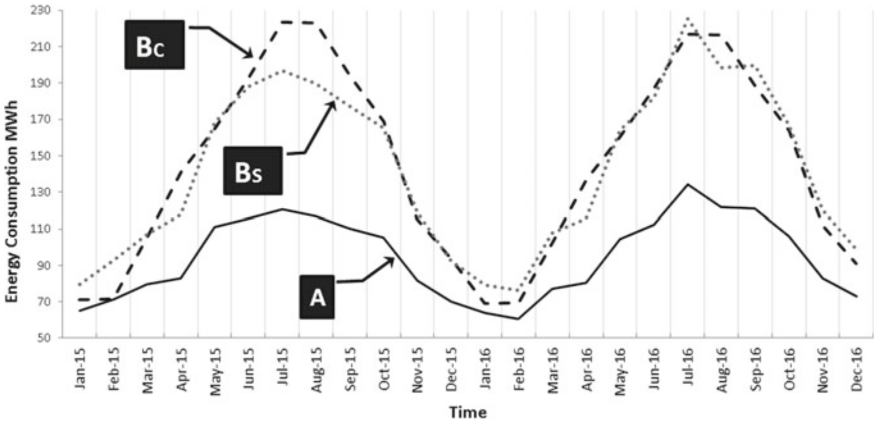



**Fig. 2** Estimated energy consumption if no retrofitting is done. Bs is calculated using the computer simulation. Bc is calculated using the CDD method (shown here for base temperature = 18 °C)

Using Fig. 2, the estimated saving based on the simulation result will be the difference between the values in line (Bs) and the values in line (A) for each of the studied years (e.g. 2015, 2016, 2017, 2018). We will refer to this simulation-based saving value as ($S_{Simulation}$). Similarly, the estimated saving based on the CDD method will be the difference between the values in the line (Bc) and the values in line (A) for each of the studied years. We will refer to this CDD-based saving value as ($S_{CDD}$). The deviation in using the CDD method in estimating the energy saving is calculated using Eq. (4) for each year and for each of the used base temperatures from 15 to 25 °C as shown in Table 2.

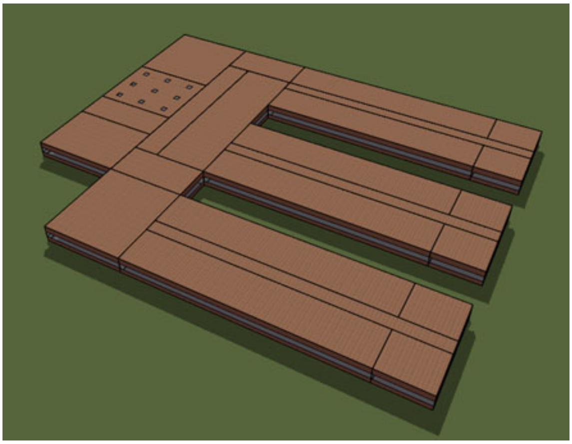
$$Deviation = \frac{(S_{CDD} - S_{Simulation})}{S_{Simulation}} \tag{4}$$

The same process is repeated but for two types of buildings and for three types of ECMs. The objective is to check if the nature of the building and the used ECMs will make a meaningful difference. The buildings types are:

**Table 2** Percentage of deviation in estimating energy saving when using the CDD method

| Base temp. °C | 15 (%) | 16 (%) | 17 (%) | 18 (%) | 19 (%) | 20 (%) | 21 (%) | 22 (%) | 23 (%) | 24 (%) | 25 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2015 | 2.0 | 2.2 | 2.5 | 2.6 | 2.5 | 2.1 | 2.1 | 1.4 | −0.6 | −2.9 | −5.8 |
| 2016 | −4.3 | −4.6 | −5.0 | −5.8 | −7.0 | −8.1 | −9.5 | −11.8 | −15.5 | −18.5 | −21.5 |
| 2017 | 4.2 | 4.7 | 5.3 | 5.7 | 5.1 | 4.6 | 3.9 | 2.8 | 1.1 | 0.5 | −0.3 |
| 2018 | 1.9 | 2.1 | 2.2 | 2.5 | 2.8 | 2.8 | 2.7 | 1.9 | 0.2 | −0.8 | −2.8 |
| Ave. deviation | **1.0** | **1.1** | **1.2** | **1.3** | **0.9** | **0.3** | **−0.2** | **−1.4** | **−3.7** | **−5.4** | **−7.6** |

**Fig. 3** The model for the primary school used

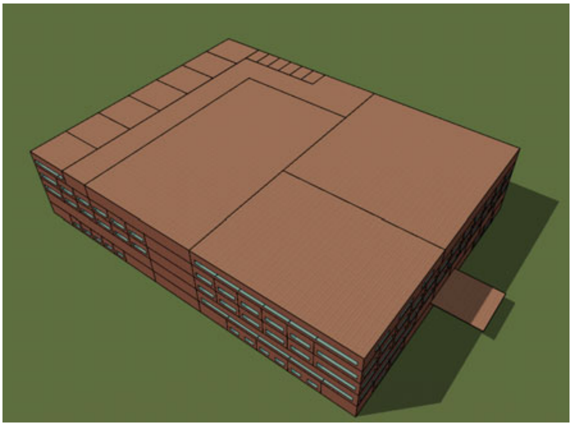


1 A primary school with a single floor and finger plan as shown in Fig. 3. Because of the form and the function of the building, it is considered to have an externally dominated cooling load and its energy performance is greatly impacted by the weather.
2 A hospital with a multi-story and deep plan as shown in Fig. 4. Because of the form and the function of the building, it is considered to have an internally dominated cooling load and its energy performance is less impacted by the weather.

Both modeled buildings are provided as templates by the software IES VE. The weather data for Sharjah is used for the years 2014 until 2018 and the cooling set point temperature is 24 °C. The three types of ECMs are:

1 ECMs directly related to the weather. The used ECMs are i) double the efficiency of the HVAC system used (from COP = 3.1 to COP = 6.2) and ii) double the R

**Fig. 4** The model for the hospital used



value of the roof (from R = 3.5 m$^2$°K/W to R = 7.0 m$^2$ °K/W). This is referred to as ECM (A).

2 ECMs not-directly related to the weather. The ECM used is replacing the florescent lighting with much more efficient LED light (The value for w/m$^2$ for each space is halved). This is referred to as ECM (C).

3 Both of the above ECMs are used. This is referred to as ECM (B).

The resulting consumption from the simulation in each case is the total building energy consumption and similarly is the estimated saving.

## 3 Results

Figure 5 shows the results of running the process for the school using the above mentioned three types of ECMs and for a range of base temperatures from 15 to 25 °C. The deviations have very different values for the same base temperature in

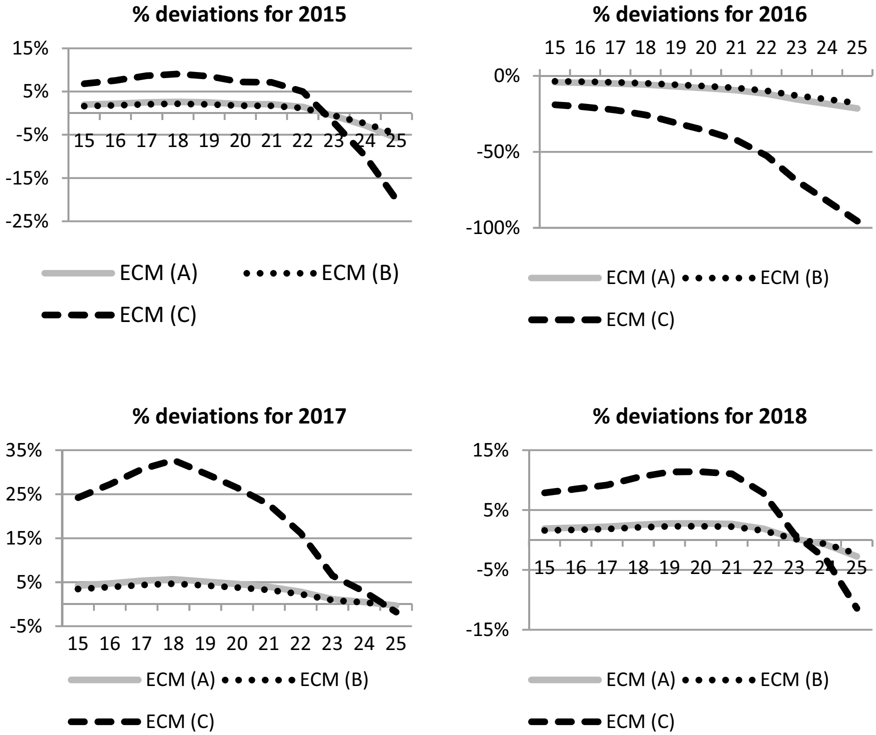



**Fig. 5** Change in the % deviation in energy savings due to the change in CDD base temperature for the different types of ECMs and for the different years under study. Note the different scales for the % deviation

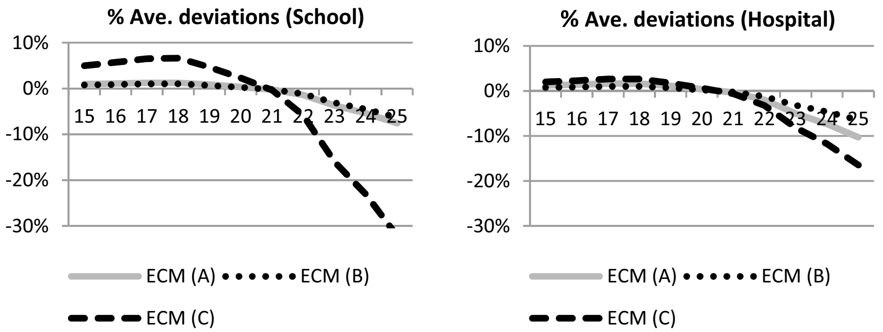



**Fig. 6** Average of the % deviations for the four years under study, for the different types of ECMs, and for the two building types

each year. However, ECM (C) which is not-directly related to the weather, always shows much bigger deviation values. This confirms the need to have sub-metering for these types of ECMs and to not depend on the total consumption of energy to estimate the resulting savings. The % deviations for the other two types of ECMs barely exceed 5% except for the year 2016.

The % deviations tends to converge to zero near a particular base temperature. However, this temperature changes every year. This is with the exception of the year 2016 which had less CDD than that of 2014 regardless of the base temperature as it was in general a cooler year than the others. Its % deviations are getting bigger as the base temperature increases.

Figure 6 shows the % deviations when averaged over the four years. There is a trend that is appearing for both the school and the hospital. The % deviations are converging towards zero for the three types of ECMs around the temperature 21/21.5 °C even though one building is internally dominated and the other is externally dominated. This is an interesting observation and can lead to a guideline for selecting an appropriate base temperature for calculating the CDD for a particular city.

## 4 Conclusion

This preliminary examination of the deviation in energy saving estimations due to the use of the Degree Days method should encourage both owners and ESCO to identify a better base temperature to use. More studies need to be done for longer periods of time, for different cities, and for more building types to provide better guidance. It is also important to note that the % deviation in using the CDD method is generally low except for the type of ECMs that are not-directly related to the weather.

## References


1. European Energy Efficiency Platform: Energy Performance Contracting. https://e3p.jrc.ec.europa.eu/articles/energy-performance-contracting. Last accessed 29 April 2019
2. Efficiency Valuation Organization: International Performance Measurement and Verification Protocol. https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp. Last accessed 29 April 2019.
3. BizEE: Custom Degree Day Data. https://www.degreedays.net/. Last accessed 29 April 2019
4. Bromley, M.: Degree days—understanding heating and cooling degree days. https://www.degreedays.net/introduction. Last accessed 29 April 2019
5. Azevedo, J., Chapman, L., Muller, C.: Critique and suggested modifications of the degree days methodology to enable long-term electricity consumption assessments—a case study in Birmingham, UK. Meteorol. Appl. **22**(4), 789–796 (2015)
6. IES Homepage: http://www.iesve.com/. Last accessed 29 April 2019

# Impact of Climate Zone and Orientation Angle on the Recurring Massing School Typologies in Turkey

**Yasemin Afacan**

**Abstract** In this study, the impact of different climate zones on same massing typologies of a typical school building with different orientation angles was quantified through building energy simulations of a case building in Turkey. The most schools in Turkey do not comply with the current energy code because they were built prior to the code. Thus, there is a crucial need to investigate their energy efficiency for potential retrofits. The results of the study exemplified how the breakdowns in energy use and carbon emissions would significantly influence design decision-making process of a school. Considering the four climate scenarios, mainly the influence of an orientation angle on energy use intensity (EUI) is higher than its influence on carbon emissions. This study differed from other sustainability researches in terms of defining building massing in schools with an emphasis on environmentally climate responsive school design, which is a holistic approach and comprehensive understanding of high-performance energy efficiency. A climate responsive massing should address the questions beyond well-known standards, and define a new holistic model that uses the optimum orientation, and surface to volume ratio of the building to reduce energy loads and achieve high-performance energy efficiency.

## 1 Introduction

School buildings play a critical role to contribute to the health and well-being of every society [1]. Schools represent a unique environment that differ from other building types, given that in a school, there are four times more occupants per square meter than in a typical office building [2]. Occupants spend much of their time inside classrooms. This occupancy schedule patterns make school buildings responsible for a significant portion of the total energy consumption of the non-residential sector. Schools require special attention on sustainable building managements so that early

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decisions on building massing, classroom layouts, geometry parameters and spatial configurations of each function have critical impact on energy efficiency. Previous massing studies in schools have largely focused on solely plan layout, such as linear, corridor etc., and compactness of geometrical shape parameters related to different typologies [3], such as L-C-U-H shapes, linear corridor or central with different classroom dimensions, pavilion, slabH, slabV and courtyard types etc., to compute energy performance of schools [4–6]. However, compactness of a shape is not always the optimal solution for energy efficiency [7–9]. Even with the same shape, it is not possible to have well-specified energy measures for schools [9].

Although there are a number studies on the relationship between energy efficiency and building forms in developed countries, there is a lack of studies analysing correlations among energy use, different climate scenarios and building orientations of similar massing typologies in developing countries, such as Turkey. In Turkey, in recent years due to the difficulty of producing different projects for each school considering diverse range of climate types, time constraints, staff shortage and financial problems, the production of a typical project application has become more intense. Thus, this study investigates how the energy efficiency of a similar building massing varies depending on the four climate zones and simulates a typical Turkish school building in the four representative cities at the four different orientation angles. Based on the results of climate zone assessments, it proposes a simulation-based climate proofing in order to define a set of proper massing parameters and to decide the correlations among massing typologies, different climate zones and the key energy loads of schools, such as heating, cooling etc.

## 2 Energy Impacts of School Typologies

Energy impacts of buildings have been discussed first in United Nations Brundtland Commission in 1987, then UN Commission Report in 1992 on sustainable development and Kyoto Conference by UN Framework on climate change. In 2002 European Energy Efficiency Directive [10] investigated building optimization to reduce their impacts on energy consumption. In 2012 and 2018, net zero energy buildings have been presented by the European Directives [11, 12]. Hence, most of the school buildings both in Europe and in most of the countries around the world were built before those dates of the directives so that they could not satisfy energy efficiency directives [13]. Thus, there are lots of studies exploring energy efficiency in school buildings, measures related to building envelope, and enhance energy performance through environmentally responsive design.

There are uncertainties in energy performance of schools depending on the country, location and climate zones. Reviewing the literature on the energy impacts of school typologies showed that there are many different definitions of typologies and energy consumption patterns accordingly. Some studies defined typology classifications as massing types based on the overall configurations [14–16]; whereas the others described it based on the proportions of a 2D drawing [17, 18]. Afacan and

Ranjbar [9] investigated the five most commonly used school massing typologies in the contemporary school architecture: (1) Spine/street—major school functions along a central linear space; (2) City/town—a loose type of massing with more potential of legible school functions; (3) Atrium- a full height atrium serving passive solar design, thermal inertia and access outside views; (4) Strawberry/cluster—a central core providing circulation; and (5) Courtyard—flexible layout around the courtyard with enhanced energy efficiency benefits. These typologies did not differ according to the age of the students. They were prevalent for primary, secondary and high schools. They found significant differences in terms of annual energy use, annual energy cost and annual carbon dioxide ($CO_2$) emissions among the massing types, and suggested a new holistic model based on the ratio of surface area to volume more for reducing energy loads of a typical high-performance schools [9].

According to the Statistics of the Turkish Ministry of National Education, there are 25.5 million students which means that one third of the Turkey's population spends the majority of their time in school buildings [19]. In the academic year of 2017–2018 in Turkish primary and high schools, about 18 million students taught by 1 million teachers in total 66,000 schools [20]. Thus, school buildings in Turkey have a great importance in energy consumption. The total energy consumption of non-residential sector in Turkey has increased 174% compared to the energy consumption in 1990. The schools contribute 23% to this total energy consumption, which forces the educational building retrofit to tackle this challenge [19]. Due to their high-energy consumption, high occupant density and high activity patterns, schools represent a significant category among the other building typologies to be responsible for a considerable amount of energy consumption. In UK and US, school buildings are responsible for 10% and 13% of total energy consumption respectively [13]. Since Turkey has experienced a considerable surge in energy demand [21], achieving energy efficiency in current school building stocks becomes crucial because sustainable design, planning and construction decrease energy consumption by reducing environmental pollution, controlling energy waste patterns, maintenance and transportation costs [7].

With regards to the European Energy Efficiency Directives, in 2000 Turkey considered energy efficiency measures for the schools that were newly constructed, but the majority of the existing schools were constructed before 2000 without a focus on energy performance and were not gone any energy refurbishment later on. In Turkey, typical school projects were designed by the Ministry of Public Works to be used in all regions until the year 1970 [20]. Later, in 1980, there were minor revisions in these typical projects regarding regional energy differences. After 1997, when 5-year compulsory primary education was extended to 8 years. The adaptation of existing buildings was mostly done with the addition of floors, which ignored the relationship between energy demand and massing typology.

# 3 Materials and Methods

## *3.1 Selection of Climate Zones and the Reference Cities*

According to Köppen-Geiger Climate Classification [22], Turkey's climate is defined as mild Mediterranean. However, there are significant differences in climatic conditions in Turkey because of its diverse geographical characteristics. For example, in the Mediterranean region, the mountains are parallel to the sea, which makes the coastal region milder with warm summers and mild-to-cool winters than the Central Anatolia. On the other hand, the inland regions have a dry climate with hot summers and cold winters. So, the climate classification of the Turkish Standard 'TS 825 Thermal Insulation Requirements in Buildings' [23] defined 4 climate zones. In 2008, TS 825 was adapted from 'ISO 9164- thermal insulation calculation of space heating requirements for residential buildings' [24] and 'BS EN 832-thermal performance of buildings calculation for energy use for heating residential buildings' [25]. Although it neglects the cooling loads, it is still the mandatory document in Turkey regarding energy efficient heating energy requirements for all buildings. Figure 1 illustrates how these four climate zones are distributed on Turkey.

In this study, the case building was situated in Konya, which was located in the third climate zone as a hot-summer Mediterranean climate with hot summers and snowy winters [26]. The case building was constructed in 1993 without considering the energy efficiency. It had a double-loaded corridor plan, used a central heating system and was ventilated by manually opened windows. Three representative cities, Istanbul, Izmir and Erzurum, from the other three climate zones were used to simulate the projected energy efficiency performance of the case study building regarding the different climate zones (Table 1). Istanbul has a borderline Mediterranean climate, humid subtropical climate and oceanic climate, with a hot dry summer, pleasantly

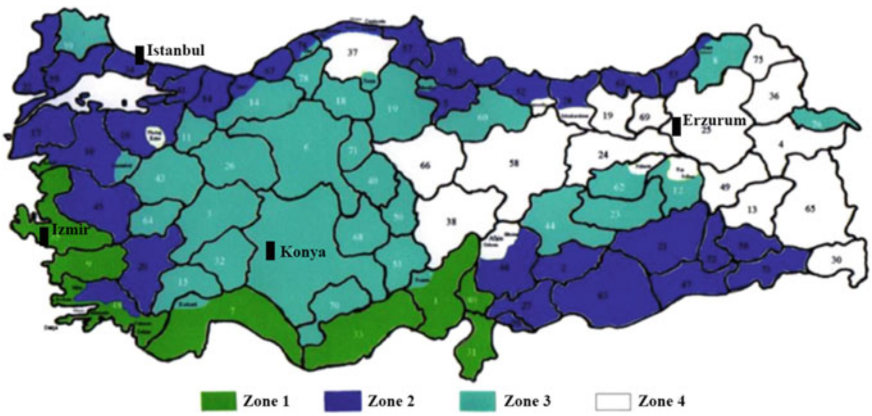


**Fig. 1** Four-climate zone of Turkey based on TS 825

**Table 1** Climate zone and descriptions

| Zone number | City | Zone description |
|---|---|---|
| Zone 1 | İzmir | Mediterranean climate zone—hot and dry summers, warm and rainy winters |
| Zone 2 | İstanbul | Borderline Mediterranean climate, humid subtropical climate and oceanic climate—a hot dry summer, warm spring and autumn, and cold winters |
| Zone 3 | Konya | Hot-summer Mediterranean—hot summers and snowy winters |
| Zone 4 | Erzurum | Humid continental climate—hot and dry summers, and cold and snowy winters |

warm spring and autumn, and cold winters with rare snow [22]. İzmir is located in the Mediterranean climate zone, where summers are hot and dry, and winters are warm and rainy. Erzurum has humid continental climate with hot and dry summers, and cold and snowy winters [22]. In the literature, there are lots of studies on the impact of different climate zones to ensure energy efficiency. This study differed from these sustainability researches in terms defining building massing in schools with an emphasis on environmentally climate responsive school design, which is a holistic approach and comprehensive understanding of high-performance energy efficiency. A climate responsive massing should address the questions beyond well-known standards, and define a new holistic model that uses the optimum orientation, and optimum surface to volume ratio of the building more for reducing energy loads than a typical high performance schools.

### 3.2 Building Envelope Details

The school had a total gross area of 5400 m$^{2.}$ The building was a four storey building in U-Shape with 19 classrooms and 760 primary school children and 37 teachers (Figs. 2 and 3). The construction standards of the case building are presented in Table 2, and the main parameters of the building envelope materials are given in Table 3. The central heating system with radiators was used for heating. There was no cooling equipment in the typical school building. Cooling was achieved through natural ventilation by manually operated windows. There were no automatic lighting controls. The common lighting equipment in the typical school building was fluorescent lighting, cool-white fluorescent bulbs (LPD = 12 W/m$^2$).

### 3.3 Data Analysis, Modelling and Simulation

The preliminary data collection and analysis consisted of a review of the energy bills of the school, typical occupancy data, and technical specifications of the building. A site visit was done to the building to examine actual system and get a deeper insight of the school's operation. Natural gas and electricity bills of the school were analysed to calibrate the simulation data. Inside and outside photographs of the building were taken. An infrared camera was used to capture the entire temperature profile of the building and to see temperature differences on surfaces. Figure 4 shows an example image of what the thermal camera observed regarding heat losses. The problematic areas were mostly window frames. Although they were insulated, there was no rubber gasket or weather-stripping around the opening, air escapes around the edges.

The study developed a dynamic calibrated energy simulation model of the school building by using Sefaira program simulations. Sefaira's Real-Time Analysis Plugins use EnergyPlus, a validated professional energy simulation tool [27], as their primary simulation engine to assess energy and thermal performance based on architecture,


Fig. 2 Aerial images of the site and the case building

lighting and mechanical systems, occupancy and use, and local weather. Constant feedbacks on envelope and material U values were provided by design parameters in Sefaira's Real-Time Analysis.

## 4 Results and Discussion

For each climate context, simulations were run for annual energy use, energy use intensity (EUI) cost and annual $CO_2$ emissions. In addition to the climatic parameters, the building performance was also calculated regarding the four orientations of the case building in each city; (i) baseline model; (ii) 90° rotated model; (iii) 180° rotated model, and (iv) 270° rotated model.

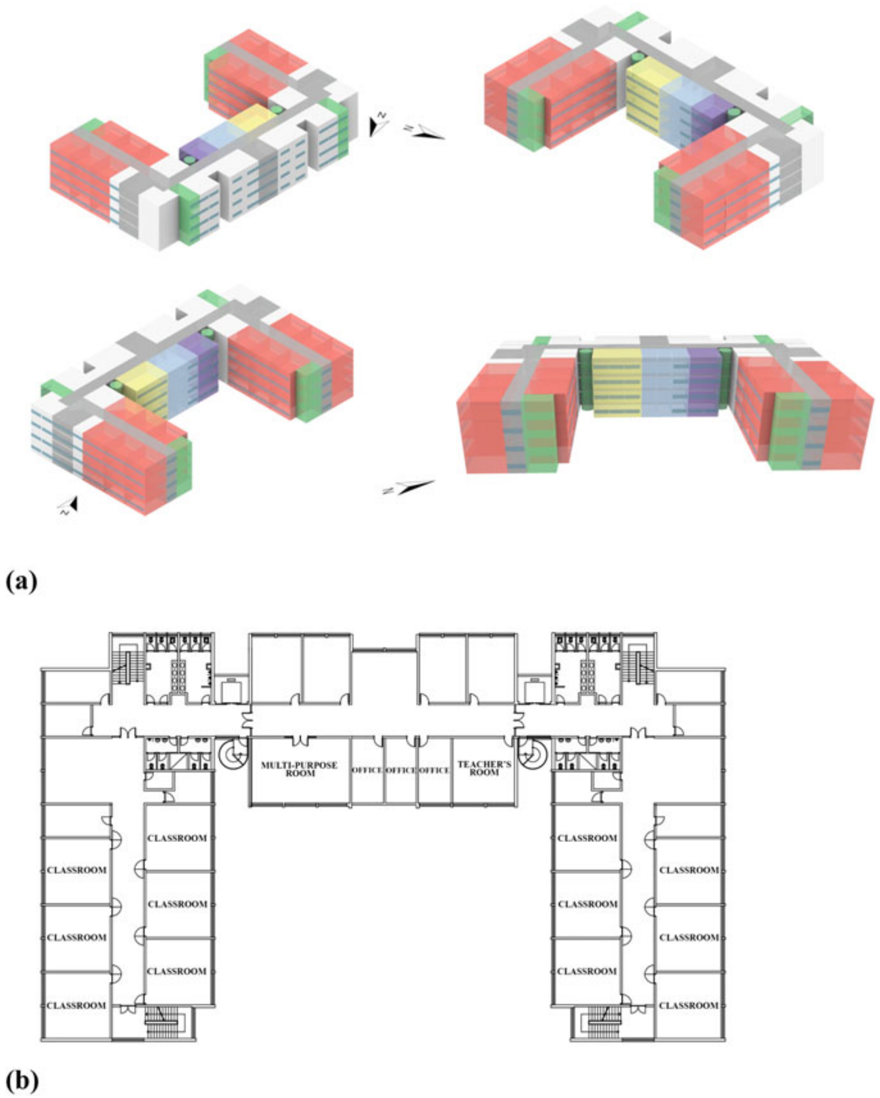


**Fig. 3** **a** Plan view of the first floors of the case building; **b** four views of the case building

**Table 2** The construction standards of the case building

| Climate zone | City | U (W/m$^2$ K) External wall | Ground floor | Roof | Glazing |
|---|---|---|---|---|---|
| 3 | Konya | 1.06 | 1.42 | 0.73 | 3.49 |

**Table 3** The main parameters of the building envelope materials

| Material | d (m) | λ (W/m K) | R ($m^2$ K/W) |
|---|---|---|---|
| *External walls* | | | |
| Cement plaster | 0.03 | 1.6 | 0.019 |
| Brick Wall | 0.28 | 1.2 | 0.233 |
| EPS | 0.16 | 0.04 | 1.60 |
| Cement plaster | 0.03 | 1.6 | 0.019 |
| *Ground floor* | | | |
| Laminate floor | 0.008 | 0.115 | 0.07 |
| Cement mortar | 0.05 | 1.4 | 0.036 |
| Plain concrete | 0.10 | 1.65 | 0.03 |
| Reinforced concrete | 0.20 | 2.5 | 0.08 |
| Damp proof membrane | 0.05 | 0.3 | 0.167 |
| Gravel | 0.10 | 2.0 | 0.05 |
| *Roof* | | | |
| Glasswool | 0.05 | 0.05 | 1.00 |
| Reinforced concrete | 0.20 | 2.50 | 0.08 |
| Cement plaster | 0.03 | 1.6 | 0.019 |

### *4.1 Impact on Energy Consumption*

The EUI changes from 103 kWh/m$^2$/year (minimum) to 136 kWh/m$^2$/year (maximum) (Table 4). These values, even the high one, are good values, because according to ASHRAE 2018 Advanced Energy Design Guide for K-12 School Buildings [28] for achieving 50% energy savings, the targeted value for EUI is around 110 kWh/m$^2$/year for these four climate zones. The reason for these low EUI values is the high performance envelope considering lighting and cooling. The classes are scheduled until 4.00 p.m. so that most of the time daylighting satisfies the visual performance. The summer holidays, from 1st June to 1st September, are assumed unoccupied so that less cooling or even no cooling is required. However, it should be noted that in buildings, where daylighting is not as much as available as the others, and where buildings are occupied during the summer period, the EUI is much higher.

As seen from Table 4, similar to the previous researches mentioned in the literature section, this study also found that a proper orientation angle results in the reduction of energy consumption. However, different than those researches, this study identified that the impact of orientation on energy consumption in Mediterranean zones are not as much as significant compared to the zones, where summers are very hot, and winters are very cold and snowy. By orienting the building at an angle of 180°, there would be a reduction of EUI of 9% in non-Mediterranean zones, whereas 4% in Mediterranean zones. This finding is critical during the decision making process of a more environmentally responsive school massing. To maximize energy efficiency,

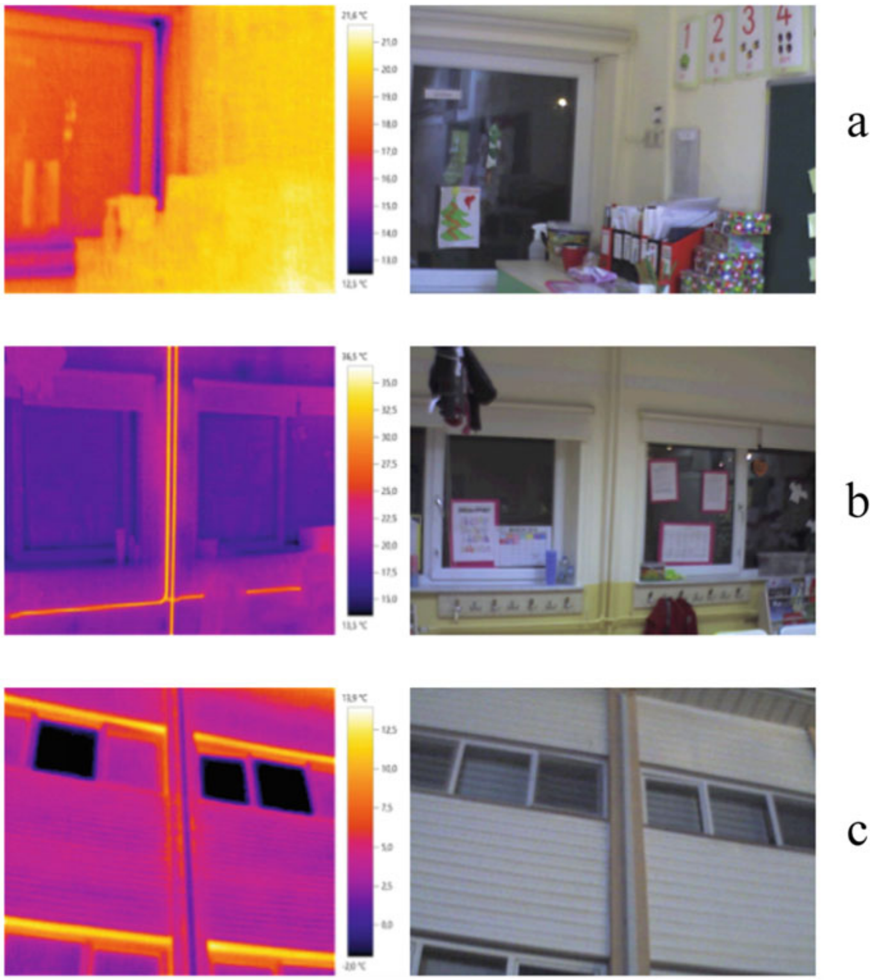

**Fig. 4** Thermal camera view of a window wall **a**, **b** from inside and **c** outside

the priority could be given on the size and number of classrooms, number of stories, window to wall ratio and room depth, which could have a direct impact on annual heating and cooling energy.

Figure 5 illustrates the energy breakdown. Mainly heating energy increased in climatic zones, in which lowest winter temperatures occurred. However, comparing this heating demand profile against the cooling energy consumption, it was clear that they were not in the same pattern. This was due to the fact that cooling in Turkey is achieved by natural ventilation in most of the schools. Although this leaded to decrease cooling energy consumption, it resulted in unhealthy consequences in terms of indoor environmental quality provided to students. The $CO_2$, temperatures and humidity levels in classrooms without proper ventilation reach above the limits after

**Table 4** The energy use intensity (EUI) of each city in four different orientations

| City | Orient degree | Air handling | Cooling | Heating | Energy Use | Annual cooling energy per unit area (kWh/m$^2$/year) | Annual heating energy per unit area (kWh/m$^2$/year) | EUI (kWh/m$^2$/year) |
|---|---|---|---|---|---|---|---|---|
| | | AHU design airflow (L/s) | Cooling equip. design capacity (kW) | Heating equip. design capacity (kW) | HVAC (fancoil + central) energy per unit area (kWh/m$^2$/year) | | | |
| Konya | 0°-Baseline | 6427 | 290.4 | 379.9 | 84.94 | 9.62 | 49.29 | 130.34 |
| | 90° | 6427 | 292.0 | 379.4 | 83.01 | 8.92 | 48.31 | 128.41 |
| | 180° | 6427 | 273.5 | 377.8 | 81.12 | 8.69 | 46.99 | 125.52 |
| | 270° | 6427 | 330.7 | 379.4 | 86.67 | 10.73 | 48.76 | 136.07 |
| Erzurum | 0°-Baseline | 6427 | 292.0 | 351.1 | 80.62 | 17.59 | 33.02 | 126.02 |
| | 90° | 6427 | 274.7 | 348.0 | 74.36 | 16.31 | 28.70 | 119.76 |
| | 180° | 6427 | 281.3 | 347.0 | 72.45 | 16.11 | 26.79 | 117.85 |
| | 270° | 6427 | 313.1 | 351.5 | 82.42 | 18.95 | 32.18 | 128.82 |
| İstanbul | 0°-Baseline | 6427 | 398.2 | 336.6 | 67.97 | 14.81 | 26.00 | 113.37 |
| | 90° | 6427 | 401.3 | 327.7 | 67.24 | 14.16 | 25.79 | 112.64 |
| | 180° | 6427 | 394.9 | 328.0 | 65.55 | 13.93 | 24.76 | 110.95 |
| | 270° | 6427 | 441.3 | 336.7 | 70.25 | 15.87 | 25.96 | 115.65 |
| İzmir | 0°-Baseline | 6427 | 385.0 | 291.0 | 62.33 | 18.88 | 13.44 | 107.73 |
| | 90° | 6427 | 392.7 | 276.7 | 59.70 | 18.05 | 11.04 | 105.10 |
| | 180° | 6427 | 376.8 | 277.4 | 58.57 | 17.69 | 10.73 | 103.97 |
| | 270° | 6427 | 424.0 | 290.5 | 65.32 | 20.54 | 13.06 | 109.72 |

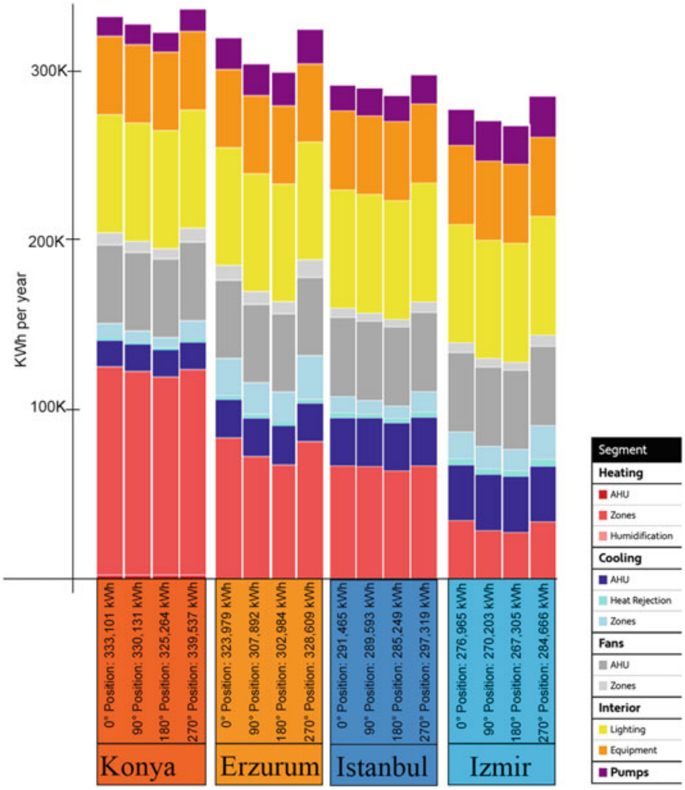


**Fig. 5** The energy breakdown regarding the climate zones and orientation

twenty minutes of the occupation [2, 4]. Moreover, getting fresh air through manually operated windows also create uneven heat distribution and thermal discomfort especially for the students sitting near windows [4]. Another significant finding was that the interior energy demands regarding lighting and other electrical equipment did not differ much regarding both the climatic zones and orientation. The reason for this finding was that there were typical and similar lighting systems in most of the schools without paying attention on its impact on health, performance and stress of students. However, the use of lighting sensors has not only positive effect on glare reduction and appropriate illuminance levels, but also it directly impacts EUI value of a school building with a same massing typology.

## 4.2 *Impact on $CO_2$ Emissions*

The highest annual net $CO_2$ emissions were obtained in both Erzurum and İzmir at the orientation angle of 270° (Table 5). Although these two climate zones were the least

**Table 5** Annual energy costs and $CO_2$ emissions of each city in four different orientations

| City | Orient degree | Energy costs | | | | | | $CO_2$ Emissions |
|---|---|---|---|---|---|---|---|---|
| | | Annual Energy Cost ($) | Annual Elect. Cost ($) | Annual Gas Cost ($) | Annual Energy Cost Per Area ($/m2) | Annual Elect. Cost Per Area ($/m2) | Annual Gas Cost Per Area ($/m2) | Annual Net $CO_2$ Emissions (kg/ $CO_2$e/year) |
| Konya | Baseline | 67,262.9 | 55,809.6 | 11,453.3 | 26.16 | 21.71 | 4.45 | 1,131,572.18 |
| | 90° | 66,378.3 | 55,152.5 | 11,225.8 | 25.82 | 21.45 | 4.37 | 129,801.63 |
| | 180° | 65,677.0 | 54,757.9 | 10,919.1 | 25.55 | 21.30 | 4.25 | 128,332.10 |
| | 270° | 68,689.4 | 57,358.0 | 11,331.4 | 26.72 | 22.31 | 4.41 | 134,172.17 |
| Erzurum | Baseline | 71,699.4 | 64,025.4 | 7674.0 | 27.89 | 24.90 | 2.98 | 137,883.31 |
| | 90° | 69,358.9 | 62,687.8 | 6671.2 | 26.98 | 24.38 | 2.59 | 132,989.74 |
| | 180° | 68,916.5 | 62,689.7 | 6226.8 | 27.81 | 24.38 | 2.42 | 131,931.61 |
| | 270° | 73,320.4 | 65,840.7 | 7479.7 | 28.52 | 25.61 | 2.91 | 140,808.56 |
| İstanbul | Baseline | 66,190.4 | 60,146.5 | 6043.9 | 25.75 | 23.39 | 2.35 | 126,746.08 |
| | 90° | 65,785.2 | 59,790.3 | 5994.9 | 25.59 | 23.26 | 2.33 | 125,963.88 |
| | 180° | 65,093.8 | 59,339.6 | 5754.3 | 25.32 | 23.08 | 2.24 | 124,547.31 |
| | 270° | 67,780.0 | 61,747.3 | 6032.6 | 26.36 | 24.02 | 2.35 | 129,708.18 |
| İzmir | Baseline | 68,034.9 | 64,910.0 | 3124.9 | 26.46 | 25.25 | 1.22 | 128,666.32 |
| | 90° | 67,318.0 | 64,750.8 | 2567.2 | 27.18 | 25.19 | 1.00 | 127,036.67 |
| | 180° | 66,687.3 | 64,194.0 | 2493.3 | 26.94 | 24.97 | 0.97 | 125,820.51 |
| | 270° | 70,271.9 | 67,236.2 | 3035.7 | 29.33 | 26.15 | 1.18 | 138,796.76 |

efficient for the case building in terms of carbon emissions, the EUI values in Erzurum and Izmir were not the highest values (Fig. 6). The reason for this emission result was the differences in breakdowns of energy performance and emissions regardless of the climate type. It was striking that the emissions of the cooling load in these two cities were higher than the other two. In Izmir, cooling load was mainly concerned with AHU systems, and in Erzurum with zone cooling. This result highlighted the essential role of climate based heating and cooling strategies in terms of the decarbonisation of electric industry, rather than prototyping of the same heating and cooling systems, which caused higher values of annual energy use. These simulated results were also in line with the literature and underline the critical importance of indoor comfort conditions that were also strongly correlated with passive and active measures of a building envelope and interior architecture of the school building. As illustrated in Table 5, annual energy costs per area were also higher in these cities. This result confirmed that emissions due to the heating could be reduced but this reduction could lead to the increased of carbon emissions due to cooling. As it was stated by Dino and Akgul [29], the intensity of cooling is much more higher than heating for Turkey.

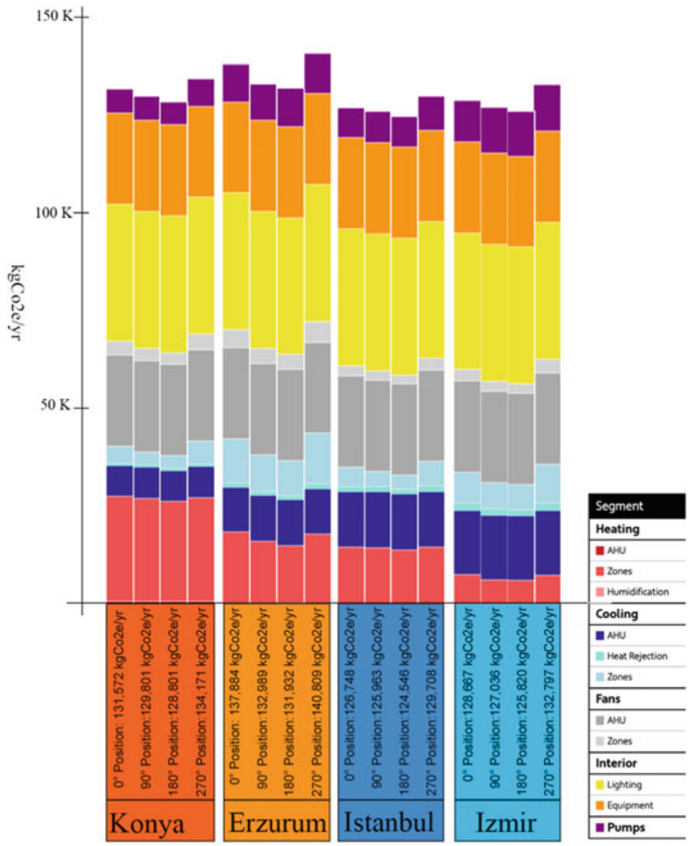


**Fig. 6** The $CO_2$ emissions breakdown regarding the climate zones and orientations

According to the findings, several retrofit scenarios could be developed. As passive strategies, the U values of roof, walls and glazing could be lowered to reduce both $CO_2$ emissions and energy consumption. Shading devices or shutters could be added into the critical facades. A green roof would also help lowering urban heat island effect, as well as providing recreational space for children. As active strategies, air-conditioning equipment or heat recovery units could be introduced to classrooms considering their structural system and suspended ceiling availability. The HVAC management is a complex and dynamic issue that should be considered along carbon density and electricity generations.

To further discuss the results, the study identified the essential role of the two following massing strategies: (i) optimizing the building orientation and (ii) defining a set of massing parameters. Building orientation is an energy performance-related factor that cannot be modified, but managed through retrofit passive design strategies. It plays a key role in energy efficient school design. However, it is not enough alone. Making optimized decisions on orientation parameters at the conceptual stage of design process could help to maximize all aspects of energy performance. Decisions on orientation in construction or occupation phase would be too late. Thus, the simulated results in the study pointed to the future need to explore measures for climate adaptation of a proper massing typology and to taking account interior layout and classroom proportions based on the various orientation angles. So, the study proposed a multi-criteria decision making optimization that should include a more extensive manipulation of interior and exterior relationships. Although the simulations done in the study were limited with the four climate zones, and four orientation angles for each zone, for future studies a decision matrix for retrofitting strategies could be constructed, where a new set of climate variables could be identified, and prioritized data of design requirements could be correlated with those variables.

In addition to the proper choice of a good site and orientation based on the variables of that site, spatial layout design and functional organizations are essential components of defining a set of massing parameters. We have not found any earlier studies configuring climate-based massing types for minimal energy use based on multiple usage and seasonal and daily occupancy schedule. To achieve such efficiency and improve energy performance, this study presented a unique opportunity for the exploration of what a school massing type should offer for designing new buildings as well as retrofitting existing according to different climate scenarios. Thus, it suggested climate based exploration strategies of building massing in schools with an emphasis on environmentally responsible school interior design.

## 5 Conclusion

In this study, the impact of different climate zones on the same massing typologies with different orientation angles was quantified through building energy simulations of a case building in Turkey. The results of the study exemplified how the breakdowns in energy use and carbon emissions would significantly influence design decision-making process of a school building. It could result in different massing and orientation choices to achieve energy efficiency. In the study, as expected, different climate zones resulted in different heating and cooling requirements. Considering the four climate scenarios, mainly the influence of orientation angle on EUI was higher than its influence on carbon emissions. Considering the four orientation angles, energy use in itself of each zone remained relatively constant regarding heating loads, but energy use varied considerably regarding cooling loads. However, carbon emissions of each zone remained constant regarding both the heating and cooling loads. These results contributed to the advancement of the research in developing countries that are undergoing rapid building and urban regeneration process, because it does not only propose strategies for new school design, but also retrofitting the existing ones trough a simulation-based climate proofing. The implications of this study could be summarized from the two points of view. The first point is related with its practical implications suggesting that the Ministry of Public Works could use the typical school projects across all the regions by taking adaptive actions on different heating and cooling loads through passive measures. In this context, the same school massing could be treated as a shell, which is later modified in site depending on the trade-offs between climatic conditions and energy consumption patterns. The second point is that there is a need for adaptive energy models specific to school buildings. Instead of referring to the climate zone requirements, these models should take the hottest occupied and coldest occupied months into consideration to calculate $CO_2$ emissions. To extend the contribution of this study in design practice and generalize the effect of school building massing on energy efficiency, a detailed climate impact analysis, where combinations of building shapes, window to wall ratio, room depth and orientation parameters, could be performed as a future study. In addition, both design and construction of schools should consider the subjective preference of users even during massing decisions. Proper school massing will not only improve energy savings, but also enhance subjective feeling of all users.

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## References

1. Ashrafian, T., Moazzen, N.: The impact of glazing ratio and window configuration on occupants' comfort and energy demand: the case study of a school building in Eskisehir, Turkey. Sustain. Cities Soc. **47**, 101483 (2019).
2. da Graça, V.A.C., Kowaltowski, D.C.C.K., Petreche, J.R.D.: An evaluation method for school building design at the preliminary phase with optimisation of aspects of environmental comfort for the school system of the State São Paulo in Brazil. Build. Environ. **42**, 984–999 (2007)
3. Crowe, N.: Studies in typology. J. Archit. Educ. **38**(1), 10–13 (1984)
4. Montenegro, E., Potvin, A., Demers, C.: Impact of school building typologies on visual, thermal and energy performances. In: Proceedings of 28th International Conference on Passive and Low Energy Architecture, pp. 2012–2017. PLEA, Lima, Perú (2012).
5. Quan, S.J., Economou, A., Grasl, T., Yang, P.P.J.: Computing energy performance of building density, shape and typology in urban context. Energy Procedia **6**, 1602–1605 (2014)
6. Zhang, A., Bokel, R., van den Dobbelsteen, A., Sun, Y., Huang, Q., Zhang, Q.: The effect of geometry parameters on energy and thermal performance of school buildings in cold climates of China. Sustainability **9**, 1708–1727 (2017)
7. Hawkes, D.: The Environmental Tradition: Studies in the Architecture of Environment, 1st edn. E & FN Spon, London (1996)
8. Douglas, J.: Building Adaptation. Butterworth-Heinemann, Edinburgh (2006)
9. Afacan, Y., Ranjbar, A.: Impact of building massing on energy efficient school buildings. In: Littlewood, J., Howlett, R., Capozzoli, A., Jain, L. (eds.) Sustainability in Energy and Buildings. Smart Innovation, Systems and Technologies, vol. 163. Springer, Singapore (2020)
10. EU Directive 2002/91/EC of the European parliament and of the council of 16 December 2002 on the energy performance of buildings. Off. J. Eur. Union 65–71 (2002)
11. EU Directive 2012/27/EU of the European parliament and of the council of 25 October 2012 on energy efficiency. Off. J Eur. Union Dir., 1–56 (2012).
12. EU Directive 2018/844 of the European parliament and of the council of 30 May 2018 amending directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency (2018)

13. Krawczyk, D.A.: Theoretical and real effect of the school's thermal modernization—a case study. Energy Build. **81**, 30–37 (2014)
14. Granadeiro, V., Correia, J.R., Leal, V.M.S., Duarte, J.P.: Envelope-related energy demand: A design indicator of energy performance for residential buildings in early design stages. Energy Build. **61**, 215–223 (2013)
15. De Jaeger, I., Reynders, G., Ma, Y., Saelens, D.: Impact of building geometry description within district energy simulations. Energy **158**, 1060–1069 (2018)
16. Ndiaye, D.: The impact of building massing on net-zero achievability for office buildings. Build. Simul. **11**, 435–448 (2018)
17. Gratia, E., De Herde, A.: Design of low energy office buildings. Energy Build. **35**(5), 473–491 (2003)
18. Dogan, T., Saratsis, E., Reinhart, C.: The optimization potential of floor-plan typologies in early design energy modeling. In: 14th International Conference of IBPSA - Building Simulation 2015, BS 2015, Conference Proceedings, pp. 1853–60 (2015)
19. Turkish Statistical Institute, http://www.turkstat.gov.tr/VeriBilgi.do?alt_id=39. Last accessed May 2019
20. Turkish Ministry of National Education, http://www.meb.gov.tr/en/. Last accessed Feb 2019
21. Ozcan, M.: The role of renewables in increasing Turkey's self-sufficiency in electrical energy **82**, 2629–2639 (2018)
22. Koppen Climate Classification|climatology. Encyclopedia Britannica, https://www.britannica.com. Last accessed 1 Jan 2019
23. TSE 825: Turkish Standard, Thermal insulation requirements for buildings (2008)
24. ISO 9164.1989. Thermal Insulation Calculation of Space Heating Requirements for Residential Building, Geneva, Switzerland (1989)
25. BS EN 832:2000. Thermal Performance of Buildings, Calculation of Energy Use for Heating. Residential Buildings (2000)
26. Konya Climate and Temperature, https://en.climate-data.org/asia/turkey/konya/konya-190/, last accessed 2019/01/01.
27. Garwood, T.L., Hughes, B.R., Oates, M.R., O'Connor, D., Hughes, R.: A review of energy simulation tools for the manufacturing sector **81**, 895–911 (2018)
28. ASHRAE. Advanced Energy Design Guide for K-12 School Buildings. U.S. Green Building Council (2018)
29. Dino, I.G., Meral Akgül, C.: Impact of climate change on the existing residential building stock in Turkey: an analysis on energy use, greenhouse gas emissions and occupant comfort. Renew. Energy **141**, 828–846 (2019)

# Analysis of the Influence of Aerodynamic Roughness on Urban Vertical Space Form: An Example of Shenzhen Central Area

**Di Song, Ming Lu, Jun Xing, Jing Liu, and Lu Wang**

**Abstract** This paper selects the impact of urban roughness element on ventilation as a research perspective, taking the central area of Shenzhen as an example, extracting vertical spatial shape influence parameters, and analyzing aerodynamic roughness and spatial shape based on different land use types. Then the relationship between roughness and spatial form is constructed to clarify the parametric interpretation between the roughness of the underlying surface of the urban space and the spatial form, so that subsequent urban development can combine this relationship to obtain better ventilation effects.

## 1 Introduction

In the process of urban development, the distribution of high-rise buildings in the artificial underlay surface accounts for an increasing proportion. In the vertical direction, reasonable ventilation conditions are closely related to the health and comfort of residents [1, 2]. Therefore, it is necessary to quickly estimate the impact of urban ventilation to guide future urban development, the layout of different types of land and even the distribution of buildings in the land [3]. At the same time, the huge

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amount of data contained in the urban space also puts forward requirements for the convenience of the evaluation process and the use of tools.

## 2 Literature Review

Due to the non-uniform nature of the complex spatial form of the city, the air flow within the city is complex [4]. The high-density artificial environment increases the vertical height of the urban canopy and also strengthens the barrier to wind [5]. Therefore, there is a close relationship between the spatial shape formed by the artificial environment and the weakening of wind speed [6]. Theoretical research on the wind speed attenuation trend is mainly explained by aerodynamic roughness parameters [7] The roughness length ($Z_0$) is used to explain the height where the average wind speed is 0, and express the weakening effect of the urban canopy on the wind speed. displacement height ($Z_d$) expresses that the effect of airflow and underlying surface occurs at a certain height, and this height represents the roughness [8]. The size of the two parameters directly affects the energy exchange between the earth and the atmosphere, and at the same time has a close relationship with the urban spatial form [9]. The determination of the two parameters can be calculated by wind speed observation, or calculated by urban spatial morphological characteristics [10]. The morphological parameters used in the calculation also changed from the initial only based on the height of the building to later gradually introducing standard deviation, extreme value, average value and other parameters to participate in the calculation. Grimmond and Oke combined the urban form to point out the empirical calculation method of the two parameters, and at the same time verified The rationality of the calculation method proposed by Raupach [11, 12]. Macdonald introduced the windward area and improved the drag coefficient of rough elements, making the calculation method more sensitive to rough elements with higher density and higher non-uniformity [13]. Kanda et al. pointed out that the calculation method that considers all parameters at the same time has formed very good results in the verification examples of Japanese cities [14]. Kent et al. conducted a comparative study on calculation methods in London and believed that considering more parameters would help improve the roughness calculation accuracy of the complex underlying surface [15].

For the city itself, a large number of buildings and different height distributions make it very difficult to directly perform numerical simulations. Therefore, other methods are needed to predict the ventilation environment of the city. Mikhailuta combines weather data and comparisons with urban development to determine the relationship between the two [16]. Yuan, Ren combined GIS data and roughness parameters to analyze urban ventilation conditions [17]. In addition, there is also an analysis of the urban ventilation influence through the overall urban void, obstruction and vertical section parameters [18]. In the way of rapid urban modeling, it is often based on two-dimensional basic data, combined with Autocad and SketchUp to complete the modeling [19]. The use of GIS modeling is suitable for conventional buildings. At the same time, in order to quickly assess the wind environment, the use of a regular aerodynamic roughness database can effectively reduce the complexity of the model and make the modeling process more efficient [20].

From the above research, in the face of a complex and non-uniform underlying surface, aerodynamic parameters are still the current mainstream calculation method for describing spatial roughness, and the spatial shape parameters required in the calculation are gradually becoming more complex and precise. For the huge amount of data of urban space, the rules of modeling under GIS platform will facilitate the rapid extraction of morphological parameters, but studies the relationship between roughness and spatial form weak. Based on the existing foundation, under the premise of rapid modeling and parameter extraction, this research expands the description of vertical spatial morphology and establishes an association relationship with roughness to provide a reference for morphological description and statistical laws for subsequent urban development.

## 3 Methodology

### *3.1 Database Construction*

In this study, the basic information of urban buildings is obtained by domestic electronic map providers, and the height of urban buildings is checked by combining three-dimensional panorama and field investigation, and a vector layer with a spatial resolution of 1 m is formed [21, 22]. The database needs to be combined with the needs of ventilation impact analysis, simplifying some details of the building, and then encapsulating it into a ARCGIS element file and collecting the relevant information of spatial points, lines, and areas in it [23]. According to the national standard " Code for classification of urban land use and planning standards of development land", it is divided with reference to the intermediate category, which is used as the use mark of land and buildings [24], and finally the urban space element classes required for the analysis are formed.

### *3.2 Vertical Morphological Parameter Selection*

In the vertical direction, the most intuitive parameter of a city is the height of the building. In addition, in order to truly express the complex heterogeneity of the urban space, Need to select the average value ($Z_h$), standard deviation ($\sigma_h$), maximum value of the height ($H_{\max}$), plan area fraction ($\lambda_p$), surface area fraction ($\lambda_b$), and windward area fraction ($\lambda_f(\theta)$) to reflect the difference in urban spatial height distribution, canopy height, and the degree of obstruction to incoming wind [23, 25]. Taking into account the uncertainty of the urban wind flow direction, the windward area of each building under different wind direction distributions needs to be weighted $\overline{\lambda_f}$. In the same way, considering the area inequality of similar heights of urban buildings, it is also necessary to introduce the plane of the building to weight the average height $\overline{z_h}$.

### 3.3 Methods of Analysis

The calculation of roughness parameters $Z_0$ and $Z_d$ from the perspective of morphology is mainly based on the formula pointed out by Kanda et al. [14]:

$$\mathrm{Z}_0 = \left[20.21 * \left(\frac{\lambda_p \sigma_h}{\overline{Z_h}}\right)^2 - 0.77 * \left(\frac{\lambda_p \sigma_h}{\overline{Z_h}}\right) + 0.71\right] * \left(1 - \frac{\mathrm{Z_{dm}}}{\overline{Z_h}}\right)\mathrm{EXP}\left\{-\left[0.5\beta\frac{\mathrm{C_{1b}}}{\mathrm{k}^2}\left(1 - \frac{\mathrm{Z_{dm}}}{\overline{Z_h}}\right)\lambda_\mathrm{f}\right]^{-0.5}\right\} \tag{1}$$

where:

$$\mathrm{Z_{dm}} = \left[1 + 4.43^{-\lambda_p}\left(\lambda_p - 1\right)\right] * \overline{Z_h} \tag{2}$$

$$\mathrm{Z_d} = -0.17 * \left(\frac{\sigma_h + \overline{Z_h}}{H_{\max}}\right)^2 + \left(1.29 * \lambda_p^{0.36} + 0.17\right) * \left(\frac{\sigma_h + \overline{Z_h}}{H_{\max}}\right) \tag{3}$$

where $Z_{dm}$ is the dynamic roughness calculation method proposed by Macdonald in [26], $\beta = 1.0$ is the drag correction parameter [15], and $C_{1b} = 1.2$ is the drag coefficient [27]. The calculation of the above formulas and various vertical morphological parameters, through the construction of Excel functions and Grasshopper scripts and expansion, finally forms a basic database for urban vertical ventilation impact analysis, and is visualized in the database space through the ARCGIS platform, and the roughness and vertical Analysis of the correlation between the morphological parameters and the degree of mutual importance (Table 1).

## 4 Analysis of the Impact of Urban Vertical Ventilation

### 4.1 The Central Area of Shenzhen Overview

The location of the study, Shenzhen, is a super-large city in Guangdong, located on the coast of South China, with a subtropical monsoon oceanic climate [28]. Hot in summer and warm in winter, the dominant wind direction throughout the year is NNE-NE-ENE, the probability of static wind is 2.1%, the average wind speed is 2.25 m/s,

**Table 1** Analysis method of Urban Spatial shape parameters

| Parameters | Expression method |
|---|---|
| Weight the average height ($\overline{z_h}$) standard deviation ($\sigma h$), maximum value of the height ($H_{max}$) | AVERAGE command, sequential command, STDEVP command |
| Number of height intervals | SUMPRODUCT command |
| Plan area fraction $\lambda_p$ | ARCGIS-VB script operation |
| Surface area fraction $\lambda_b$ | Analysis Tools, ARCGIS-VB script operation + SUMIF function command |
| Weighted windward area fraction ($\overline{z_f}$) | Grasshopper + ARCGIS VB script operation + SUMIF function command |

and the overall wind speed shows a downward trend year by year [29] (Figs. 1 and 2). Combined with the needs of national development, the current construction land is tight and the construction density is high, which reduces the ventilation rate. Therefore, the research value of urban ventilation impact analysis and improvement of urban air circulation is of great value.

The research institute refers to the three districts of Nanshan, Futian, and Luohu in the central area. This area is the longest construction period in Shenzhen, the main area of politics, economy, production and life, and there are mountains with high vegetation coverage in the north. Import element data through ArcMap and form basic element maps and statistical tables. After statistics and field surveys are approved, the area contains 99,210 buildings, 9681 pieces of land of various types, and an area of 265.78 square kilometers. The number of buildings is huge and the uses are complete, including all types in the useful land classification. The statistics of each land use are shown in Table 2.

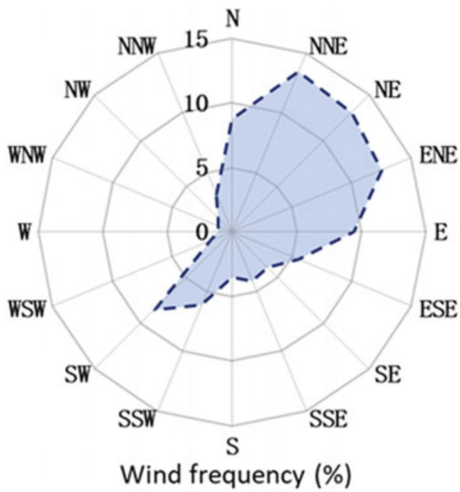


**Fig. 1** Yearly wind frequency distribution in Shenzhen

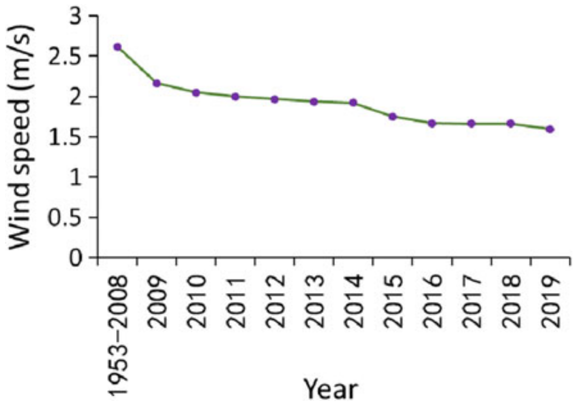


**Fig. 2** Yearly wind speed distribution in Shenzhen

## *4.2 Planar Spatial Analysis*

(1) Weighted average ($\overline{Z_h}$) standard deviation ($\sigma_h$), maximum value ($H_{\max}$): Overall, the minimum value of the building in the central area is 3 m and the maximum is 599.1 m. the weighted average height is 29.39 m, and the standard deviation is 23.74. From the perspective of the proportion distribution (Fig. 3), the main height of buildings below 36 m occupies more than 88% of the proportion, constituting the largest rough influence surface under the canopy. From the perspective of height extremes and weighted averages of various types of land (Fig. 4; Table 2), building extremes mainly exist in commercial and commercial, high-tech parks, and second-class residential land. From the perspective of standard deviation, the fluctuations are relatively high. Larger values mainly exist in commercial, medical and second-class residential buildings. The current situation is mostly high-rise/super high-rise buildings with multi-story annex buildings.

(2) Plan area fraction ($\lambda_p$) and surface area fraction ($\lambda_b$): According to statistics, the total area of the building base within the central area is 338,200 square meters, with an overall density of 0.13, which is prone to wake turbulence and affect the downwind area of the city [30]. According to the statistics and spatial distribution of $\lambda_p$ values of various types of land (Fig. 5), the land parcels prone to wake turbulence account for a relatively high proportion. Among them, urban villages are prone to flooding due to the high construction density. The main urban green areas and borders Ports and road traffic facilities are prone to isolated flow, which promotes urban ventilation (Table 2).

From the perspective of the spatial distribution of the surface area fraction (Fig. 6), the main business districts and Central Business District in the three districts have concentrated a large number of rough elements. At the same time, they have obtained most of the building surface area due to the large height. In addition, high-rise residential areas and densely distributed urban village units also have a larger $\lambda_b$ value. The $\lambda_b$ value tends to 0 due to the very few

**Table 2** Statistical table of vertical morphological parameters of urban space

| Land use nature | Code | Land area (km$^2$) | Amount | $H_{\max}$ (m) | $\sigma_h$ | $\overline{Z_h})$ | $\lambda p$ | $\lambda_b$ | |
|---|---|---|---|---|---|---|---|---|---|
| administration | A1 | 2.89 | 1627 | 199.4 | 21.671 | 21.908 | 0.239 | 1.204 | |
| culture | A2 | 1.02 | 365 | 94.7 | 21.668 | 11.636 | 0.389 | 1.132 | 0.219 |
| Education and Research | A3 | 10.77 | 4748 | 120.0 | 19.814 | 12.399 | 0.195 | 0.971 | 0.220 |
| physical education | A4 | 1.51 | 346 | 84.8 | 18.895 | 9.206 | 0.233 | 0.552 | 0.097 |
| medical hygiene | A5 | 1.19 | 831 | 116.3 | 27.600 | 20.080 | 0.263 | 1.725 | 0.431 |
| Social welfare, historic sites and religion | A679 | 0.13 | 160 | 35.2 | 10.364 | 9.103 | 0.322 | 1.302 | 0.288 |
| Business | B1 | 6.36 | 4197 | 375.6 | 23.196 | 23.418 | 0.392 | 1.705 | 0.388 |
| Commercial affairs | B2 | 11.40 | 5571 | 599.1 | 55.401 | 45.908 | 0.324 | 2.678 | 0.711 |
| Entertainment, public outlets and other services | B349 | 7.01 | 1917 | 89.1 | 11.688 | 7.291 | 0.112 | 0.333 | 0.067 |
| Green space and square | G123 | 33.00 | 2207 | 86.6 | 8.567 | 6.410 | 0.014 | 0.043 | 0.009 |
| Regional traffic, public facilities, special facilities and border ports | H2349 | 8.00 | 1168 | 104.6 | 13.335 | 9.486 | 0.081 | 0.248 | 0.050 |
| Agriculture and forestry | E2 | 95.57 | 1013 | 28.8 | 7.579 | 4.173 | 0.002 | 0.007 | 0.001 |
| Reserved, to be built | E9 | 14.77 | 2619 | 120.0 | 10.182 | 8.740 | 0.060 | 0.183 | 0.037 |
| industry | M | 11.52 | 6016 | 304.3 | 17.482 | 13.075 | 0.271 | 0.989 | 0.217 |
| Roads and traffic | S2349 | 2.00 | 398 | 54.0 | 14.763 | 10.613 | 0.196 | 0.468 | 0.081 |
| 1st residential building | R1 | 0.58 | 709 | 34.6 | 11.805 | 5.523 | 0.227 | 0.999 | 0.237 |
| 2nd esidential building | R2 | 44.08 | 35,269 | 388.1 | 37.763 | 28.645 | 0.281 | 2.692 | 0.671 |
| Village in the City | R3 | 7.87 | 27,689 | 63.5 | 20.593 | 8.506 | 0.427 | 3.608 | 0.993 |
| Public facilities, logistics and warehousing | UW | 6.12 | 2360 | 54.0 | 14.214 | 7.833 | 0.221 | 0.603 | 0.117 |

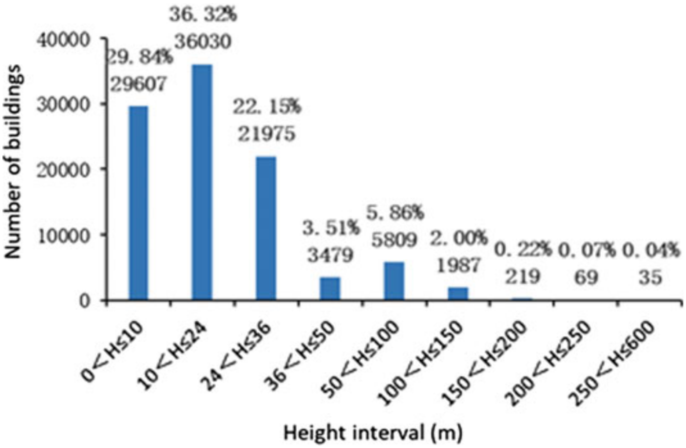


**Fig. 3** Building height distribution in central area

buildings in the urban green space and agricultural and forest land, and the roughness is very low (Table 2).

(3) Weighted windward area fraction $\left(\overline{\lambda_f}\right)$: Affected by the element rule processing of the database, the statistics of the windward surface have the same area in the opposite direction. However, since the wind frequency distribution in Shenzhen is different in all directions, a weighted statistical result of 16 wind directions is finally obtained. The overall windward area score of Shenzhen is 0.22, and the spatial distribution reaches the highest value near the Central Business District of each district (Fig. 7). Among all types of land, administrative office, medical, commercial and commercial, second-class and third-class residential buildings all have higher windward areas, Easy to cause insufficient space comfort. The low-value areas mainly include woodland, green space, various transportation facilities, and sports venues (Table 2).

## *4.3 Physical Space Analysis*

In the central area as a whole, the existence of most of the land and its buildings will cause obstacles to urban ventilation. The $Z_d$ value of the displacement height is between 0.630, indicating that the vertical influence height of the urban cushion to the wind is 630 m. The roughness length $Z_0$ value is between 0 and 607, indicating that the first quiet wind area appears when the wind speed is 607 m, and these effects are caused by the construction of super high-rise buildings. From the distribution of the two parameters of each land use, the $Z_d$ value of most of the land is between 30 and 60, and half of the $Z_0$ value is between 2 and 10, which has an obstructive effect on the vertical ventilation of the city; the other half is less than 1. It will promote

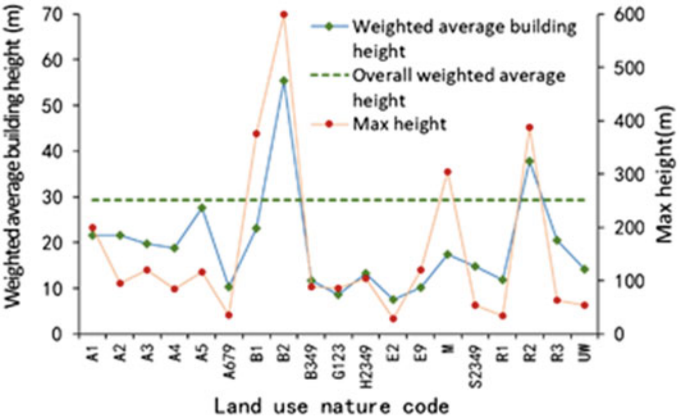


**Fig. 4** Building mean/extreme line chart in central area

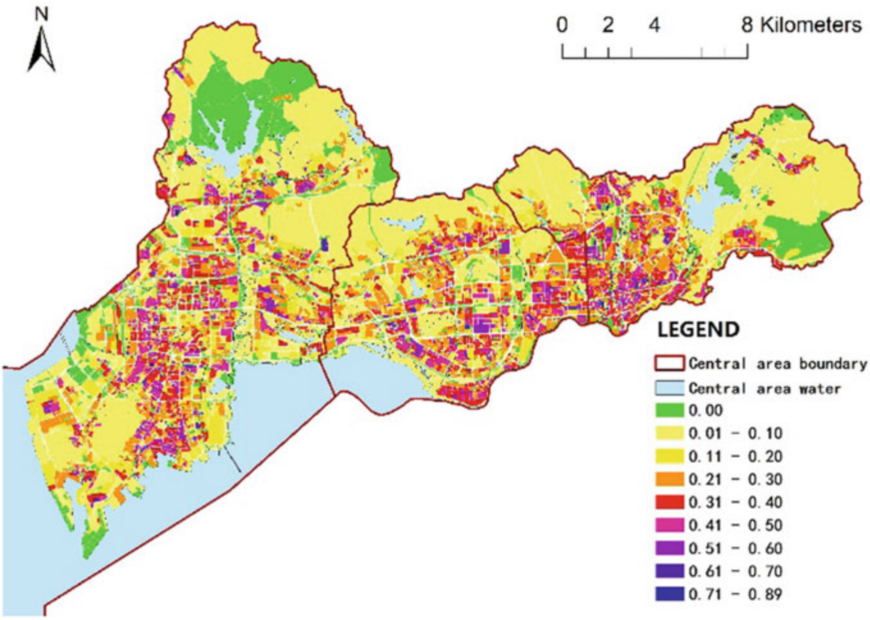


**Fig. 5** Central area fractional map

the ventilation of the city; the existence of super high-rise commercial buildings and residential buildings makes the $Z_0$ value of both high, which hinders higher canopy ventilation (Figs. 8 and 9).

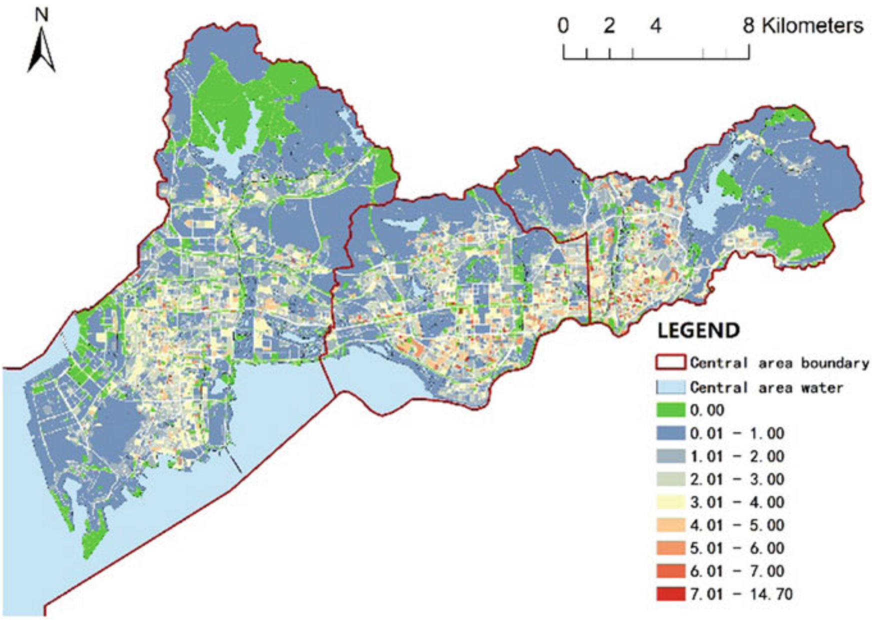


**Fig. 6** Surface area fraction diagram of central area

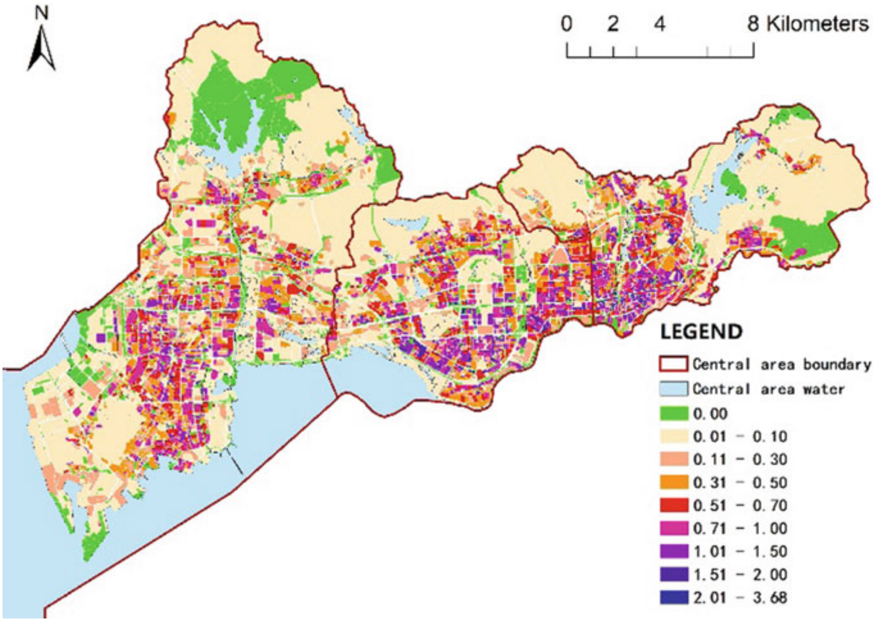


**Fig. 7** Distribution map of the weighted windward area score of the central area

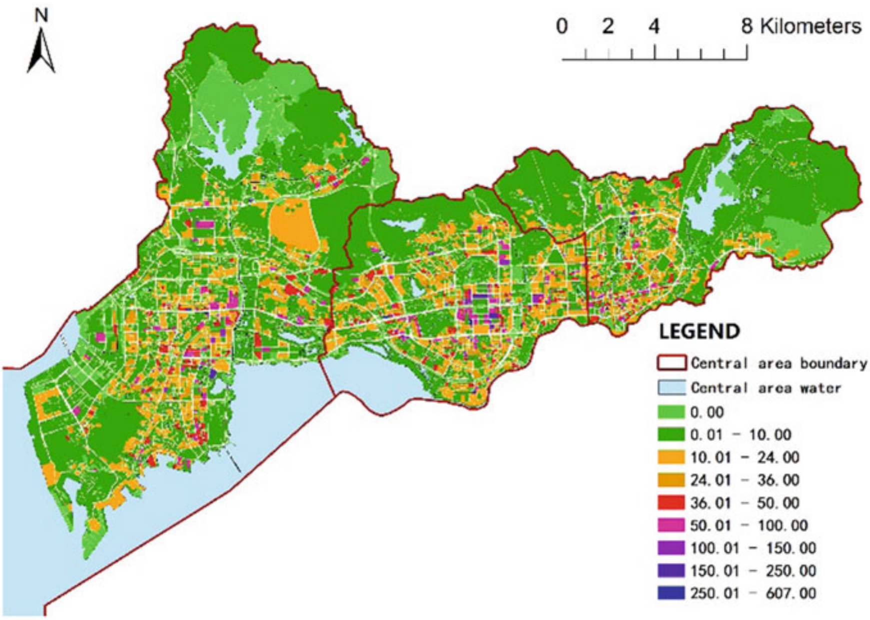


**Fig. 8** Distribution of zero plane displacement $Z_d$ in the central area

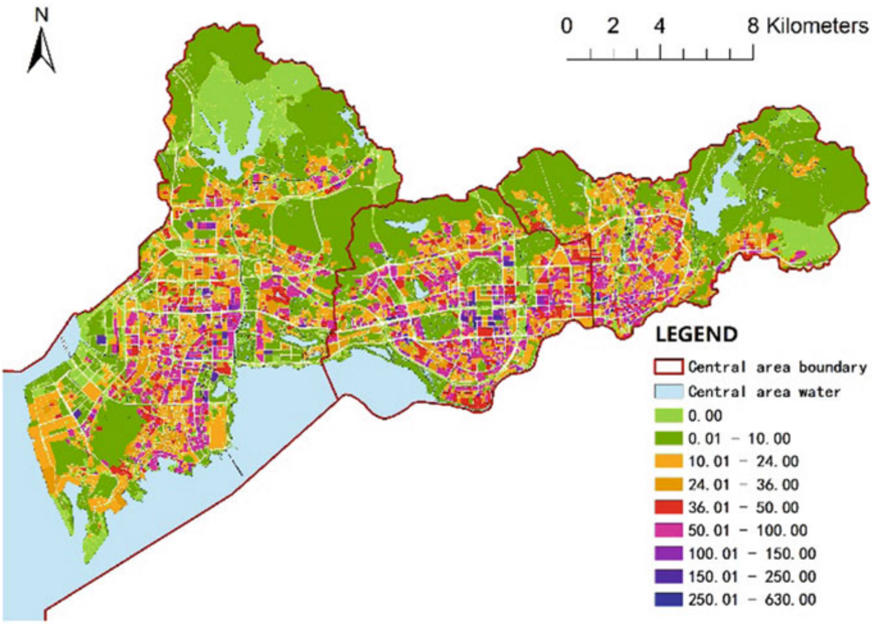


**Fig. 9** Distribution of roughness length $Z_0$ in the central area

### 4.4 Correlation Analysis of Vertical Parameters and Roughness

Using aerodynamic roughness parameters and urban vertical spatial morphological parameters to carry out a univariate regression analysis, the analysis results and correlations are shown in the figure (Fig. 10). In the results, the roughness length $Z_0$ and the standard deviation and extreme values are significant Correlation. The displacement height $Z_d$ is significantly correlated with the weighted average height, standard deviation, and extreme value, and has a good correlation with the surface area score and the weighted windward area score.

The multiple regression analysis of the aerodynamic roughness parameters and the vertical spatial morphological parameters is carried out, and the importance distribution of each spatial morphological parameter to the displacement height $Z_d$ and

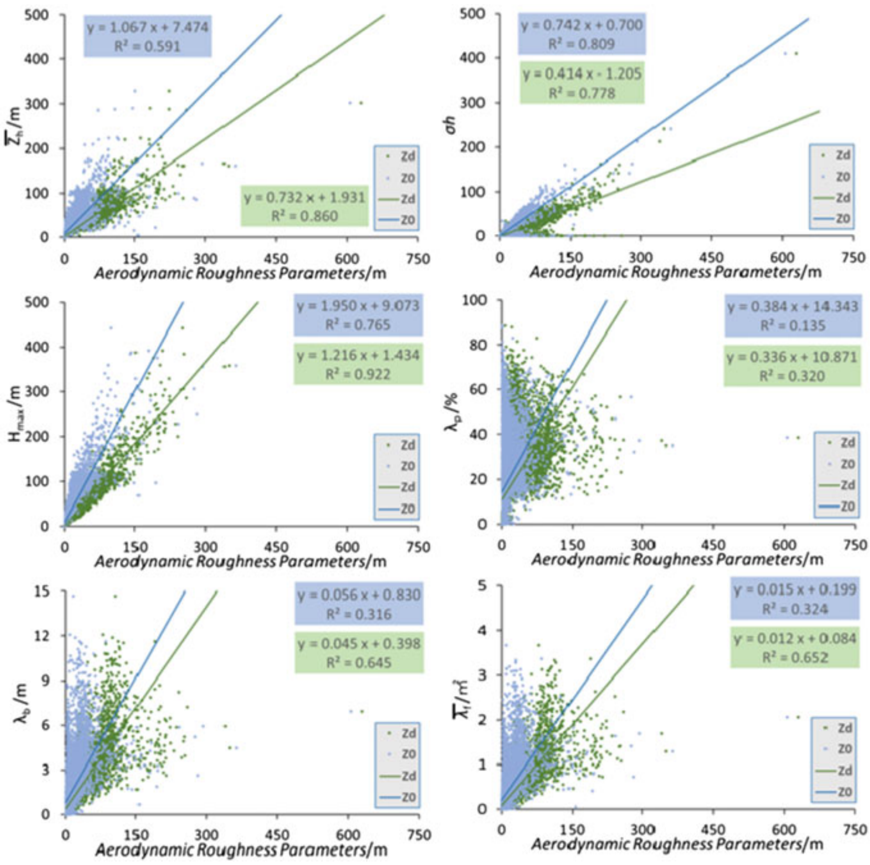


**Fig. 10** Schematic diagram of the relationship between aerodynamic roughness parameters and vertical parameters

the roughness length $Z_0$ is obtained:

$$\mathrm{Z_d} = -1.449 + 0.104\mathrm{H_{max}} + 0.827\sigma_h + 8.345\lambda_p + 0.1\lambda_b + 0.537\overline{Z_h} + 7.469\overline{\lambda_\mathrm{f}} \tag{4}$$

$$\mathrm{R}^2{=}0.984 \quad \beta_{\mathrm{H_{max}}}{=}\ 0.131 \quad \beta_{\sigma_h} = 0.388 \quad \beta_{\lambda_p} = 0.050$$
$$\beta_{\lambda_b}{=}\ 0.006 \quad \beta_{\overline{Z_h}} = 0.424 \quad \beta_{\overline{\lambda_\mathrm{f}}} = 0.112$$

$$\mathrm{Z_0} = -0.271 + 0.079\mathrm{H_{max}} + 0.769\sigma_h - 0.669\lambda_p - 0.928\lambda_b + 0.217\overline{Z_h} - 2.636\overline{\lambda_\mathrm{f}} \tag{5}$$

$$\mathrm{R}^2 = 0.862 \quad \beta_{\mathrm{H_{max}}} = 0.176 \quad \beta_{\sigma_h} = 0.635 \quad \beta_{\lambda_p} = -0.007$$
$$\beta_{\lambda_b} = -0.092 \quad \beta_{\overline{Z_h}} = 0.301 \quad \beta_{\overline{\lambda_\mathrm{f}}} = -0.069$$

From the above equation, the vertical spatial form parameters that can explain the central area of 98.4 and 86.2% $Z_d$, $Z_0$ changes, which have an important impact on the value of $Z_0$ is the standard deviation (0.635), the weighted average of the height (0.301) and the extremum (0.176), the weighted height average (0.424), standard deviation (0.388), extreme value and weighted windward area (0.131/0.112) have an important influence on the $Z_d$ value.

## 5 Discussion

The current cities are showing increasingly strong heterogeneity and high roughness, and the canopy height is gradually becoming higher due to the construction of super high-rise buildings. In this study, The novelty is embodied in the regression analysis of spatial morphological parameters and aerodynamic parameters that affect the vertical direction, the use of unary regression analysis to grasp the impact of a single parameter of air obstruction, and the use of multiple regression analysis to grasp the degree of influence of multiple parameters on air obstruction The size enables the future development of the city to control the parameters to expand the design, thereby reducing the scope of influence of the spatial roughness. The follow-up research will carry out the numerical simulation study of typical cases, and further couple with the vertical wind speed and pressure, and finally form a more suitable urban space development strategy.

The limitation at this stage is that the windward area calculated by the Grasshopper script can be adapted to large-scale urban spatial data extraction, but the windward area extraction for more complex and irregularly shaped buildings still has limitations. Commonly used software, such as Sketch Up, can directly perform architectural three-dimensional projection and combine it with the database, which can improve the accuracy of the research.

Under future urban development, huge changes in heterogeneity and canopy height will be inevitable. For Shenzhen, the subject of this study, there is still a large amount of land to be constructed in the stage of plan approval or construction. In the future In the development of the city, the architectural form and distribution will be more complex and diverse, and the requirements for architectural form and spatial height and density distribution will be more precise. In this way, it promotes the effective circulation of wind in the vertical space of the city.

## 6 Conclusions

This study uses GIS and Grasshopper platform to extract city-related parameters, and combines Excel function calculations to build a model suitable for city-scale analysis, and then combines aerodynamic roughness parameters and vertical spatial shape parameters for statistical analysis.

The research results show that displacement height and roughness length can be used as vertical ventilation influence indicators for large-scale urban central areas under the current algorithm, and they are positively correlated with vertical spatial morphological parameters. Taking Shenzhen central area as an example, the total height of the urban canopy is 599.1 m, the main vertical roughness is within a range of 36 m above the ground; super high-rise buildings are mostly distributed on commercial and second-class residential land in the central area.

The linear regression model shows that the influence of vertical spatial morphology parameters on aerodynamic roughness parameters can explain the influence of more than 85% of the spatial morphology in Shenzhen's central area on vertical ventilation. From the point of view of importance, in the future urban construction of Shenzhen, attention should be paid to the control of the height difference of the buildings in the plot, building density, the height and location of the tallest building, and the relationship between building volume and height.

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## References

1. Chang, H., Xiang, C., Duan, C., et al.: Study on the thermal performance and wind environment in a residential community. J. Hydrogen Energy **41**(35), 15868–15878 (2016)
2. Ragheb, A.A., El-Darwish, I.I., Ahmed, S.: Microclimate and human comfort considerations in planning a historic urban quarter International Journal of Sustainable. Built Environ. **5**(1), 156–167 (2016)
3. Wen, C.-Y., Juan, Y.-H , Yang, A.-S.: Enhancement of city breathability with half open spaces in ideal urban street canyons – Sci. Direct Build. Environ. **112**, 322–336 (2017)
4. Zhou, S., Shu, W.: Urban Climatology. Meteor-ological Press (1994)
5. Li, T.: Research on urban wind tunnel construction and planning method based on urban form and surface roughness. Master thesis, Shenzhen University (2017)

6. Hsieh, C.M., Huang, H.C.: Mitigating urban heat is-lands: a method to identify potential wind corridor for cooling and ventilation. Computers Environ. Urban Syst. **57**, 130–143 (2016)
7. Ju, Y.: Research on kinetic roughness and thermodynamic roughness of different underlying surface types. Master thesis, Nanjing University of Information Science & Technology (2012)
8. Tang, Y., Ma, B., Wang, X., et al.: Analysis on applicability of morphology methods in the estimation of aerodynamic parameter of urban areas in Shanghai. Torrential Rain Disasters **39**(4), 382–391 (2020)
9. Graf, A., Boer, A., Moene, A., et al.: intercomparison of methods for the simultaneous estimation of zero-plane displacement and aerodynamic roughness length from single-level eddy-covariance data. Bound.-Layer Meteorol. **151**(2), 373–387 (2014)
10. Li, Y., Gao, Z., Lenschow, D.H., et al.: An improved approach for parameterizing surface-layer turbulent transfer coefficients in numerical models. Bound.-Layer Meteorol. **137**(1), 153–165 (2010)
11. Grimmond, C., Oke, T.R.: Aerodynamic properties of urban areas derived from analysis of surface form. J. Appl. Meteorol. **38**(38), 1262–1292 (1999)
12. Raupach, M.R.: Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. Bound.-Layer Meteorol. **71**, 211–216 (1994)
13. Hawkes, D.J., Macdonald, R., Walkter, S., et al.: Measurements of dispersion within simulated urban arrays—a small scale wind tunnel study. J. Appl. Meteorol. **80**, 178–196 (1996)
14. Kanda, M., Inagaki, A., Miyamoto, T., et al.: A new aerodynamic parametrization for real urban surfaces. Bound.-Layer Meteorol **148**, 357–377 (2013)
15. Kent, C.W., Grimmond, S., Barlow, J., et al.: Evaluation of urban local-scale aerodynamic parameters: implications for the vertical profile of wind speed and for source areas. Bound.-Layer Meteorol. **164**(2), 183–213 (2017)
16. Mikhailuta, S.V., Lezhenin, A.A., Pitt, A., et al.: Urban wind fields: phenomena in transformation. Urban Climate **19**, 122–140 (2016)
17. Yuan, C., Ren, C., Ng, E.: GIS-based surface roughness evaluation in the urban planning system to improve the wind environment—a study in Wuhan, China. Urban Climate **10**, 585–593 (2014)
18. Steemers, K.: Sustainable urban design: Issues, research and projects. World Architect. **8**, 34–39 (2004)
19. Xiao, X., Zhu, Q., Du, Z., et al.: A semantics-constrained profiling approach to complex 3D city models. Comput. Environ. Urban Syst. **41**(9), 309–317 (2013)
20. Luo, Y., He, J., et al.: A rule-based city modeling method for supporting district protective planning. Sustain. Cities Soc. **28**, 277–286 (2017)
21. Google 2020 HD Map-Google Online Satellite Map. http://www.ugucci.com
22. Baidu Map-Baidu online panoramic map. http://quanjing.baidu.com/#/
23. Song, D., Lu, M., Xing, J.: Analysis of the spatial morphology facing wind environment in harbin cen-tral area. Sustain. Energy Build. **203**, 1–15 (2021)
24. Code for classification of urban land use and planning standards of development land (GB 50137—2011). National Standards of People's Republic of China (2011)
25. Song, D., Lu, M., Qiu, Z., Liu, J., Wang, L.: Analysis of spatial roughness characteristics of harbin central district based on ventilation influence low temperature. Architect. Technol. **43**(02), 5–9 (2021)
26. Grimmond, C., King, T.S., Roth, M., et al.: Aerodynamic roughness of urban areas derived from wind observations. Bound.-Layer Meteorol. **89**(1), 1–24 (1998)
27. Hawkes, D.J., MacDonald, R., Walkter, S., Spanton, A.M.: Measurements of dispersion within simulated urban arrays—a small scale wind tunnel study. J. Appl. Meteorol. **80**, 178–196 (1996)
28. Gao, M.: Research on the method of building shape deliberation based on CFD wind environment simulation and comfort evaluation types. Master thesis, Jinan University (2020)
29. Annual Climate Bulletin of Shenzhen Meteorological Bureau (1953–2019). http://weather.sz.gov.cn/qixiangfuwu/qihoufuwu/qihouyuce/yueqihouqushiyuce/
30. Oke, T.R.: Street design and urban canopy layer climate. Energy Build. **11**(1–3), 103–113 (1988)

# Assessing the Impact of Lockdown Due to COVID-19 on the Electricity Consumption of a Housing Development in the UK

**Renata Tubelo, Eldar Naghiyev, Mark Gillott, Lucelia Rodrigues, and Rob Shipman**

**Abstract** In March 2020, the United Kingdom (UK) government ruled that householders must stay home as a response to the COVID-19 outbreak to help flatten the curve of the epidemic and reduce the exponential growth of the virus. Commercial activities, workplaces and schools were obliged to temporarily close in compliance with the government rules. This first and most restrictive lockdown took place from late March to early May 2020 when occupants had to stay in their homes except for very restricted essential activities. Two other lockdowns were introduced in November 2020 and January 2021, alongside with a range of restrictive measures during 2020. This offered an unprecedented opportunity to investigate the impact of a prolonged period of occupancy on household electricity consumption. In this work, the authors compared electricity consumption data collected from 21 energy-efficient houses in Nottingham, UK, during these lockdown periods to the same period in the previous year. The findings indicated that the monthly electricity consumption in April 2020, during the strictest lockdown, increased approximately 7% in comparison to the same period in 2019. Hourly average electrical power demand profile during this lockdown showed earlier and longer peaks in the evenings with the emergence of a new midday peak in comparison to typical daily peaks prior to lockdown. Total electricity consumption increased by 17% in 2020–2021, when restrictive measures were in place.

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## 1 Introduction

The domestic sector accounts for 30% of UK national electricity consumption [1]. The contribution of self-generation within the sector has increased considerably, corresponding to 1.6 TWh of electricity in 2018, which still only represented 1.5% of the sector's electricity consumption [1]. This highlights the importance of reducing demand as well as encouraging self-generation to move towards a carbon neutral path.

Household electricity consumption has been slightly reduced over the years due to continued energy-efficiency improvements and renewable generation [1]. These improvements include optimisation on the housing size and shape, the design of well-sized windows for natural lighting and the use of energy efficient lighting and appliances. The reduction in the domestic consumption was also driven by changes in energy policies and awareness such as the use of Energy Performance Certificates (EPCs), appliance energy ratings and smart meters.

Nonetheless, one of the most important factors in the household energy consumption still is the patterns of use and occupancy, attributed to occupants' behaviour [2–4]. Common related indicators include the number and age of occupiers, the proportion of time residents spend in their homes, the way that they inhabit the indoor spaces (e.g., lights on, multiple use of electrical appliances and equipment), activities conducted (e.g., cooking, sleeping) and the amount of electrical equipment and its usage.

Householders have historically spent a significant amount of time in their homes, but changes in modern lifestyle have increased the number of hours that they are out. Prior to the pandemic, the increase of working hours and commuting times are some of the reasons that have contributed to less time at home [5]. The emergence of the COVID-19 pandemic in early 2020 forced the implementation of lockdown measures by the UK government in order to flatten the curve of the epidemic and reduce the exponential growth of the virus [6]. This maximised the time spent at home for the great majority of people, prompting a series of challenges within the built environment and a great opportunity for research into energy usage within fully occupied domestic buildings and the impact of this on their communities.

UK policy responses to COVID-19 were very distinct and rapidly evolved over the course of 2020 [7]. Establishing a timeline of these responses was an essential step to understand their impact on the domestic sector. For this study, the main interest is to understand the policies that focused on limiting people's movement in 2020 and 2021 to reduce the spread of COVID-19. These can be seen in Fig. 1.

In this paper, the authors looked at electricity consumption data of 21 dwellings to assess potential changes in their electricity demand due to the stay home measures in response to the COVID-19 pandemic. This situation offered a unique opportunity to investigate prolonged occupancy in housing and the overall impact on the built environment and energy systems. This work can contribute to increase preparedness to adapt homes and their energy systems, inform the optimisation of community energy schemes and help increase the resilience of urban and energy infrastructures.

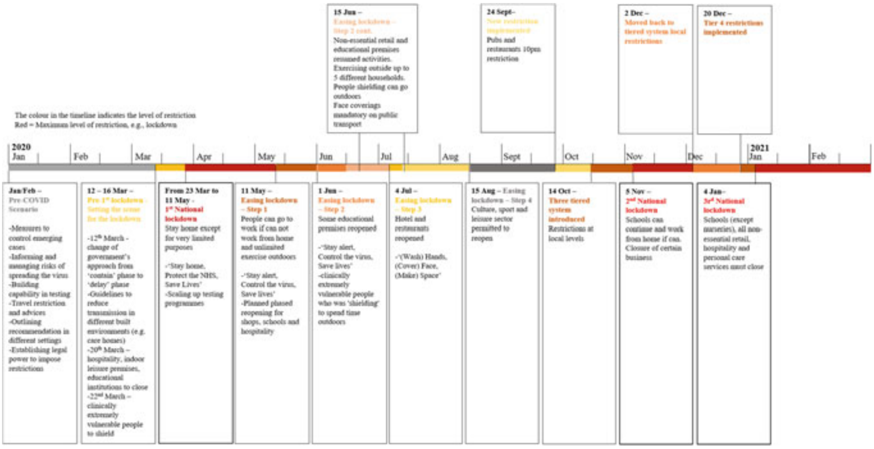


**Fig. 1** Timeline of national restrictions to limit spread of COVID-19 as illustrated by the authors, based on Dunn et al. [7]

Please note that this investigation is limited to the electricity consumption of domestic buildings and non-domestic building is out of the scope of this study.

## 2 UK Domestic Electricity Consumption

Data from Office of Gas and Electricity Markets (Ofgem), organisation that regulates electricity and natural gas in Great Britain, estimates a typical domestic consumption value (TDCV) of 2900 kWh/year in 2020 [8], a reduction from the previous years, estimated to be 3,100 kWh/year in 2017 [9] and 3200 kWh/year in 2013 [10, 11]. Using 2020 data, this represents approximately 8 kWh daily and 242 kWh monthly.

These are median figures and exclude very high users of electricity, and hence can be thought of as being more representative of typical household consumption.

Nonetheless, a study conducted between 2010 and 2011 investigated 251 owner-occupier households and identified higher TDCV equivalent to nearly 3700 kWh/year [12]. This corresponds to over 10 kWh daily and nearly 310 kWh monthly. These figures exclude heating demand, which is mostly supplied by gas in the UK.

Typical UK domestic electrical energy consumption profile consists of daily peaks that occur in early mornings and evenings [13]. Morning peaks have been reduced over the years associated to changes in modern lifestyle. Evening peaks have been delayed in time also due to changes in people's work and social routines. The latter is relatively consistent in itself throughout the year and is the highest level of household electricity demand [5].

The magnitude of the peaks is not only determined by the time of the day, but also by the day of the week (weekday or weekend) and seasonality [5]. Whilst the daily demand in the week is bigger than in the weekend, it is estimated that the difference between weekdays and weekend days has diminished [5] given the range of activities the occupants do outside of their homes over the weekends. Also, seasonality effect should be accounted in the energy use. Whilst, cold appliances (fridge/freezer) are responsible for higher energy usage in summer, lighting, wet appliances (washing/drying) and cooking (e.g., oven, hob, kettle, microwave) have higher usage in winter [14, 15].

A study that analysed households electricity consumption data between 1974 and 2014 demonstrated that one of the shifting patterns associated to the electricity consumption reduction over the years was food-related [5]. It consisted of the reduction of breakfast and lunch times and the push to a later evening peak, which was driven by social transitions such as patterns of employment, longer working hours, home-coming times, and commute hours. The study also suggested that the household's electrical energy consumption during typical work hours was reduced over the years as a consequence of a social lifestyle, with fewer people working from home and most households in a working-away system, that included not only males but females [5].

In the context of the COVID-19 outbreak and the imposed Stay Home period, these changes in the household's electricity consumption were attenuated as most meals were eaten at home, commuting was excluded from the daily routine and working hours were flexible. These changes applied to most who were not essential workers, such as health and delivery workers in the first national lockdown.

UK electricity demand dropped by 12% during the second quarter of 2020, the period corresponding to the first lockdown, with an estimated annual fall of 6% [16]. This was attributed to the reduction in services (commerce, education) and industry [17]. As a consequence, households nationwide experienced an increase in electricity demand. However, domestic electricity demand was reported to have increased by only 3–6% during the first lockdown, rather than dramatically surging [17, 18]. Considering UK average electricity prices of 0.144 GBP/kWh [19], this would correspond to an average annual electricity bill increase of 15–29 GBP, respectively.

## 3 Method

Electricity consumption data collected from 21 dwellings was used to analyse the impact of prolonged occupancy on domestic energy consumption. The investigation considered the period from the start of March 2020 to the end of February 2021, which corresponded to a year-period where a range of national restrictive measures were in place. Electricity data from the same corresponding period in 2019 and early 2020 was used for comparison purposes.

### *3.1 Trent Basin Community Energy Scheme*

Trent Basin is a housing development and community energy scheme built in Nottingham. It comprises low-energy houses and community assets, which include one of Europe's largest community energy batteries with a capacity of 2.1 MWh and a photovoltaic panel system rated at 200 kWp. The development is structured into different phases. The first phase is the object of this work, which includes 35 semi-detached and terraced 3-storey houses (3–5 bedrooms) with areas of nearly 110 $m^2$, and a block of flats with 10 units (2–3 bedrooms) of circa 60 $m^2$ [20]. The project was selected due to the availability of robust datasets and access to buildings and their users.

### *3.2 Monitoring Households*

A total of 21 participating households were considered in this study. Electricity data was collected over a period of two years using Class 1 energy sensors [21]. The sensors were installed in the consumer unit and connected to a cloud platform for data storage and analysis [22], which allowed the continuity of data collection during the pandemic. Motion count data was also used to provide occupancy information. Data was collected from a passive infrared motion sensor, installed in the main hallway of each property. A count was incremented whenever the sensor was triggered thus giving an indication of occupancy. The data collected was made available through an on-line data platform.

In the monitored houses, electricity is the energy source for lighting, cooking, appliances, and electrical equipment, while gas is the source for hot water and heating. Gas consumption is not analysed in this work due to lack of metering and little use of central heating due to an energy-efficient envelope, which reduces overall consumption.

## 4 Results

Yearly average electricity consumption across the 21 monitored households corresponded to 3054.4 kWh in 2020–2021 during COVID-19 restrictions, this represented a consumption of nearly 17% more than in 2019–2020, prior to restrictions (Table 1). Considering UK average electricity price of 0.144 GBP/kWh [19], this corresponds to an increase of 65 GBP per year per household. Monthly consumption was consistently higher in 2020–2021 in comparison to 2019–2020 (Fig. 2). The average daily electricity consumption was equivalent to 8.4 kWh, over 1 kWh per day more than in 2019–2020.

Total yearly electricity consumption per property (Fig. 3) corroborates the findings

**Table 1** Electricity consumption in 2019–2020 and 2020–2021, in kWh

| Period | 2019 March to 2020 February | 2020 March to 2021 February |
|---|---|---|
| Daily average | 7.1 | 8.4 |
| Monthly average | 216.9 | 254.5 |
| Yearly average | 2603.4 | 3054.4 |

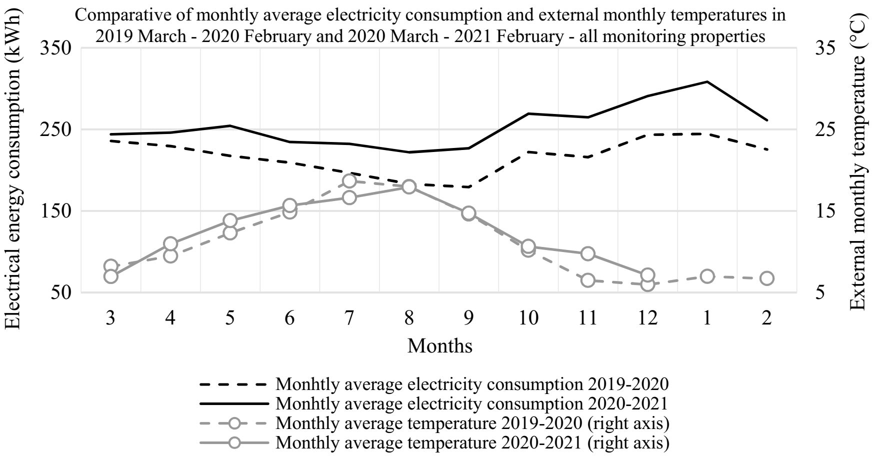


**Fig. 2** Monthly average electricity consumption—all properties

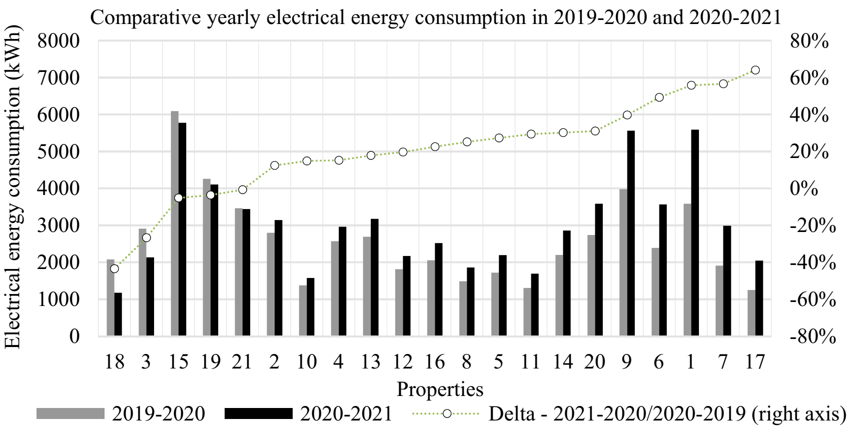


**Fig. 3** Total yearly electricity consumption in 2019–2020 and 2020–2021—per property

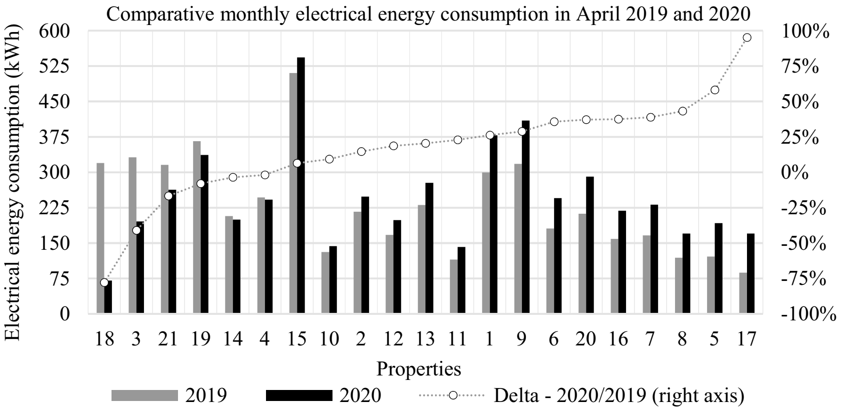


**Fig. 4** Monthly electricity consumption in April 2019 and 2020—per property

that suggest higher electricity consumption during the year of COVID-19 restrictions in comparison to the previous year. A total of 16 households (76% of the sample) showed a higher consumption in 2020–2021 than the same period in 2019–2020 and this varied from a minimum of over 10% to nearly 65% more, depending on the household. Five households (24% of the sample) had lower consumption in 2020–2021 in comparison to the prior year. This was relatively large in two of the households (properties number 3 and 18), with consumption reductions of 27% and 43%, respectively; Properties number 15, 19 and 21 had slightly lower energy consumption in 2020–2021, a reduction of approximately 5% compared to the previous year.

Looking at the monitoring households individually and using data from April 2020, which corresponded to the period with the strictest lockdown and restriction measures, the findings suggested that most of houses showed an increase of their electrical energy consumption in comparison to the same period in 2019. This increment in the demand varied from 9% to up to 95% more in April 2020 than in 2019 (Fig. 4).

However, a total of 6 households (29% of the sample) showed higher demand prior to the restriction measures in 2019–2020 (these were properties number 3, 4, 14, 18, 19 and 21). In 2 out of these 6 houses (house number 4 and 14) this difference was very small and considered to be almost negligible. This might suggest that there were not significant changes in the household's lifestyle (e.g., working from home prior to lockdown, pensioners, key workers).

Property number 18 showed a considerable drop in energy consumption in April 2020, which when correlated with collected motion count data for the corresponding period, suggested an unoccupied or partially occupied house in comparison to the same period in 2019. Motion count was 20 in April and 601 in March 2020. This same property had readings of 4198 and 4812 in March and April 2019, respectively. It should be mentioned that the national restriction measures limited households to

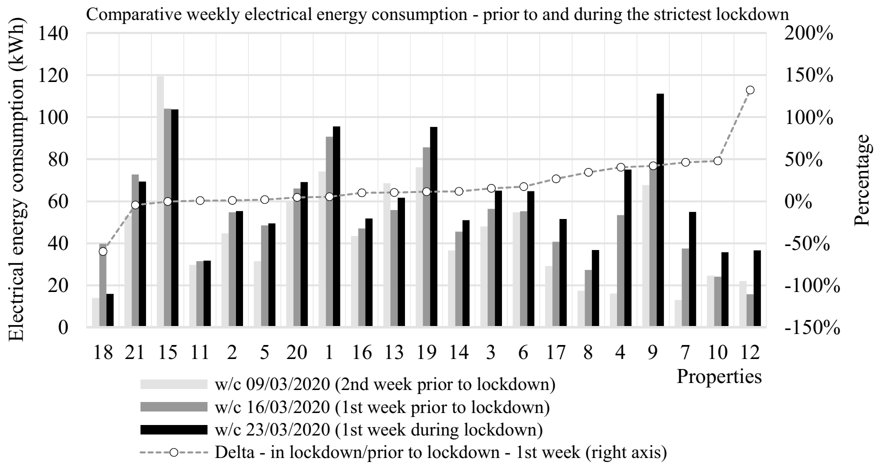


**Fig. 5** Weekly electricity consumption per property—weeks prior to and first week in lockdown

mix with each other. As consequence, some households opted to stay and self-isolate at other residencies with family members.

The week prior to the first and strictest lockdown (commencing on 16th March) was compared to the first week in lockdown (commencing on 23rd March). The findings indicated an increase in energy consumption in the majority of monitored houses. However, this increase showed a variation from approximately 1% (house number 11) to up to 132% (house number 12) (Fig. 5). Only three dwellings had a higher consumption in the week prior to lockdown in comparison to the first week in lockdown (house number 15, 18 and 21). This was largest in property number 18, which, as mentioned before, was associated to an unoccupied or partially occupied property. The data also suggested a progressive increase in electricity consumption as lockdown approached. Two weeks prior to lockdown, electricity consumption was lower than the week that led to lockdown in most properties.

Hourly average electrical power demand of 21 properties (represented by different colours) with a quarter hour resolution were plotted comparing April 2019 and 2020 (Fig. 6). The results highlighted a late morning peak, followed by a new peak around noon as a result of meals being prepared at home and a more distributed evening peak, starting earlier in comparison to the period prior to the lockdown.

## 5 Discussion

Data from the Trent Basin monitored households was used to explore the impact of the COVID-19 pandemic on domestic electricity consumption. The results of 21 households during a 2-year period revealed an overall increase in consumption of 17% during the restriction period (March 2020 to February 2021) in comparison

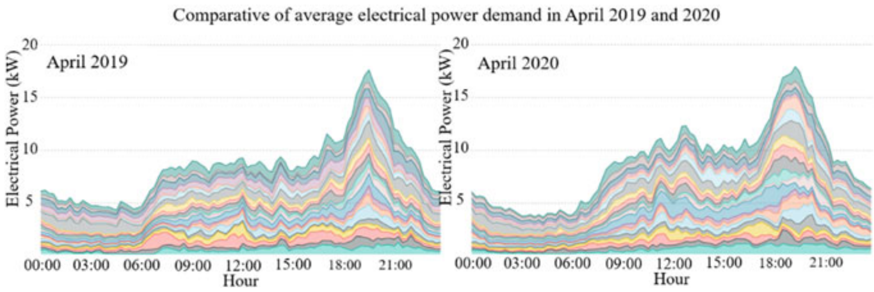


**Fig. 6** Hourly average electrical power demand in April 2019 and 2020—per property

to the same period prior to restrictions (March 2019 to February 2020). Assuming UK average electricity unit prices, this would increase energy bills by approximately 65 GBP per year per household. These findings are higher than those suggested by the electricity providers, which state an electricity consumption increase of 3–6% within the UK domestic sector, as a consequence of the stay home measures of the second quarter of 2020. Furthermore, all months during the restriction period (2020–2021) had higher consumption in comparison with the period before restrictions. The highest differences were in September 2020 and January 2021, which represented a consumption 27% and 26% higher than the same period prior to restrictions, respectively. It should be noted that 2020–2021 included a range of different levels of restrictions and the period included in this investigation accounted for the three lockdowns in the UK (Fig. 1). Yet, the national electricity impact of the COVID-19 restrictions measures in the domestic sector still needs to be fully accounted for and this study aims to contribute to bridge this gap.

When comparing Fig. 1, which illustrates the national policies to tackle COVID-19, and Fig. 2, which shows monthly average electricity consumption in 2020–2021, there is no direct correspondence. One of the lowest differences in the consumption between 2020–2021 and 2019–2020 occurred in April, the same period when the strictest lockdown was in force. Energy consumption increased by 7% and was slightly higher than the expected national range at that time (3–6%) [18]. It should also be mentioned that the monthly average temperature in April 2020 corresponded to 11 °C, 1.5 K higher than in 2019, and this might have helped reduce this difference in the consumption between 2020 and 2019. This suggests that occupancy patterns are not the only determinant of increased energy consumption but other variables such as lifestyle and temperatures are other important factors influencing demand.

This intertwined relationship between prolonged occupancy and weather can also be observed when looking at September 2020, when monthly averages between 2019 and 2020 were practically the same (14.7 °C) but the consumption in 2020 had one of the highest differences in comparison to the same period in 2019. In September, the measures were eased but staying home and social distancing were strongly advised and were common practice.

Looking at households individually during the strictest period, 71% of the households had increased demand and 29% had decreased demand related to the previous year. However, in at least one case, lower demand in lockdown was associated with reduced occupancy. This shows the importance of combining energy consumption data with occupancy data (e.g., motion count, questionnaires) for better understanding of how residents have inhabited their homes and what changes were made.

Another relevant aspect to be considered within this context is the increased ownership of electrical vehicles (EV). The reduced need for EV charging when working from home tends to significantly decrease electricity consumption in comparison to when the period that EV charger is used on a regular basis.

Even though this work used motion count as an approximation for occupancy, one of the limitations is the lack of evidence gathered with the residents about how the houses were inhabited. This would help better understand the data collected and explain deviations in the data in more detail.

Also, future research will look at individual appliances usage to evaluate habits and routines that have changed or become more pronounced during the restriction period. This can feed into the definition of pandemic dwelling profiles, useful for energy consumption predictions.

## 6 Conclusions

This work examined electrical energy data of energy-efficient homes, which are part of a community energy scheme, in Nottingham, UK. A total of 21 homes were monitored over a 2-year period. This research aimed to investigate whether there was an increase in the electricity demand in 2020–2021 when compared to 2019–2020, as a result of the UK measures restricting people's movement to reduce the spread of COVID-19.

Findings suggested that during 2020–2021 the households had an average increase in their annual average consumption of 17% when compared to 2019–2020, which corresponds to an additional cost of approximately 65 GBP assuming UK average electricity unit prices. At a household level, analysis of weekly data prior to and during lockdown showed a large variance, with the majority of homes increasing their electricity demand, varying from nearly 1% up to 132%. Several properties showed a reduction in the consumption of up to nearly 60% but the highest reduction was associated to an unoccupied or partially occupied property. Cross-comparison of consumption and occupancy data, in the form of motion counts, was shown to be helpful to identify if houses were inhabited or not. The research also suggested that factors such as external temperature play an important role along with lifestyle and patterns of occupancy.

Hourly analysis identified a new trend in the electricity consumption, with a new peak around noon when cooking was added to the baseline of daily consumption.

Early morning electricity demands were delayed when compared to the previous pattern, while evening peaks were earlier than before and spread across the evening.

## References

1. Department for Business; Energy & Industrial Strategy: Digest of UK Energy Statistics (DUKES): electricity. DUKES Chapter 5: statistics on electricity from generation through to sales (2019)
2. Bao, H., Li, S.: Housing wealth and residential energy consumption. Energy Policy **143** (2020)
3. Escobar, P., et al.: Modeling and analysis of the electricity consumption profile of the residential sector in Spain. Energy Build. **207** (2020).
4. Sukarno, I., Matsumoto, H., Lusi Susanti, L.: Household lifestyle effect on residential electrical energy consumption in Indonesia: on-site measurement methods. Urban Climate **20** (2017)
5. Anderson, B., Torriti, J.: Explaining shifts in UK electricity demand using time use data from 1974 to 2014. Energy Policy **123**, 544–577 (2018)
6. UK Government: Prime Minister's statement on coronavirus (COVID-19): 23 March 2020. Prime Minister Boris Johnson addressed the nation on coronavirus, 24 July 2020. Available from: https://www.gov.uk/government/speeches/pm-address-to-the-nation-on-coronavirus-23-march-2020
7. Dunn, P., et al.: COVID-19 Policy Tracker 2020. The Health Foundation (2021)
8. Ofgem: Decision on revised Typical Domestic Consumption values for gas and electricity and economy 7 consumption split. 6 Jan 2020. Available from: https://www.ofgem.gov.uk/system/files/docs/2020/01/tdcvs_2020_decision_letter_0.pdf
9. Ofgem: Decision on revised typical domestic consumption values for gas and electricity and economy 7 consumption split. 3 Aug 2017. Available from: https://www.ofgem.gov.uk/publications-and-updates/typical-domestic-consumption-values-2017-decision-letter-0
10. Ofgem: Decision Letter: Revision of Typical Domestic Consumption Values. Ofgem (2010)
11. Ofgem: Decision: new typical domestic consumption values. 13 Sept 2013. Available from: https://www.ofgem.gov.uk/publications-and-updates/review-typical-domestic-consumption-values-2013
12. Energy Saving Trust: Powering the Nation: Household Electricity-Using Habits Revealed. London, United Kingdom (2012)
13. Pimm, A., Cockerill, T., Taylor, P.: The potential for peak shaving on low voltage distribution networks using electricity storage. J. Energy Storage **16**, 231–242 (2018)
14. Intertek: Household Electricity Survey: A Study of Domestic Electrical Product Usage. 2012, Intertek Testing & Certification Ltd., Milton Keynes
15. Drysdale, B., Wu, J., Jenkins, N.: Flexible demand in the GB domestic electricity sector in 2030. Appl. Energy **139**, 281–290 (2015)
16. IEA: Electricity Market Report. International Energy Agency (IEA), France (2020)
17. IEA: COVID-19 impact on electricity. 28 May 2021. Available from: https://www.iea.org/reports/covid-19-impact-on-electricity
18. BBC: Coronavirus: Domestic Electricity Use Up During Day as Nation Works from Home. BBC (2020)
19. Power Compare: Compare 2021 Electricity Prices: Average UK Rates & Tariffs Per kWh. 31 Mar 2021. Available from: https://powercompare.co.uk/electricity-prices/
20. Rodrigues, L., et al.: User engagement in community energy schemes: a case study at the Trent Basin in Nottingham, UK. Sustain. Cities and Soc. **61** (2020)
21. Schneider Electric: PowerTag Wireless Energy Sensor. 22 Oct 2018. Available from: https://www.schneider-electric.com/en/product-range-presentation/63626-powertag
22. Shipman, R., Gillott, M.: SCENe Things: IoT-based monitoring of a community energy scheme. Future Cities Environ. **5**(1), 6 (2019)

# Embodied Energy and Global Warming Potential of Radon Preventive Measures Applied in New Family Houses

**Licia Felicioni, Antonín Lupíšek, and Martin Jiránek**

**Abstract** Radon inside buildings represents the primary source of human exposure to ionising radiation in the world. Studies in many countries have shown that high indoor radon levels are the second most frequent cause of lung cancer. This gas can enter a building through cracks, fractures, or other leaky places in structures that are in contact with the soil, incrementing the radon concentration indoors. The radon protective measures on buildings represent embodied and operational environmental impacts, which were more or less neglected so far. Nevertheless, as buildings have become more energy-efficient, the radon preventive measures impacts are recognised as being more and more significant and shall be thoroughly investigated. This paper performs a comparative analysis of embodied primary renewable and non-renewable energy and global warming potential (GWP) for alternative preventive measures. On this basis, the paper aims to assess the additional contribution of embodied impacts of three types of radon preventive measures for a single-family house located in a potential radon prone area. The embodied impacts are calculated for the A1-A3 LCA stages associated with the radon preventive measures and compared them against each other to find the additional embodied impacts compared to a family house without radon protection. The results indicate that the embodied energy and the GWP increase as more protective elements the measure contains, also considering the impacts of soil excavation.

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## 1 Introduction

Radon gas has been recognised as the second most frequent cause of lung cancer after tobacco smoke [1], with a vulnerability that accounts for 10–15% [1, 2]. For many people, it is the primary source of exposure to ionising radiations [3, 4]. Radon is defined as a silent killer since it is invisible, tasteless and odourless [5, 6]. This radioactive noble gas that is in the soil (and in a lower percentage in the construction materials and water [7]) can easily enter the buildings through cracks, pipes, and fractures at the foundation level [8]. The radon supply rate from the soil to the indoor environment is proportional to the soil's permeability [9]. Once radon is inside the building, it accumulates in the spaces directly in contact with the ground (ground floors, underground floors, cellars) [10]. The European Union with the Directive 2013/59/Euratom [11] recommends that, if the average radon concentration in a dwelling exceeds 300 $Bq/m^3$ (the action level), measures should be taken to decrease the amount, indifferently for new and existing buildings or residential and work buildings.

A European Union's challenge is to address a drastic decrease in demand for energy in the building sector, now amounting to 40% of the total European consumption with related 36% $CO_2$ emissions [12]. The EU/2010/31 directive [13] indicates the minimum requirements for service and technical solutions should be accomplished within an optimised balance between investments and energy savings obtained during the building life cycle. However, the energy spent and the greenhouse gases emitted during the materials production stages (e.g. materials extraction and manufacturing) cannot be omitted.

Currently, the literature does not present studies on the environmental impacts deriving from the production of materials used to design radon protective/preventive measures. A literature review has been conducted in research engines and databases (specifically Elsevier's Science Direct, MDPI, Google Scholar) to identify studies on radon measures in buildings and their impacts on the environment. The keywords "radon in buildings", "radon and environmental impacts", "radon protection and sustainability", and "radon measures embodied impacts" have been used for the research. The results highlighted that there is still a gap in the literature about this topic, which is why this paper is focused on it and tries to narrow it down. However, studying different measures in the perspective of sustainability is not new [14, 15]; radon measures use components, such as waterproofing materials, that are used in roofs. Thus, to some extents, the effects of such roof materials on the environment have been studied for slightly different purposes [16].

Indeed, this work aims to highlight the additional embodied primary renewable and non-renewable energy (EE) (expressed in GJ) and embodied global warming potential (GWP) (expressed in kg $CO_2$ eq.) for radon preventive measures for single-family houses, as they are an essential part of attempts to reduce radon risk [4, 17].

This manuscript does not aspire to cover all the environmental impacts of radon preventive measures over the entire building life cycle. However, it highlights the "cradle-to-gate" boundary, strictly connected to the material production stream (from the supply of raw material to the delivery to the gate). Based on these premises, the analysis proposed aims to define three indicators for the A1-A3 product stage (embodied renewable/non-renewable energy and GWP) related to four different protective scenarios for a single-family house case study. The aim of the manuscript is looking for additional environmental embodied impacts of radon preventive measures. This assessment is done comparing the three variants' results with a basic floor solution in the range of embodied energy and carbon per $m^2$ (e.g. GWP/$m^2$) of the same single-family house.

## 2 Context to Literature and Project

A key priority of the Directive 2013/59/Euratom [11] is reducing the exposure to radon in buildings. Moreover, the Directive increases the awareness of radon risk indoors by implementing rules in every European country since 2018 with consequent monitoring and mitigating actions [3].

New buildings should be designed and built using preventive measures to reach a radon concentration as low as plainly obtainable [18]. Many European countries are spending resources developing programs for such aim [19]. The problem of high radon indoors concentration is present in Europe and countries (e.g., Canada [6], United States [20]) where the heating indoors is privileged since there is a high-temperature difference between outdoors and indoors in winter [21, 22]. Moreover, the building thermal retrofitting may improve the envelope airtightness and, consequently, reduce the air exchange rate if the ventilation is not precisely and simultaneously controlled [7, 10, 23]. This phenomenon, accompanying a possible reduction of the air exchange rate, leads to higher indoor radon concentrations in thermally retrofitted residences [24, 25].

This paper was created as a part of the EU RadoNorm project [26] under the umbrella of the Horizon 2020 framework programme (H2020). The project scope looks towards effective radiation protection based on improved scientific evidence and social considerations. The authors' task is related to assessing the impact of various types of buildings radon protective and remedial measures on the environment. This paper is part of a broader study that compares other scenarios and parameters.

## 3 Methodology

### *3.1 Variants*

In this work, a two-floors new single-family house is selected as a case study because it could be seen as representative and easily replicable. The building footprint is

**Table 1** Scenarios of preventive measures incorporated in floor structures

| Scenario | Description |
|---|---|
| A | Floor without radon preventive measures |
| B | Floor with continuous PVC-P radon-proof membrane |
| C | Floor with continuous PVC-P radon-proof membrane + natural ventilation of the gravel layer with the exhaust above the roof (exhaust pipe is within the building) |
| D | Floor with continuous PVC-P radon-proof membrane + natural ventilation of the floor air gap made of plastic components with the exhaust above the roof (exhaust pipe is within the building) |

Scenario A is for reference
*PVP−P* Softened polyvinyl chloride

72.4 m$^2$, with a standard height of 2.7 m per floor. The building footprint represents only the floor area that interfaces with the ground; it does not have a basement.

Among the current known radon preventive techniques for a single-family house [4], three have been chosen for this work and are summarised in Table 1 (scenario B to D).

These described scenarios are compared with variant A—basic strip foundation without specific radon-preventive measures—to understand the additional embodied impacts of the considered protective techniques. To better comprehend the location of the solutions, Fig. 1 shows a schematic representation of the ground floor for scenario C and D.

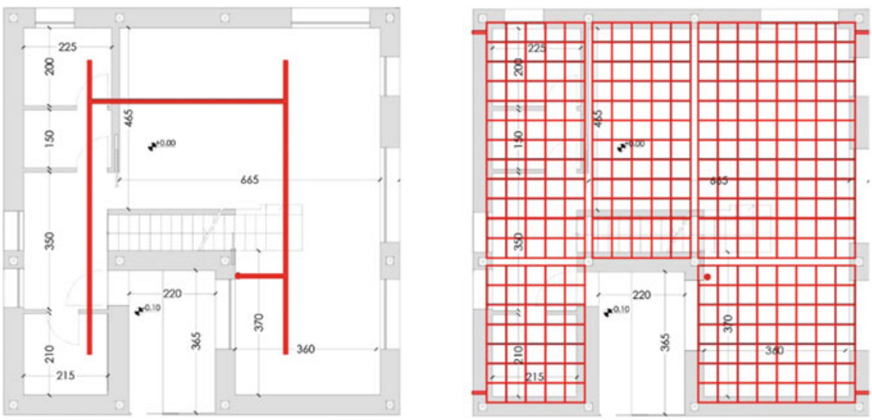


**Fig. 1** The building layout for which the assessment has been considered. On the left, representation of scenario C with perforated tubes and vertical exhaust pipe. On the right, representation of preformed plastic components (50 × 50 cm), inlets in the corners, and vertical exhaust pipe (on the right)

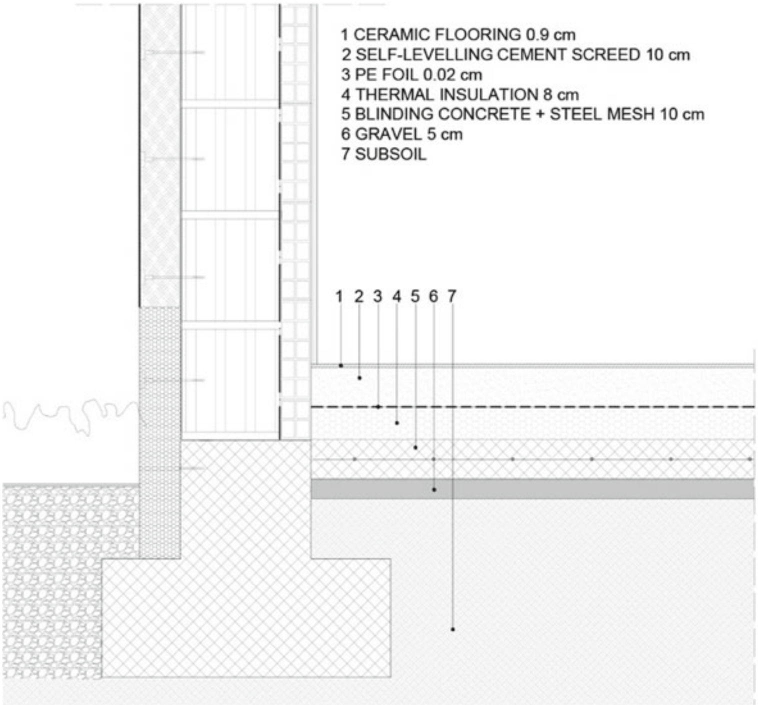


**Fig. 2** Detail of basic floor structure without radon-proof techniques

### Scenario A

This first scenario is a basic floor structure placed between concrete foundation strips without radon protection that is taken into consideration for assessing the additional impacts of the variants with radon preventive solutions (Fig. 2). In all four scenarios, the exterior wall is designed with a clay block wall with a reinforced concrete structure and external insulations; however, in the calculation, the external wall and the foundation strips are not considered because they are present in all cases and, consequently, they are not relevant for assessing the impacts of the radon-proof solutions.

### Scenario B

The second scenario chosen presents the same foundation systems offered by scenario A but with an additional radon-proof membrane between thermal insulation and the blinding concrete layer (Fig. 3) [27]. This softened PVC membrane improves the foundation's protection, avoiding soil gases from entering the house [6, 28, 29].

### Scenario C

The third scenario is similar to scenario B, but flexible perforated pipes in the gravel layer (15 cm in thickness) are placed (Fig. 4). These pipes are connected to a vertical

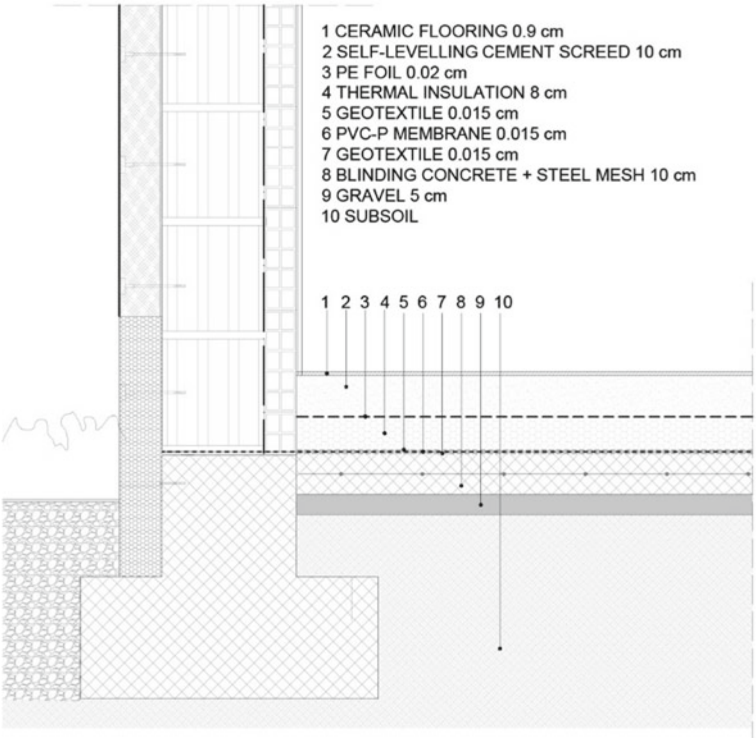


**Fig. 3** Detail of a floor structure with continuous radon proof membrane

exhaust pipe (diameter 12.5 cm) that work as an outlet. This solution works passively. At least one perforated pipe is laid under each room. The diameter of perforated pipes was considered to be 8 cm.

### Scenario D

The fourth scenario includes the air gap with preformed plastic components (also known as igloos), a PVC-P radon-proof membrane, four inlets, and a vertical exhaust pipe (Fig. 5). This technique involves drawing the air naturally using the exhaust pipe that runs through the building from the air gap to the roof (60 cm above the roof latest layer). The inlets allow the outdoor air to enter the air gap and, with the principle of cross ventilation, dilute the radon concentration through the exhaust pipe that works as an outlet [30]. This solution requires special attention in sealing the air gap to avoid increasing energy costs and long-term problems of frozen pipes and cold floors; consequently, it is necessary an extra layer of thermal insulation [21]. This technique could be transformed into an active system (active soil depressurisation) if a roof fan is placed at the extremity of the exhaust ventilation pipe and the inlets are sealed [6].

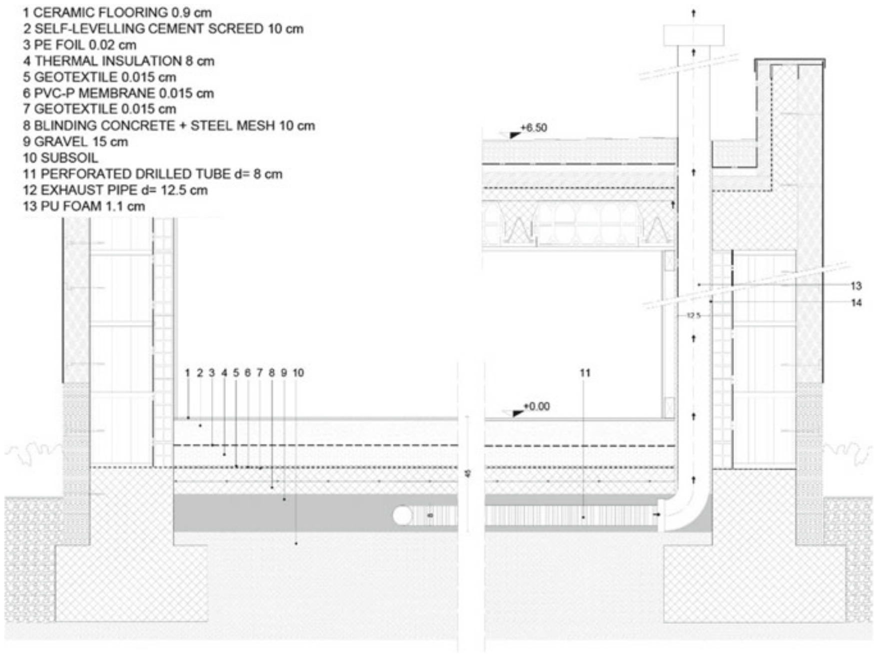


**Fig. 4** Natural ventilation of the subfloor gravel layer with perforated pipes and a vertical exhaust pipe

## 3.2 Indicators

After selecting the floor scenarios, the Environmental Product Declarations (EPDs) collection for the environmental data for the LCA product stage (A1-A3) was done for each building element. Indeed, the foundation system was considered as the sum of building elements (e.g., concrete, pipes) composed of sub-elements (e.g., insulation and finishing). The impact of building's operational energy and water consumption has not been selected for this assessment. Inputs for embodied impacts were found in online and open-source databases, such as EPD International [31], Ökobaudat [32], EPD Online Tool [33], and EPD Ireland [34]. A potential constraint using the presented method is given by using the construction options available in these LCA open-source databases. Table 2 shows which environmental impacts were collected for each building element in the A1-A3 product stage:

## 3.3 Impact Assessment

The total embodied impact calculation was not conducted in any specific LCA software but directly in MS Office Excel. Needed data were imported from the EPDs

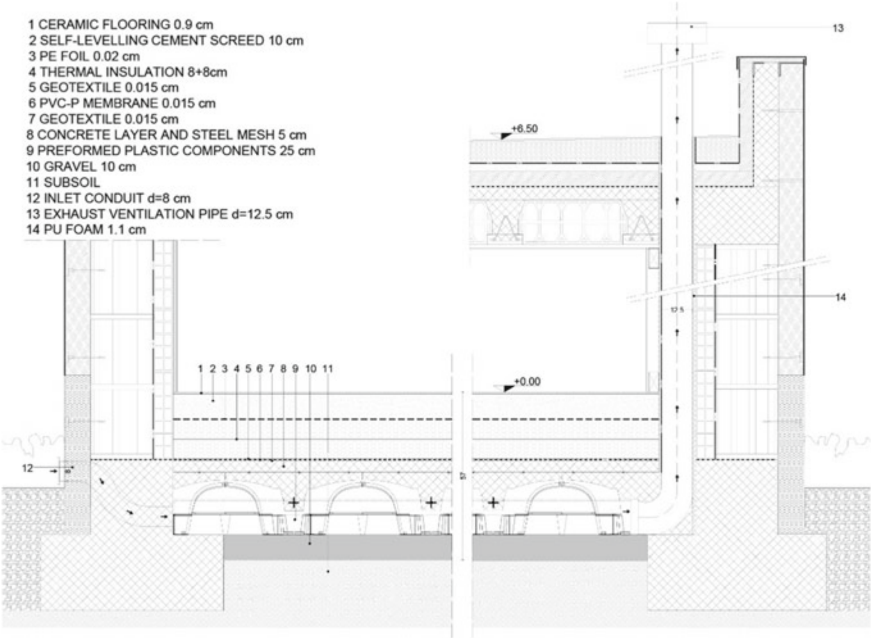


**Fig. 5** Air gap with igloos and exhaust vertical ventilation pipe

**Table 2** Impact categories and their unit of measurements

| Impact categories | Acronym | Unit measure |
|---|---|---|
| Primary energy (non-renewable) | PENRT | [GJ] |
| Primary energy (renewable) | PERT | [GJ] |
| Global warming potential | GWP | [kg $CO_2$ eq] |

collected from LCA open-source databases. The bill of quantities was used to calculate each material's embodied impacts once all the data were converted to the same declared unit—1 kg. Consequently, the sum of the embodied impacts per each category was done to have the total embodied energy and embodied GWP for each scenario. These final values were compared to understand the additional impacts radon preventive measures have compared to scenario A (basic floor structure without radon-preventive techniques).

## 4 Results

The case study model's building elements and their embodied energy and GWP were processed to calculate the total embodied impacts for the four scenarios. The range

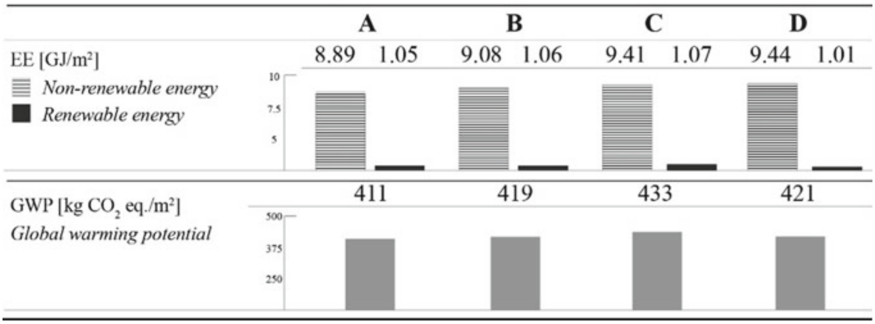


**Fig. 6** Analysis of embodied impacts of the selected scenarios (A-B-C-D) per 1 $m^2$

of the embodied impacts are presented in Fig. 6, both for embodied energy (EE), divided into non-renewable (PENRT) and renewable (PERT), and GWP expressed in embodied emission of greenhouse gases (GHG) for each floor scenario. The embodied non-renewable energy is increasing every scenario that present radon preventive measure, especially in scenario D with a growth of 6.2% compared to scenario A; moreover, in the renewable energy embodied impact, and it is visible an increase of 1.7% for the scenario C compared to the variant without radon preventive techniques. Even for GWP in the radon preventive scenarios, there is an additional impact, primarily for scenario C, that presents a growth of 5.2%. The impacts derivating from the extraction process are counted in the sum. The selected machine is a skid-steer loader that burns 0,13 kg of diesel for excavating 1 $m^3$. The excavation machine's consumption is proportional to the soil cut volume; for this reason, scenario D presents the highest embodied impacts since it needs a soil excavation of 33 cm more profound than scenario A (22 cm more than scenario C).

## 5 Discussion

The results on embodied impacts for different floor scenarios allow observing how radon preventive techniques produce more or less evident effects during the "cradle-to-gate" stage. One of the relevant outcomes of this study is that radon-preventive measures bring additional embodied impacts compared to a basic floor scenario that does not include any gas protection techniques. For instance, scenario B, compared to scenario A, presents a PVC-P membrane, showing an increase of 2.0% in total embodied energy and 1.8% in GWP. These results explain the additional impacts of a simple radon-proof membrane. Figure 6 highlights that scenario D has not much higher embodied impacts than C, even if many radon preventive techniques are adopted. The explanation of this result is probably given by the quantity of concrete used in the foundation. In scenario C, the quantity of concrete is higher by 1 cm than in the D (10 cm in C for the concrete screed and 5 cm for screed + 4 cm of concrete average uniform thickness needed for fill the igloos crowns in D). This 1 cm difference influences the results of embodied impacts because the embodied energy and GHG emissions of concrete are higher than other building components.

### *5.1 Limitations of the Study*

The study is limited since simplified boundary conditions (foundation system and not the whole building) have been considered in running the calculation of embodied impacts during the A1–A3 product stage. Results can be different according to the EPDs and the open-source LCA databases chosen.

## 6 Conclusion

This paper was created as a part of the EU RadoNorm project under the umbrella of the Horizon 2020 framework programme (H2020). This project aims to reduce the indoor level of radon concentration, but one task is to analyse the additional embodied impacts of radon control techniques for three indicators (PERNT, PERT, and GWP). This work has considered a single-family house case study since it is the most manageable and replicable solution. Three different floor scenarios with passive radon preventive measures have been chosen and compared to a standard solution without anti-radon specifics. The results highlight the additional embodied impacts of different radon preventive scenarios. However, the results differ greatly in dependence mainly on the quantity of concrete used in the foundation since it has a quite high impact on the environment. Further development of the study would undoubtedly benefit if a complete life cycle, including production, construction, use, and end of life stages, is considered and active anti-radon techniques chosen.

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## References

1. World Health Organization: WHO Handbook on Indoor Radon: A Public Health Perspective. Geneva (2009)
2. Amin, R.M.: A study of radon emitted from building materials using solid state nuclear track detectors. J Radiat Res Appl Sci **8**, 516–522 (2015)
3. Cucoş, A., Cosma, C., Dicu, T., Papp, B., Horju-deac, C.: Ventilation systems for indoor radon mitigation in energy-efficient houses. Ecoterra—J. Environ. Res. Prot. **12**, 14–20 (2015)

4. International Atomic Energy Agency: Protection against Exposure Due to Radon Indoors and Gamma Radiation from Construction Materials—Methods of Prevention and Mitigation. Austria, Vienna (2021)
5. Government of Canada: Summary Report on Active Soil Depressurization (ASD) Field Study. Canada, Ottawa (2016)
6. Zhou, L., Berquist, J., Li, Y., Whyte J, Gaskin, J., Vuotari, M., Nong, G.: Passive soil depressurization in Canadian homes for radon control. Build. Environ. **188**, 107487 (2021)
7. Jiránek, M., Kačmaříková, V.: Dealing with the increased radon concentration in thermally retrofitted buildings. Radiat. Prot. Dosimetry **160**, 43–47 (2014)
8. Stietka, M., Baumgartner, A., Seidel, C., Maringer, F.J.: Development of standard methods for activity measurement of natural radionuclides in waterworks as basis for dose and risk assessment—first results of an Austrian study. Appl. Radiat. Isot. **81**, 294–297 (2013)
9. Arvela, H., Holmgren, O., Hänninen, P.: Effect of soil moisture on seasonal variation in indoor radon concentration: modelling and measurements in 326 Finnish houses. Radiat. Prot. Dosimetry **168**, 277–290 (2016)
10. Collignan, B., Le Ponner, E., Mandin, C.: Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics. J. Environ. Radioact. **165**, 124–130 (2016)
11. European Commission: Directive 2013/59/Euratom (2013)
12. Bean, F., Volt, J., Dorizas, V., Bourdakis, E., Staniaszek, D., Roscetti, A., Pagliano, L.: Future-proof buildings for all Europeans. A guide to implement the energy performance of buildings directive. Build. Perform. Inst. Eur. **844**, 76 (2018)
13. European Parliament: Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (2010)
14. Hu, M., Milner, D.: Visualizing the research of embodied energy and environmental impact research in the building and construction field: a bibliometric analysis. Dev. Built. Environ. **3**, 100010 (2020)
15. Abouhamad, M., Abu-Hamd, M.: Life cycle assessment framework for embodied environmental impacts of building construction systems. Sustainability **13**, 1–21 (2021)
16. Gonçalves, M., Silvestre, J.D., de Brito, J., Gomes, R.: Environmental and economic comparison of the life cycle of waterproofing solutions for flat roofs. J. Build. Eng. **24**, 100710 (2019)
17. Arvela, H., Holmgren, O., Reisbacka, H.: Radon prevention in new construction in Finland: A nationwide sample survey in 2009. Radiat. Prot. Dosimetry **148**, 465–474 (2012)
18. Holmgren, O., Arvela, H., Collignan, B., Jiránek, M., Ringer, W.: Radon remediation and prevention status in 23 European countries. Radiat. Prot. Dosimetry **157**, 392–396 (2013)
19. Bochicchio, F., Hulka, J., Ringer, W., et al.: National radon programmes and policies: the RADPAR recommendations. Radiat. Prot. Dosimetry **160**, 14–17 (2014)
20. Obenchain R, Young SS, Krstic G (2019) Low-level radon exposure and lung cancer mortality. Regul. Toxicol. Pharmacol. **107**, 104418
21. Rahman, N.M., Tracy, B.L.: Radon control systems in existing and new construction: a review. Radiat. Prot. Dosimetry **135**, 243–255 (2009)
22. Abdelouhab, M., Collignan, B., Allard, F.: Experimental study on passive soil depressurisation system to prevent soil gaseous pollutants into building. Build. Environ. **45**, 2400–2406 (2010)
23. Jiránek, M., Kačmaříková, V.: Applicability of ventilation systems for reducing the indoor radon concentration. Radiat. Prot. Dosimetry **191**, 202–208 (2020)
24. Arvela, H., Holmgren, O., Reisbacka, H., Vinha, J.: Skip Nav Destination Article Navigation Review of low-energy construction, air tightness, ventilation strategies and indoor radon: results from Finnish houses and apartments. Radiat. Prot. Dosimetry **162**, 351–363 (2014)
25. Ringer, W.: Monitoring trends in civil engineering and their effect on indoor radon. Radiat. Prot. Dosimetry **160**, 38–42 (2014)
26. RadoNorm.EU (2021) RadoNorm - Managing risks from radon and NORM. https://www.radonorm.eu/. Accessed 2 Feb 2021
27. Scivyer, C.R.: Radon protection for new buildings: a practical solution from the UK. Sci. Total Environ. **272**, 91–96 (2001)

28. Government of the United Kingdom: Site preparation and resistance to contaminants and moisture (2013). https://doi.org/10.4324/9780203023266-11
29. Jiránek, M., Kačmaříková, V.: Radon diffusion coefficients and radon resistances of waterproofing materials available on the building market. J. Environ. Radioact. 208–209, 106019 (2019)
30. National Radon Program Service Reducing Radon in Your Home. https://sosradon.org/reducing-radon-in-your-home. Accessed 10 Feb 2021
31. International EPD: The International EPD system (2021). https://www.environdec.com/library. Accessed 8 Feb 2021
32. German Federal Ministry of the Interior Building and Community Ökobaudat. https://www.oekobaudat.de. Accessed 8 Feb 2021
33. Institut Bauen und Umwelt e.V. EPD Online Tool. https://ibu-epd.com/en/. Accessed 8 Feb 2021
34. Irish Green Building Council EPD Ireland. https://www.igbc.ie/epd-search/. Accessed 8 Feb 2021

# Automatic Architectural Drawing Labelling Using Deep Convolutional Neural Network

**Seyed Masoud Sajjadian, Mina Jafari, and Xin Chen**

**Abstract** Architectural designers and technologists are able to make an assessment on buildability, thermal and hygrothermal performance of design details. To process drawings, human vision segments, classifies and distinguishes the drawing objects on the basis of their knowledge. With the rapid advancement of Artificial Intelligence methods, vast opportunities become available for performing tasks that used to require human intelligence or assistance by humans. Image processing and analysis is one of these tasks that consists of the manipulation of images using algorithms. There are various applications in different fields, and the use of it is increasing exponentially. This paper explores the use of image processing in identifying building materials in order to check compliance with building regulations and identify anomalies. In this paper, an encoder-decoder based deep convolutional neural network (DRU-net) for image segmentation is applied on architectural images to segment various materials including insulations, bricks and concrete in the conceptual development phase. An experimental analysis is performed on numerous detail drawings and an evaluation is made by mathematical models.

## 1 Introduction

Building regulations are an essential part of the UK government approach to protect health and well-being of users, conserve fuel and preserve environment. Building Control Bodies (BCBs) have the authority to ensure requirements are met in each construction project. However, variety of construction methods and complexity of drawings, unpredictable changes and pressure of time may cause an increase in human errors. No substantial studies exist (as of today) to adequately demonstrate

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the compliance level to regulations typically achieved in each project. However, numerous studies reported significant failures in complying with building regulations not only in the UK but also in other countries like Canada and Australia. They also reported complexity of regulations, lack of consistency and knowledge of detail drawings, adequate monitoring and time pressure, etc. are causes of non-compliance [1].

Architecture and construction have significantly benefited from a wide range of computer programs from modelling to management and analysis. However, the industry still suffers from the lack of substantial digitization like other sectors and is among the least digitized [2]. The industry still relies on paper to manage most of it processes that includes design drawings, procurement, daily progress reports, etc. The lack of a common and integrated platform in projects and the loosely coupled systems of tools where each component has limited knowledge of the other are known to be the main reasons for the industry's insignificant productivity in digitization compared to other industries [3].

The rapid development of Artificial Intelligence and deep learning as a subfield of it could help the construction industry in various aspects. Generally, deep learning is inspired by the human brain and learns from large amounts of data. It consists of networks capable of learning and the related algorithms perform a task repeatedly to improve the outcome similarly to how humans learn from an experience [4]. The networks work on the basis of a collection of nodes (artificial neurons) that model the neurons in a human brain as shown in Fig. 1. There has been numerous advantages to this method in fault tolerance, ability to learn very complex issues and development potential [5], industrial engineering inspection processes, quality control and detection of contaminants, in building performance to determine comfort level [6, 7] and in medical sciences [8].

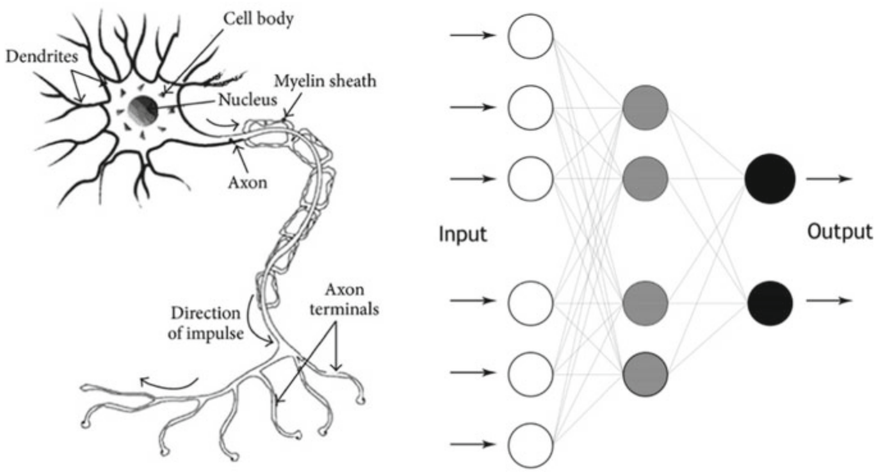


**Fig. 1** Structural of biological neuron, image on the left from [13]

Image segmentation is a process of dividing an image into some categories of objects. Currently most of the segmentation methods depend on thresholding algorithms [9]. Gunay et al. [10] conducted a study on detecting occupants' presence in offices using image processing algorithms and correctly interpreted 95% of the occupied period and 93% of the unoccupied period. Similar study is conducted by Benezeth et al. and they reported an accuracy of 97% [11] Further studies by Amin et al. on potential accuracy of people counting systems on low resolution images resulted an error of within 3% in eighteen experiments [12]. Because of such reliability, in this paper, an image segmentation method based on deep learning is used to segment architectural images. In the following the method is described in detail.

## 2 Methods

In order to prove compliance with building codes it is vitally important to make a clear demonstration between the specification of the used materials and the relevant requirement from a building code (e.g. how the design detail claim the required U-Value). The framework for the programme is adjusted as follows and shown in Fig. 2.

### 2.1 Data Preparation

Numerous detail drawings from Robust Detailing Limited, Accredited Construction Details (ACDs) and Building Research Establishment (BRE) in compliance with the energy efficiency requirements (Part L) of the Building Regulations were chosen to train the model. Each drawing is given a scale in order to determine the construction layer thicknesses. Each material in the drawing is given a colour that works as a

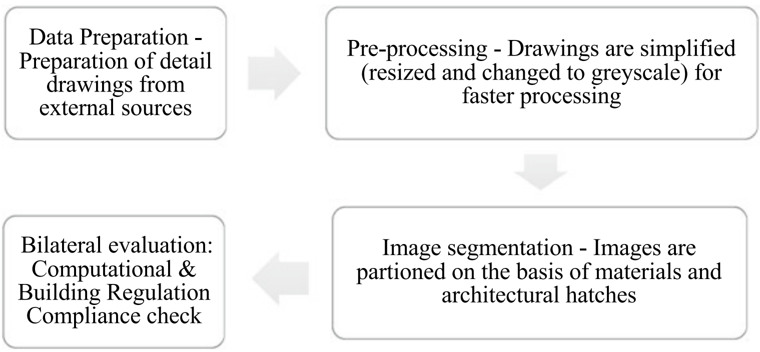


**Fig. 2** The overall scheme of our proposed method

reference code for material thermal specification. The colour can be mapped for a separate drawing by the model.

## 2.2 Image Segmentation

The goal of image segmentation is to label each pixel of an image. The output of the model is a high resolution image (the same size as input image) in which each pixel is classified to a particular class. Figure 3 presents some image examples and their corresponding ground truth labels.

The performance of computer vision systems has been significantly improved in a wide range of applications by the idea of deep convolutional neural network (DCNN) proposed by LeCun [15]. DRU-net [16] is chosen to be used as the DCNN model in this paper. DRU-net is an encoder-decoder DCNN model for image segmentation. This network includes two paths, encoder and decoder. Encoder is used to extract the context and meaningful features from the input images, while the decoder enables an accurate localization by transforming these features into a segmentation map corresponding to the input image. The structure of the encoder consists of a stack of convolutional and max pooling layers, and the decoder includes convolutional and

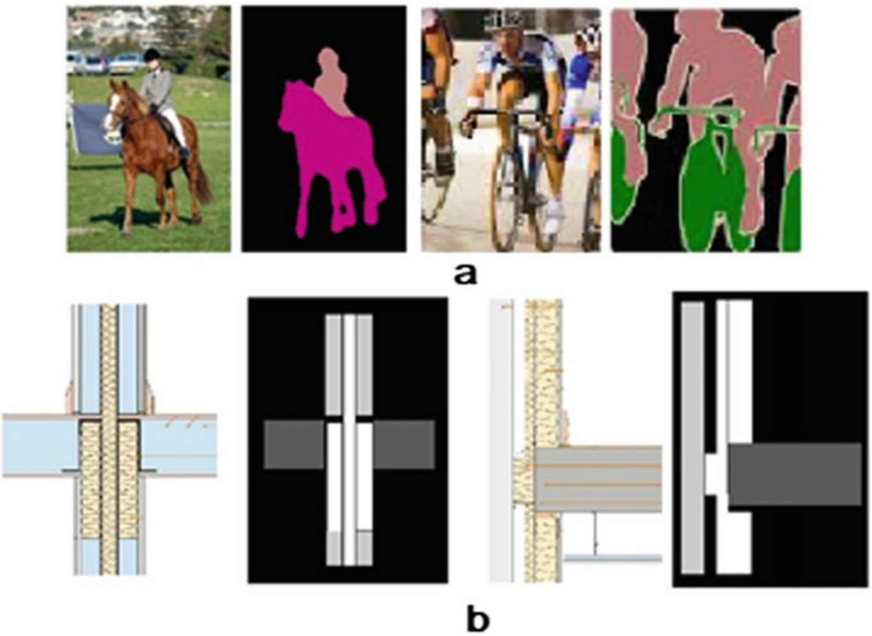


**Fig. 3** The images and the corresponding ground truth labels. **a** natural images [14], **b** architectural images used in this study

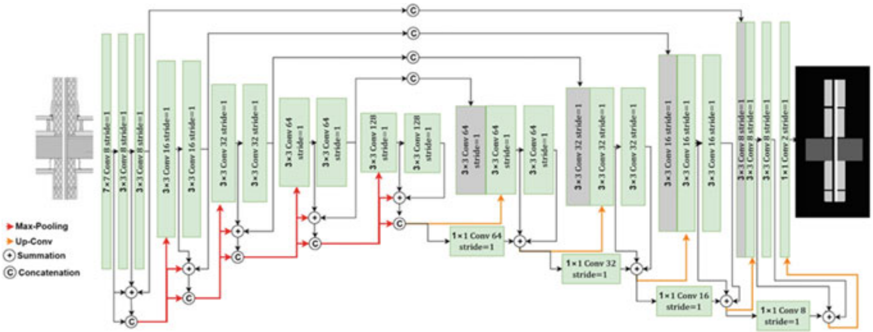


**Fig. 4** The structure of DRU-net [16]

transposed convolutional layers. Figure 4 presents this network. For more details about the network, the readers are encouraged to read [16].

The input to this model is the architectural images and their corresponding ground truth labels, and the output is the segmentation results produced by the DRU-net as shown in Fig. 4.

### 2.3 Evaluation

The accuracy of the proposed method needs to be evaluated to show how precise the proposed method is. The accuracy in image segmentation is measured based on the agreement between the estimated segmentation output and the ground truth segmentation mask. In this paper, the segmentation performance was assessed by using Precision, Recall, and Dice. These measures are often used to quantify the performance of image segmentation methods and reveal how similar the segmentation output of the method and the ground truth labels are. These measures are defined as follows:

$$Precision = \frac{TP}{TP + FP} \tag{1}$$

$$Recall = \frac{TP}{TP + FN} \tag{2}$$

$$Dice = \frac{2TP}{2TP + FP + FN} \tag{3}$$

where true positive (TP) represents pixels that are correctly predicted according to the target mask, whereas false positive (FP) represents pixels falsely segmented as foreground, and false negative (FN) shows pixels falsely detected as background. The higher value of these measures shows the higher performance of the methods.

In other words, a higher value shows a higher agreement between the segmentation output of the model and the ground truth segmentation mask.

### 2.4 U-Value Measurement

U-value measurement is for a building element made of uniform and parallel layers. The heat flow is straight from inside to outside through such an element. To measure the U-value, a sum of the thermal resistances of each layer is required, however all building components have non-uniformities (layers that are not parallel or plane) which means that the heat does not travel straight through them. For the purpose of U-Values, in numerical methods, construction is always considered as uniform in one direction meaning that three dimensional effects do not influence the overall U-Value significantly [17]. BS EN ISO6946 suggested calculation as follows [18] where R is material resistivity, d is the material thickness and K is thermal conductivity coefficient (K-Value):

$$R = \frac{d}{k} \tag{4}$$

$$UValue = \frac{1}{R1 + R2 + R3 + \cdots + Rn} \tag{5}$$

Furthermore, Approved document Part L1A sets out the concurrent notional dwelling specification as shown in Table 1, even though better fabric performance is likely to be required to achieve Target Emission rate (TER) and Target Fabric Energy Efficiency (TFEE) [19].

By deriving data from the drawings, calculations take place for a section on each drawings. U-Value calculator follows to the numerical method (BR 443) and make calculations based on conductivity rates and layer thickness. The method has the capacity to calculate Psi (Ψ) value too which is a measurement of heat loss (W/m K) across a given junction between the external wall and another element. The material specification should be given manually to the developed program due to diversity of materials thermal characteristic range especially insulations (Fig. 5 demonstrates the thermal conductivity rates for most commonly used insulation materials), the

**Table 1** Concurrent notional dwelling specification

| Roof | 0.13 W/m$^2$ K |
|---|---|
| Wall | 0.18 W/ m$^2$ K |
| Floor | 0.13 W/m$^2$ K |
| Party wall | 0.20 W/m$^2$ K |
| Windows | 1.4 W/m$^2$ K |

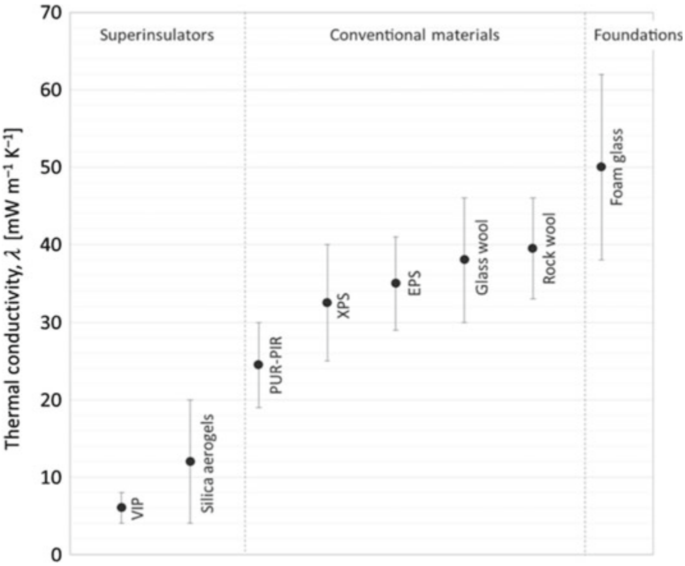


**Fig. 5** Thermal conductivity of insulation materials. The dots represent average values and the bars indicate the available range. Image from [20]

algorithm only detects the material on the basis of architectural hatch, understand the scale and runs the calculations.

## 3 Experimental Results

We trained the DRU-net on the pre-processed images and their corresponding ground truth labels of 2D architectural images. The datasets, training parameter settings and the experimental results are reported in this section.

### *3.1 Materials and Datasets*

The model is trained to recognise standard hatching styles for construction materials. For the initial phases, insulation, bricks and concrete were used in the recognition. To train the model, we prepared 12 architectural images and their corresponding ground truth labels. The images were annotated manually by an expert. For all experiments, the dataset was randomly divided to 70% for training, 10% for validation and 20% for testing. Because the amount of data available is limited, sixfold cross validation is used to reduce the sensitivity of the performance estimation to the partitioning of the data.

The deep-learning model run on a graphics-processing unit NVIDIA GeForce GTX 1080Ti. The code was implemented in Python based on Tensorflow 2.0, and the code is available at GitHub (https://github.com/MinaJf/DRU-net).

The model was trained for 100 epochs. The learning rate was set to $10^{-3}$, and decayed by multiplying 0.8 for every 10 epochs. The initial feature channel number for the encoder-decoder architecture was 16, and the number of layers for both the encoder and decoder was 5.

### *3.2 Pre-processing*

The first step is to convert the image to grayscale image. In this process, a coloured two-dimensional image is transformed into a grayscale version of the image. Coloured images introducing unnecessary information which increase the amount of training time. Therefore, the main reason of this image conversion is that grayscale image simplifies the model training and reduces the computational time.

Besides, all the images were resized to 256 × 256 pixels. Another important pre-processing step is image normalization that rescales the pixel intensity values. In this work, all resized images were normalized to the range of − 1 and 1 by using zero-mean normalization.

## 4 Results

In this section, DRU-net is compared with U-net [21] and Residual U-net (RU-net) [22] in terms of accuracy. U-net and RU-net are two DCNN models that are chosen here to compare their performance with DRU-net. Dice, Precision, and Recall for U-net, RU-net, and DRU-net are reported in Table 2. It can be seen from Table 2 that DRU-net outperformed U-net and RU-net (a higher value indicates a better performance). U-net and RU-net could not segment some of the materials resulting in zeros for Dice, precision and recall measures, while DRU-net segmented all the classes.

**Table 2** Segmentation results based on U-net, RU-net, and DRU-net

| Method | Dice | | | Recall | | | Precision | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | B | I | C | B | I | C | B | I |
| U-net | 0.634 | 0.545 | 0.178 | 0.755 | 0.587 | 0.294 | 0.560 | 0.530 | 0.225 |
| RU-net | 0.601 | **0.668** | 0.208 | 0.698 | **0.835** | 0.328 | 0.561 | 0.590 | 0.224 |
| **DRU-net** | **0.754** | 0.654 | **0.227** | **0.863** | 0.789 | **0.444** | **0.678** | **0.620** | **0.335** |

The results are reported based on dice, Precision, and Recall for all testing images
*C* Concrete, *B* Brick, *I* Insulation

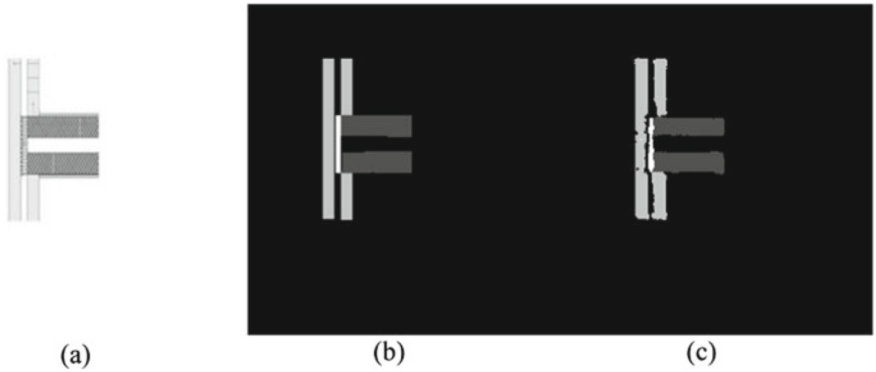


**Fig. 6** Visual results of one test example. **a** Original image, **b** ground truth label, **c** the segmented output of the proposed method

Figure 6 shows one example of architectural images with its corresponding ground truth label, and the segmentation output of DRU-net. DRU-net produced a similar visual result to the ground truth label.

The level of accuracy achieved means the layer thickness for Brick and Concrete is detected correctly with very limited failure on some pixels. However, for insulation, the algorithm failed to achieve a high level of accuracy as the number of pixels for insulation layers is lower than the other two materials that makes the learning process more difficult for insulation segmentation.

## 5 Conclusion

Architectural detail drawings are of very different configurations and therefore human evaluations are prone to errors. In this study, a DCNN model is utilized to learn how to segment the most commonly used materials in construction on the basis of standard drawings and run the required calculations to check compliance with Part L1A of the UK building regulations. This article brings out a concept where image segmentation using deep learning can be considered in examining detail drawings. The framework development can address industry-wide problems in standard compliance, reduce human errors and deliver faster drawings check. The framework requires consistent and systematic review and feedback to improve the accuracy.

Our future research focus on improving the accuracy of the algorithm used in this study by balancing the focus of model learning on materials with lower pixels.

## References


1. Baiche, B., Walliman, N., Ogden, R: Compliance with building regulations in England and Wales. Struct. Surv. **24**, 279–299 (2006)
2. Imagining Construction's Digital Future. McKinsey & Company (2016)
3. Papadonikolaki, E., Morgan, B., Davies, A.: Paving the way to digital innovation: megaprojects, institutions and agency. In: 7th International Megaprojects Workshop: Theory meets Practice—Artificial Intelligence and Megaprojects: New Processes and Value (2018)
4. Rao Karanam, S., Srinivas, Y., Vamshi Krishna, M.: Study on image processing using deep learning techniques. Mater. Today (2020)
5. Tu, J.V.: Advantages and disadvantages of using artificial neural networks versus logistic regression for predicting medical outcomes. Clin. Epidemiol. **49** (1996)
6. Sajjadian, S.M., Jafari, M., Pekaslan, D.: An expandable, contextualized and data-driven indoor thermal comfort model. Energy Built Environ. **1** (2020)
7. Sajjadian, S.M., Jafari, M., Siebers, P.-O.: An artificial intelligence method for comfort level prediction. In: International Conference on Sustainability in Energy and Buildings (2018)
8. Gheorghe Amza, C., Cicic, D.T.: Industrial Image Processing Using Fuzzy-Logic, vol. 100, pp. 492–498. Elsevier, Amsterdam (2015)
9. Fornasier, M., Rauhut, H.: Iterative thresholding algorithms. Appl. Comput. Harmonice Anal. **25**, 187–208 (2008)
10. Gunay, H.B, et al.: Detecting Occupant's Presence in Office Spaces: A Case Study. eSIM, Hamilton (2016)
11. Benezeth, Y, et al. Towards a sensor for detecting human presence and characterizing activity. Energy Build. **43**, 305–314 (2011)
12. Amin, I.J., et al.: Occupancy detection in the office by analyzing surveillance videos and its application to building energy conservation. Measurement **41**, 589–599 (2008)
13. Lee Koo, ching, et al. A Review for Detecting Gene-Gene Interactions Using Machine Learning Methods in Genetic Epidemiology. BioMed Research International (2013)
14. Long, J., Shelhamer, E., Darrell, T.: Fully convolutional networks for semantic segmentation. In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, pp. 3431–3440 (2015)
15. LeCun, Y., et al.: Gradient-based learning applied to document recognition. In: Proceedings of the IEEE, pp. 2278–2324 (1998)
16. Jafari, M., et al.: DRU-Net: an efficient deep convolutional neural network for medical image segmentation. In: 2020 IEEE 17th International Symposium on Biomedical Imaging (ISBI), pp. 1144–1148 (2020)
17. Anderson, B.: Conventions for U-Value Calculations. BRE Scotland, Garston (2006)
18. BS EN ISO 6946:2007 building components and building elements—Thermal resistance and thermal transmittance—Calculation method. British Standards Institution, London (2007)
19. Ministry of Hosuing, Communitites & Local Government. Approved Document L1A; Conservation of fuel and power. Newcastle Upon Tyne: NBS, part of RIBA Enterprises Ltd. (2018)
20. Villasmil, W., Fischer, L., Worlitschek, J.: A review an evaluation of thermal insulation materials and methods for thermal energy storage systems. Renew. Sustain. Energy Rev. **103**, 71–84
21. Ronneberger, O., Fischer, P., Brox, T.: U-net: convolutional networks for biomedical image segmentation. In: International Conference on Medical Image Computing and Computer-Assisted Intervention, pp. 234–241 (2015)
22. He, K., et al.: Deep residual learning for image recognition. In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. pp. 770–778 (2016)

# The Response of the Italian Healthcare Facilities to the COVID-19 Pandemic: Analysis of National and Regional Legislation

**Rossella Marmo, Federica Pascale, Enrico Sicignano, Pierfancesco Fiore, and Francesco Polverino**

**Abstract** Since January 2020 Italy has been countering the COVID-19 pandemic with several measures, including strategies to improve the National Health System's preparedness to such a threat. The paper aims to analyse response plans and measures against the COVID-19 pandemic within the Italian healthcare system, at national and regional level. Two objectives have been set: reviewing governmental provisions for territorial and hospital health services rearrangement; reviewing operational responses on the regional scale to address those demands. To collect and review operational responses at the regional level, six Regions have been considered as the field of study, chosen for being a relevant sample of the resident population in North, Middle and South Italy. Comparative analyses have been carried out to outline similarities and differences in managing this difficult healthcare situation. Results show that territorial medicine, particularly epidemiologic service, has been essential in facing the national crisis, but hospitals have been the main actors in addressing COVID-19 needs. Relevant structural, technological and organisational changes were needed to prepare hospitals. The built environment plays a significant role in managing the pandemic response, indeed. Further efforts to develop a novel, resilient and sustainable hospital model are needed. This study contributes to a better understanding of factors influencing current Italian hospitals' strengths and limitations, shedding light on future design models which can increase resilience in emergency conditions.

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## 1 Introduction

The world is facing one of the greatest socio-economic crises ever due to the COVID-19 pandemic [1]. Starting from December 2019 a novel virus, named SARS-CoV-2, has caused to date, March 2021, more than 2.7 million deaths around the world, according to the World Health Organization (WHO) dashboard. The pandemic not only has dramatically changed people's lives but also the Built Environment (BE) requirements. The BE serves as a potential transmission vector for the spread of COVID-19 by inducing close interactions between individuals, by containing fomites and allowing viral exchange and transfer through the air [2]. The pandemic's effects on housing, workplaces and public spaces will last [3]. Ongoing experiences might yield positive impacts for future resilience designs, plans and policies within the BE. Resilience is critically important for filling the void left by risk management, which is limited to probabilistic analysis and events, as it relates to highly uncertain and high impact events such as epidemics [4]. Past epidemics have spurred the development of new solutions for the BE, which not only solve infections but also enhance lifestyles [5]. The COVID-19 pandemic is requiring action to make the BE both resilient and sustainable. The necessity to link disaster risk reduction, climate change and sustainable development goals has been outlined [6–9]. Capolongo et al. [10] have recently claimed that public health relates to the planet's health and suggested recommendations to make cities and communities resilient to future outbreaks. Also, the pandemic consequences highlighted the need to rethink the indoor environments, as housing, in a more healthy, safe, and sustainable way [11].

During times of disasters, healthcare systems are called upon to ensure essential health services are uninterrupted while protecting healthcare workers, patients and communities at once. The WHO has recently published a suite of health service capacity assessments in order to support rapid and accurate assessments of the current and future capacities of health facilities, so that they are prepared for and responsive to COVID-19. [12]. There are examples of disaster resilience planning activities which have engaged health systems especially in overcoming climate change induced threats (e.g. hurricanes) [13]. Global efforts have been made to improve the functioning of hospitals in emergencies and disasters, developing the Hospital Safety Index [14]; similarly the Project ER One aimed at an all risk ready emergency-care facility [15]. Hospitals face big challenges as they include units with vastly different requirements (e.g. airborne infection isolation rooms and protective environment rooms) [2]. Some authors have argued that a common definition of disaster preparedness in hospital does not exist in the literature [16]. At the same time it is not easy to address how to prepare a hospital for disasters. Capolongo et al. [17] have recently proposed a Decalogue of design strategies for new and existing hospitals aimed at improving hospital resilience.

Italy has been the first western country to be affected by the COVID-19 pandemic and the first who has adopted strict safety measures to stop the transmission chain (the so-called lockdown). According to the WHO dashboard, to March 2021 it counts more than 100.000 deaths, second only to the United Kingdom within the European context. Starting from February 2020, the Italian national health system (SSN) had to quickly respond and adapt to address the surge of care and inpatient demands [18].

Governmental and regional provisions led to a rearrangement of hospital and territorial services. As a consequence, healthcare facilities have undergone extensive changes. Hospital wards and units dedicated to COVID-19 were needed and outpatient services were suspended (Decree Law 9 March 2020, no. 14), so that the oncological screening activities have decreased by more than 50% compared to 2019 [19].

According to the previous statements and scenario, it can be concluded that the BE plays an important role in the management of the pandemic and that it is important to increase the resilience of spaces and communities to quickly manage emergency conditions. This paper is part of a body of research which argues for a more sustainable and resilient model for hospitals in the post-COVID-19 era. The paper analyses response plans and measures against the COVID-19 pandemic within the Italian context, at the national and regional level. Two objectives have been set: reviewing governmental provisions for territorial and hospital health services rearrangement; reviewing operational responses on the regional scale to address those demands. Section 2 provides for data and methods used for deepening the analysis of the Italian measures to strengthen the health system. Section 3 shows the results achieved from this analysis, while Sect. 4 discusses them.

## 2 Materials and Methods

This section provides a brief overview of the Italian healthcare system and gives details about accessed databases and adopted processes to analyse healthcare facilities management during the emergency.

The SSN has implemented a decentralised model, especially since the constitutional reform of 2001 by which regions have gained legislative power in a wide range of fields, including healthcare. Health is a constitutional right; the central government defines the essential levels of care and guarantees them to all residents. The healthcare services are categorised in three macro levels: (a) public health, (b) community care, and (c) hospital care (Decree of the President of the Council of Ministers—DPCM—12th Jan 2017). Regions have the responsibility to deliver health services by means of health districts, hospitals and local health units. They autonomously regulate, organise, and administrate publicly financed healthcare [20]. Also, in addition to public companies, private healthcare facilities, the so-called accredited facilities, can participate in the delivery of essential services. This led to interregional differences in access to care [1, 21]. Bosa et al. [22] have outlined that this decentralised model led to different capacities in addressing the demand and the supply of healthcare services during the COVID-19 pandemic. On one hand it allowed local governments to tailor their responses to the needs of their population, on the other hand it might have impeded fast and integrated responses. Moreover, the COVID-19 pandemic has hit the country hard after years of strict spending reviews and severe cost containment measures which resulted in workforce shortages, insufficient communication and surveillance systems and inadequate healthcare infrastructures [22].

In order to further investigate the Italian response to the COVID-19 pandemic, in terms of national and regional urgent legislative measures, the authors have collected and reviewed regulatory provisions (i.e. Law Decree, Presidential Decree, Ministerial Circulars, Regional Orders), national guidelines (i.e. guides from the Minister of Health and the National Institute of Health), and other grey literature (i.e. reports of the National Centre for Screening Monitoring) from January 2020 to March 2021. National policies have been collected from the website of the Official Gazette of the Italian Republic. A thematic area, named "Coronavirus", of the above-mentioned gazette is available online as a dedicated collection of urgent measures to manage the COVID-19 emergency [23]. From January 2020 to March 2021 the government has published 87 documents. The authors gathered these documents in a database and used them as a reference to understand the development of the central response to the COVID-19 pandemic. They also collected and reviewed the provisions of the Minister of Health published within the same time span, for a total of 110 documents. The authors analysed the regional responses, retrieving data from the website of the National Agency for Health Regional Services [24] and from the official website of each region. Documents of particular interest for this paper are the regional plans for the rearrangement of hospital services and territorial services. Those plans have been required since 19th May 2020 by the Decree Law n.34 which argues for enhancing both hospital network and territorial services. The authors selected six regions as a field of study. The six regions were selected for being a relevant sample of resident population in northern, central, and southern Italy, and for having adopted the above-mentioned plans to examine. Comparative analyses have been carried out to outline similarities and differences in managing the healthcare crisis referring to those plans. Table 1 reports population and available plans of the selected regions.

**Table 1** Summary of examined plans for the selected regions

| Position | Region name | Population[a] | Hospital plan | Territorial plan |
|---|---|---|---|---|
| North | Lombardia | 10.027,602 | DGR[b] n. XI-3264 | DGR n. XI-3525 |
| North | Veneto | 4.879,133 | DGR n. 782 | DGR n. 782 |
| Central | Umbria | 870,165 | DGR n.1096 | DGR n.1096 |
| Central | Lazio | 5.755,700 | DCA[c] n. U00096 | Note n. 472,488 |
| South | Campania | 5.712,143 | DGR n. 304 | DGR n. 542 |
| South | Puglia | 3.953,305 | DGR n. 1079 | – |

[a] Data are retrieved from the National Institute of Statistics (ISTAT) and refer to the year 2019
[b] Regional Council Deliberation
[c] Ad acta Commissioner Decree

## 3 Results

The results are divided in two sub-sections regarding respectively national policies and regional provisions. The authors selected provisions and circulars related to healthcare facilities management, as those related to other fields of intervention (e.g. general governance, protective equipment, financial interventions etc.) are considered not to fall within the remit of this paper.

### *3.1 National Response*

A pandemic's evolution is characterised by at least four major phases: (a) interpandemic, (b) alert, (c) pandemic and (d) transition [25]. To each phase a risk management task can be ascribed (e.g. preparedness, response, and recovery). The pandemic phase, which the world is currently going through, can be further divided into three sub-phases: acute, post-acute and transition [26]. During the alert phase, the Italian Ministry of Health drafted a national task force and a scientific technical committee to coordinate the emergency interventions. Also, the Italian Government declared a state of emergency on 31st January 2020 as an extraordinary measure to ensure public health against the forthcoming pandemic. The state of emergency has two important implications for the governance of the crisis. First, the government can bypass the Parliament in the definition of legislative interventions, approving the so-called 'Decrees of the President of the Council of Ministers' (DPCM). Second, the state of emergency introduced the possibility of derogation of existing procurement rules, facilitating the acquisition of Personal Protective Equipment, tests and ventilators [22]. On 20th February 2020 the first Italian COVID-19 positive patient was reported, thus the acute phase began, and it lasted until 20th March. The acute phase was characterised by rapid growth of positive cases and insufficient contact tracing and surveillance measures [26]. The first significant national provision on healthcare facilities management is the Decree Law no. 14 of 9th March 2020. It oversaw the recruitment of healthcare personnel and the introduction of the special units of continued assistance (USCA), to be placed at least 1 every 50,000 inhabitants. USCA are in charge of managing COVID-19 patients in home-isolation. The Decree Law no. 14 has also required the division of the triage area from the admission room in emergency departments, placing attention on hospital infrastructures for the first time. Finally, outpatient activities have been suspended as well as all the other activities considered as deferrable. Shortly thereafter, the Minister of Health provided guidelines about how to define deferrable and urgent activities. The post-acute phase lasted from 21st March until 4th May 2020, during the national lockdown [26]. The surveillance system registered a flattening and then a decrease of reported COVID-19 cases, followed by a gradual reactivation of social and health services, as non-residential care homes. The epidemic transition started on 5th May 2020 and it is still ongoing at the time of writing. The most significant national provision

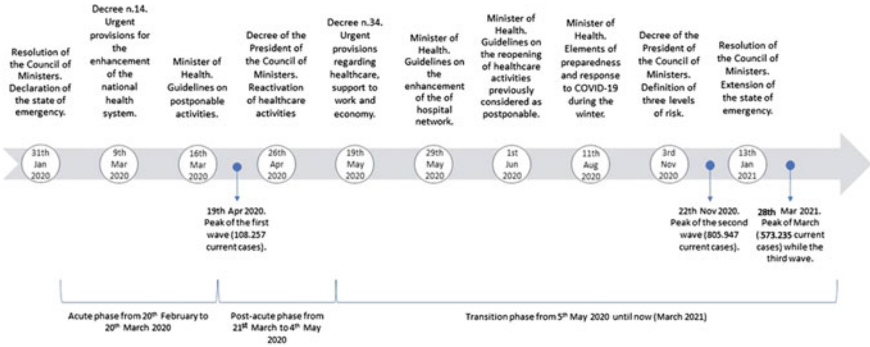


**Fig. 1** Flowchart of the main national provisions regarding healthcare facilities management from January 2020 to March 2021. Epidemiological data are retrieved from the website of the Italian Minister of Health

about healthcare facilities management is the Decree Law n. 34 of 19th May 2020. Article 1 calls for enhancement and organisational plans for the territorial healthcare services. It establishes that regions must adopt specific measures for contact tracing; they should start surveillance at residential care homes, while improving home care. Also, they can lease hotel facilities to manage and treat asymptomatic patients. Article 2 requires regions to adopt rearrangement plans for hospital networks. The main goal is to increase the number of beds in intensive and semi-intensive care units (ICU). To do so regions can also build temporary additional infrastructures. Also, dedicated pathways within healthcare facilities and additional dedicated means of transportation must be ensured for COVID-19 patients. The Minister of Health has published guidelines to support the adoption of such a plan as well as a checklist to assess the preparedness of Regional Health Systems to face the pandemic during the winter. Since November 2020 emergency interventions have depended on the risk assessed in each region, so that limitations and allowed activities can considerably vary across the country. Figure 1 depicts a flowchart of most important governmental provisions and epidemiological data from January 2020 to March 2021.

### *3.2 Regional Responses*

Within the broader national policy, each region developed one or more response plans to enhance both hospital and territorial services. As reported in Table 1, the authors have selected six regions as a field of study to deepen the operational response in the context of healthcare facilities management. Veneto and Umbria have adopted integrated plans, while the remaining regions adopted separated provisions.

Regarding the enhancement of the hospital network, the regions have followed ministerial guidelines and provided for common responses, such as: identifying COVID-19 dedicated infrastructures; increasing the ICU bed numbers; reviewing

**Table 2** Comparison of hospital-related measures adopted by the selected regions

| Measures | Puglia | Campania | Lazio | Umbria | Veneto | Lombardia |
|---|---|---|---|---|---|---|
| COVID-19 dedicated hospitals | Y | Y | Y | Y | Y | Y |
| Increase of ICU beds | Y | Y | Y | Y | Y | Y |
| Renovation of Emergency Departments | Y | – | Y | Y | Y | – |
| Additional means of transportation | Y | – | Y | Y | Y | Y |
| Additional long-term care beds | Y | – | – | Y | – | Y |
| Temporary field hospitals | – | Y | – | Y | Y | Y |
| Engagement of private hospitals | Y | – | Y | – | – | Y |
| Engagement of private facilities (other than hospitals) | Y | a | a | Y | – | a |

[a] Hotels and care homes have been involved by means of further provisions to assist and manage asymptomatic and discharged COVID-19 patients

the emergency and urgent care network (i.e. restructuring the emergency department and providing for additional means of transportation); increasing the workforce. The northern regions had started the rearrangement of their healthcare networks even before national regulation. During the continued pandemic they also provided for detailed documentation on how to renovate emergency departments and the ICU. The Lazio region has been providing, since January 2020, a wide set of guidelines and circulars on both patient and facilities management. Some regions (i.e. Puglia, Umbria, Lazio, Lombardia) immediately involved private facilities to address the surge of demand. Table 2 reports a comparison of measures to enhance the hospital network according to the analysed plans. In the table, Y stands for 'adopted'.

Territorial services management can greatly differ from one region to another as these services belong to Local Health Units. Moreover, they have secondary impacts on healthcare facilities as they generally focus on organisational measures more than infrastructural ones. However, from the analysed plans (Table 1) it is possible to outline some common measures and policies, such as: the establishment of contact tracing and surveillance systems; the introduction of the Special Units of Continued Assistance (USCA); the enhancement of integrated home assistance; coordination and information management (e.g. activating territorial operating centers); increasing workforce for primary care; additional measures (e.g. the control of private facilities offering long-term care services). Territorial medicine, particularly epidemiologic services which belong to departments of prevention, has been reinforced all over the country.

### 3.3 Discussion

Past pandemic leveraged changes into the BE, on both building and urban scale. The BE has an important role to play in supporting public health and reducing the risk of infections, indeed [5]. Solutions and strategies to move towards more sustainable and resilience buildings and cities are needed. In particular, there is a drive for improving multidisciplinary programmes to develop a new design for the hospital of the near future [17]. Within this background, this paper provides for the analysis of central and regional government provisions to rearrange healthcare facilities in Italy due to the ongoing pandemic. COVID-19 requires healthcare systems to have all essential preparedness measures in place to deal with the pandemic, while continuing to provide essential services. From the results exposed above it is possible to deduce that:

- in Italy, hospital care and territorial services have been reorganised by adopting specific regional plans.
- the changes on hospital infrastructure have been extensive. For example, to increase the ICU bed numbers, regions have restructured existing assets, built temporary field hospitals, restored unused portions of their facilities.
- the necessity to separate COVID-19 patients to reduce the risk of nosocomial transmission led to COVID-19 dedicated hubs or at least dedicated units. Either way, renovation interventions were required to control and prevent infections. Both technological features, spatial layout and organisational requirements have been reviewed in the face of the pandemic.

## 4 Conclusion

There is the need to enhance the preparedness of the national health system to cope with epidemics which have a predictable recurrence of 10 years. In this sense, a tool to assess healthcare infrastructures can help hospital managers make their asset more resilient and sustainable. This paper reports the preliminary results of a research aimed at proposing a novel model for the hospital of the future. The research has originality values as it tries to address extremely timely needs, and it has relevant practical implications regarding the need of multidisciplinary actions to define novel models for post-COVD-19 hospitals. The research will benefit (i) healthcare systems, providing advices for additional infrastructural capacities; (ii) healthcare workers, shaping safer work environments; (iii) patient's lives, modelling more resilient infrastructures to future epidemics which will enable the continuity of essential services. The research is currently limited to the Italian context. Future developments of this research will regard the acquisition of further data to determine how we will use and manage hospitals in the future. The main goal is to understand if architectural and technological changes will be needed to cope with future functional requirements of hospitals. To do so, real experiences will be gathered by means of field surveys and semi-structured interviews with healthcare professionals, hospital managers, and hospital facility managers involved in the pandemic management. Reflecting upon the Italian experience and analysing corresponding international approaches and policies will help identify the layout and engineering components of a prepared hospital in the case of epidemic. An evaluation framework can then be developed based on these components.

## References

1. Sanfelici, M.: The Italian response to the COVID-19 crisis: lessons learned and future direction in social development. Int. J. Commun. Social Develop. **2**(2), 191–210 (2020). https://doi.org/10.1177/2516602620936037
2. Dietz, L., Horve, P.F., Coil, D.A., Frezt, M., Eisen, J.A., Van Den Wymelenberg, K.: Novel coronavirus (COVID-19) pandemic: built environment considerations to reduce transmission. mSystems **5**, e00245–20 (2020). https://doi.org/10.1128/mSystems.00245-20
3. Bereitschaf, B., Scheller, D.: How might the COVID-19 pandemic affect 21st century urban design, planning, and development? Urban Sci. **4**, 0056 (2020). https://doi.org/10.3390/urbansci4040056
4. Keenan, J.M.: COVID, resilience, and the built environment. Environ. Syst. Decis. **40**, 216–221 (2020). https://doi.org/10.1007/s10669-020-09773-0
5. Pinheiro, M., Luís, N.: COVID-19 could leverage a sustainable built environment. Sustainability **12**, 5863 (2020). https://doi.org/10.3390/su12145863
6. Kelman, I.: Linking disaster risk reduction, climate change, and the sustainable development goals. Disaster Prev. Manag. **26**(3), 254–258 (2017). https://doi.org/10.1108/DPM-02-2017-0043
7. Aitsi-Selmi, A., Murray, V.: Protecting the health and well-being of populations from disasters: health and health care in the Sendai framework for disaster risk reduction 2015–2030. Prehosp Disaster Med. **31**(1), 74–78 (2016). https://doi.org/10.1017/S1049023X15005531
8. Djalante R., Shaw R., DeWit A.: Building resilience against biological hazards and pandemics: COVID-19 and its implications for the Sendai Framework. Progress Disaster Sci. **6**, 100080 (2020). https://doi.org/10.1016/j.pdisas.2020.100080
9. DeWit A., Shaw R., Djalante R.: An integrated approach to sustainable development, National Resilience, and COVID-19 responses: the case of Japan. Int. J. Disaster Risk Reduc. **51**, 101808 (2020). https://doi.org/10.1016/j.ijdrr.2020.101808
10. Capolongo, S., Rebecchi, A., Buffoli, M., Appolloni, L., Signorelli, C., Fara, G.M., D'Alessandro, D.: COVID-19 and Cities: from Urban Health strategies to the pandemic challenge. A decalogue of public health opportunities. Acta Biomed. **91**(2), 13–22 (2020). https://doi.org/10.23750/abm.v91i2.9615
11. D'Alessandro, D., Gola, M., Appolloni, L., Dettori, M., Fara, G.M., Rebecchi, A., Settimo, G., Capolongo, S.: COVID-19 and Living space challenge. Well-being and Public Health recommendations for a healthy, safe, and sustainable housing. Acta Biomed. **91**(9-S), 61–75 (2020). https://doi.org/10.23750/abm.v91i9-S.10115
12. World Health Organization: Suite of health service capacity assessments in the context of the COVID-19 pandemic, interim guidance, 2 Nov 2020. https://apps.who.int/iris/handle/10665/336278. Last accessed 20 Mar 2020
13. Flynn, S.E.: Higher Ground: The Sophisticated Healthcare Response of the SouthEast Texas Regional Advisory Council to Hurricane Harvey. Northeastern University Global Resilience Institute, Boston, MA (2018)
14. World Health Organization & Pan American Health Organization: Hospital Safety Index: Guide for Evaluators, 2nd edn. WHO, Switzerland (2015). https://apps.who.int/iris/handle/10665/258966

15. Smith, M., Feied, C., Pietrzak, M.P., Pickard, J., Hawkins, R., Vincent, D:. Project ER One Technical Reports, Phase I & II. ER One Institute, Washington, DC (2003)
16. Verheul, M., Dückers, M.: Defining and operationalizing disaster preparedness in hospitals: a systematic literature review. Prehosp. Disaster. Med. **35**(1), 61–68 (2020). https://doi.org/10.1017/S1049023X19005181
17. Capolongo, S., Gola, M., Brambilla, A., Morganti, A., Mosca, E.I., Barach, P.: COVID-19 and healthcare facilities: a decalogue of design strategies for resilient hospitals. Acta Bio Med. **91**(9-S), 50–60 (2020). https://doi.org/10.23750/abm.v91i9-S.10117
18. Armocida, B., Formenti, B., Ussai, S., Palestra, F., Missoni, E.: The Italian health system and the COVID-19 challenge. Lancet Public Health **5**(5), e253 (2020). https://doi.org/10.1016/S2468-2667(20)30074-8
19. Report on screening activities: https://www.osservatorionazionalescreening.it/content/rapporto-ripartenza-screening-maggio-2020. Last accessed 20 Mar 2021
20. Torbica, A., Fattore, G.: The "Essential Levels of Care" in Italy: when being explicit serves the devolution of powers. Eur. J. Health Econ. **6**, 46–52 (2005). https://doi.org/10.1007/s10198-005-0318-x
21. Ferré, F., de Belvis, A.G., Valerio, L., Longhi, S., Lazzari, A., Fattore, G., Ricciardi, W., Maresso, A.: Italy: health system review. Health Syst. Transit. **16**(4), 1–168 (2014)
22. Bosa, I., Castelli, A., Castelli, M., Ciani, O., Compagni, A., Galizzi, M.M., Garofano, M., Ghislandi, S., Giannoni, M., Marini, G., Vainieri, M.: Response to COVID-19: was Italy (un)prepared? Health Econ. Policy Law **5**, 1–13 (2021). https://doi.org/10.1017/S1744133121000141
23. Official Gazette of the Italian Republic: https://www.gazzettaufficiale.it/dettaglioArea/12. Last accessed 25 Mar 2021
24. National Agency for Health Regional Services: https://www.agenas.gov.it/covid19/web/index.php?r=site%2Findex. Last accessed 25 Mar 2021
25. World Health Organization: Pandemic Influenza Risk Management. A WHO guide to inform & harmonize national & international pandemic preparedness and response. WHO, Geneva, Switzerland (2017). http://www.who.int/influenza/preparedness/pandemic/influenza_risk_management/en/
26. Ministero della Salute - Istituto Superiore di Sanità: Prevention and response to COVID-19: evolution of strategy and planning in the transition phase for the autumn-winter season. Ministero della Salute, Istituto Superiore di Sanità, Rome, Italy (2020)

# Evaluation of Circular Construction Works During Design Phase: An Overview of Valuation Tools

**Nuri Cihan Kayaçetin, Stijn Verdoodt, Lode Leferve, and Alexis Versele**

**Abstract** The construction industry is one of the largest producers of waste. The Circular Economy Action Plan of the EU aims to tackle this issue and aspires to enhance the sustainability of the construction industry by adopting more circular principles and bio-based material use. For this purpose, an approach is being developed that facilitates coherence between technical, economical, legal, social aspects, and business models for circular design and building with bio-based materials in the Interreg Circular Bio-Based Construction Industry (CBCI) project. Within the scope of the project, tests and evaluations will be performed in a real-life setting, requiring the construction of a prototype house, the living lab (LL) located in Ghent. LL will be designed to incorporate circular principles like design-for-disassembly (DfD) and modular design, urban mining, reuse, use of recycled materials and compostable bio-based materials. In the search for circular construction methods a number of tools were used in an iterative process during the design phase of the living lab. In order to support the design process, an evaluation method is necessary to score the overall circularity. However, there is no standardized or well-established method to measure circularity. In this study, it is aimed to introduce a combination of existing tools on a case study. This approach should contribute to the creation of a holistic assessment of the circularity of the LL, which in turn will lead to buildings with circular material use by stimulating reuse, recycling and composting of bio-based building components.

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# 1 Introduction

The construction sector and the built environment is accounted for a large share of global material consumption [21] and represent the highest share of waste production [20]. It is one of the largest producers of waste, 36% of waste generation in the EU-27 in 2018.

Each year in the European Union an amount of 2.7 billion tonnes of waste is thrown away, 98 million tonnes of which is hazardous. On average only 40% of our solid waste is re-used or recycled, the rest going to landfill or incineration. Overall waste generation is stable in the EU, however, generation of some waste streams like construction and demolition waste, to sewage sludge and marine litter is still increasing.

Buildings are highlighted as one of three key sectors to be addressed in the Roadmap to a Resource Efficient Europe [19]. According to Revel, better construction and use of buildings could lead to significant resource savings up to 42% of our final energy consumption and about 35% of our total GHG emissions, 50% of the extracted materials, and 30% of water in some regions [10].

In this context, existing policies for promoting energy efficiency and renewable energy use in buildings need to be complemented with policies for resource efficiency of construction materials, which considers the environmental impacts across the life-cycle of buildings and infrastructure at a wider range. Life-time costs of buildings should increasingly be taken into account including construction and demolition waste rather than just the initial costs. Better infrastructure planning is a prerequisite in achieving resource efficiency of buildings and also mobility.

Significant improvements in resource and energy use during the life-cycle—with improved sustainable materials, higher waste recycling, and improved design—is expected to contribute to a competitive market and the development of a resource efficient building stock. This requires the active engagement of the whole value chain in the construction sector. Specific policies are needed to stimulate SMEs, which make up the vast majority of construction companies—to train and invest in resource efficient building methods and practices [13].

The aim of a circular economy approach in construction is to eliminate waste of valuable construction materials and re-use them once the initial life cycle of a construction project has come to an end. For this purpose, the Circular Bio-based Construction Industry (CBCI) project is examining bio-based materials used in buildings, designed to be disassembled and reused at the end of the initial design life.

In the scope of the project, the research outputs are to be displayed in real-life setting by constructing a prototype terraced single family house; the living lab (LL) located in Ghent, Belgium. The realization of the LL is conducted in a step-wise approach that includes iterative processes for design, description, criteria definition and multi-criteria assessment of building components. This study presents an assessment on circularity during the design phase for achieving a state-of-art building envelope that is suitable for a circular and bio-based construction.

## 2 Literature Review

Progress in recycling and reuse of materials in the EU is aimed to increase the circularity of the economy and to close the loops of production and consumption processes. This could be achieved by providing alternative sources of resources to maintain the actual physical stock of societies. It is also generally true that increasing circularity would not only yield benefits in material recovery but also in energy savings as reprocessed materials are expected to require less energy than primary materials [7].

According to Braungart and McDonough [4] the circular economy is a means to achieve the environmental sustainability by implementing production chains in which materials are used repeatedly, aiming at a balance between ecological systems and economic growth. A transition from the current "linear construction" to a circular construction is necessary. In addition to the sufficient use of material resources, the circular use of human resources and thereby the eradicating of poverty [16] is also an integrated part of circular economy.

A circular focus means that consumption should be prevented in circular and technological cycles and short cycling of products is preferred. Products, components, and materials are recovered and restored, through strategies like reuse, repair, remanufacture or (in the last resort) recycling [12]. Besides the material resource aspects, the focus is on circularity in terms of energy (both embodied and operational) and water usage and treatment. In addition, the Spatial Policy Plan of Flanders [22] promotes the circular use of available space.

In order to have a full-fledged circular economy, it is considered that circular principles should be supplemented with industrialized construction methods, inclusion of social economy and utilization of bio-based materials. The use of biomaterials is considered as a contribution to the circular economy in the context of innovation policy. EU's 2015 Circular Economy Action Plan and 2012 Bio-economy Strategy both have food waste, biomass and bio-based products as areas of intervention [11]. On the other hand, non-industrial materials that are manufactured by using a simple, quick but custom process with low embodied energy are not readily suitable for upscaling when compared to industrial materials that use raw materials and have standardized characteristics. Integration of the role of users is critical [17] for a circular economy to achieve a balance between the natural capital, the human capital and the remanufactured capital.

In this context, it was observed that there is a necessity for providing additional value for the utilization of bio-based materials by creating an asset in the re-use and recycle-ability with application of circular methods. In order to close this gap, assessment tools are considered as the means to introduce a first insight of potential on circularity.

# 3 Methodology

An iterative design research methodology is adopted for creation of the LL Ghent, as can be seen in Fig. 1. Depending on the principles of bio-based and circularity as given above, nine preliminary design (PD) scenarios that include the current practices as well as emerging construction techniques for the structure and building envelope are defined. By conducting a comparative study of these different PDs, critical information that is necessary for the final design is collected. The underlying reasons for performance differences are interpreted and translated into principles that are taken on in the next cycle. This interpretation was combined with economical and environmental impact results and provided as input for a decision-making process on building envelope design conducted in cooperation between CBCI project and LL contractor.

In this paper, a holistic approach for the evaluation of circular and bio-based building envelope scenarios is introduced. The aim is to adopt existing evaluation tools for the case of LL Ghent and explore an optimum combination of the tools for future use. The PDs are investigated in detail by using tools on the case study of LL Ghent, as given below:

- Design for disassembly (DfD) tool—CircuBuild
- Reuse and recycling—BBRI-VCB tool
- Preservation of materials—Platform CB'23.

## 3.1 Design for Disassembly (DfD) Tool

In order to cope with the need for resource efficiency, new principles have emerged in the construction sector. One of these principles is design-for-disassembly, a concept that has been considered as a valid strategy to achieve circular constructions. For this study, the 'Demountability Index Tool' [23] is utilized.

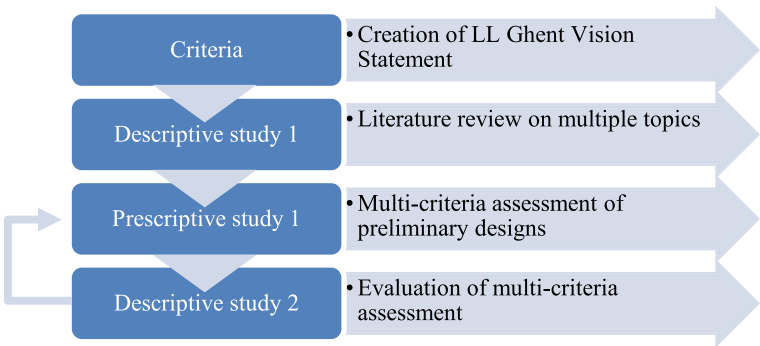


**Fig. 1** Design research methodology

The means of retrieving materials from existing buildings is defined as crucial for resource efficiency. When products are inextricably linked and retrieving materials is not possible, demolition remains as the only option. The more a building is demountable, the easier it is to retrieve products from building stock. In this perspective, demountability is a means to increase the possibility of re-use of materials in the future. It is defined as the degree to which 'objects' can be dismantled at all scales within buildings so that the object can retain its function and high-quality reuse can be realized [1]. To determine in what the above mentioned 'objects' are, to what level of detail the calculations should be done, the authors refer to the diagram in Fig. 2 of the 'Transformable Building Structures' by Durmisevic [8] showing the different building levels.

To define this level of detail, the NL/SfB methodology [2] is used. The level of detail is defined by three levels,elements (i.e. interior wall), variant element group (i.e. interior wall, not load-bearing), variant elements (i.e. fixed partition wall). In the DfD-tool an extended version of the NL/SfB methodology is used. This extension allows for a more complete overview of the different relevant building levels.

Assessment on at least variant elements detail level is determined as suitable since data for the lower levels is not adequate for analysis due to high level of complexity. Elements in such an assessment corresponds to 'structure', 'skin' and 'space plan' layers in the work of Brand [3] as shown in Fig. 3. These layers are taken into account in this paper for the calculation of demountability index.

The connection between the object and the underlying object that has a load-bearing function determines the demountability index. For instance, when considering a non-load-bearing wall, the connection with the underlying floor is calculated, not the connection with the window frame. When the wall is load-bearing, the connection with the window frame on the other hand is taken in consideration.

The four technical factors are defined for the calculation of the demountability index such as (i) type of connections, (ii) accessibility to the connections, (iii) crossings (level of integration), (iv) form enclosure (composition of objects). These factors are assessed for each object between 1.00 being the best score and 0.10 being the

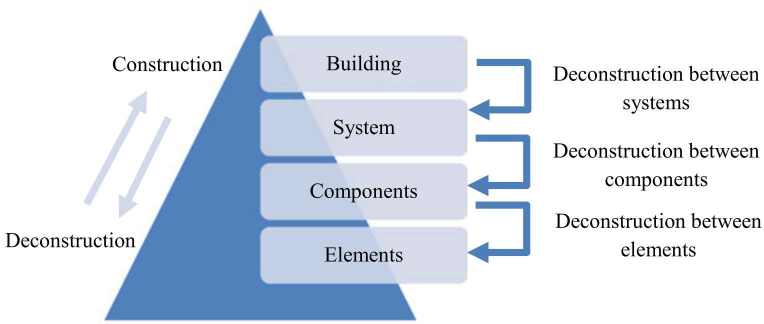


**Fig. 2** Levels of material decomposition [8]

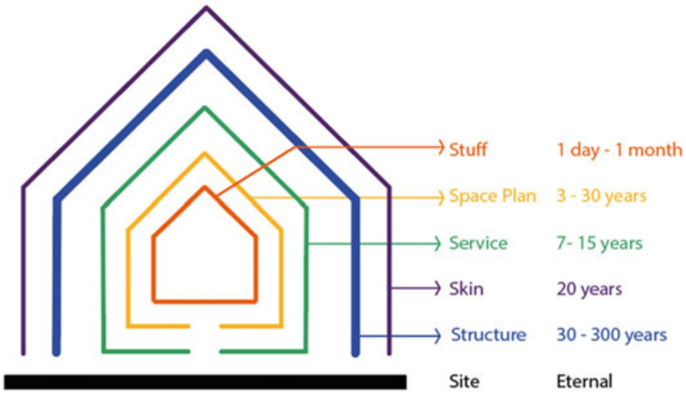


**Fig. 3** Layers of brand and respective lifetime [3]

worst score. A distinction is made between the Demountability Index of the connection (Dlc) and the Demountability Index of the composition (Dls) of the element, respectively influenced by the connection between objects and influenced by the composition of objects. As shown in Fig. 4, the demountability index is a combination of both indexes.

The circularity of products with a shorter lifetime is more relevant than products with a longer life time (e.g. a shorter lifetime implies for more replacement that require for new materials). The ultimate durability and circularity of buildings is not only related to the durability of its materials but more importantly to the way that the materials are put together [9]. Therefore, a level of importance is assigned by appointing a normalization factor between for layers such as, stuff layer with 1.0 and site layer with 0.1.

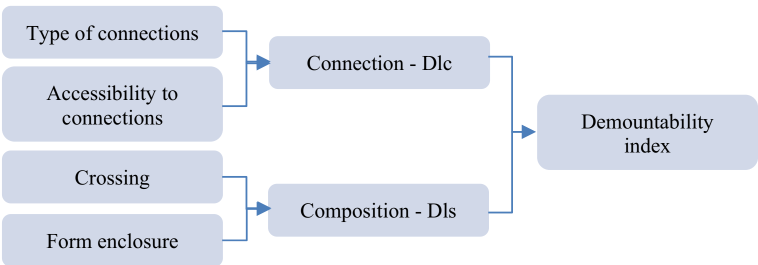


**Fig. 4** Demountability index calculation

### 3.2 *Re-use and Recycling—BBRI-VCB Tool*

The EU action plan for the circular economy [14] introduces an uptake of reuse and recyclability of products as an additional mean to improve the circularity level. For the improved demountability to be meaningful, the following potentials should also be anticipated, namely; reuse, refurbishing or recycling. It also follows a hierarchical order to reduce first, reuse as a second option, then resort to recycling. Reuse is recognized as being distinct from recycling, both in doctrine, and in the handling of the materials from the waste stream [15] of construction industry.

With the development of a guideline and measuring system for 'circular construction', the Flemish Construction Confederation and BBRI plan to introduce a tool to help developers, architects, contractors in the construction sector to support decision-making with a circular perspective. The tool contains a quantitative section, in which four main themes (change-oriented design [18], environmental impact, urban mining, transition towards a circular world) are dealt with using checklists and calculators:

For this study, 'Design for reuse and recycling' calculator is utilized, which is a part of the 'Change-orientated design' pillar. This calculator can be considered as a merge between demountability and reuse and recycling assessment. It assesses whether the building has been designed and composed in a demountable way and can easily adapt for reuse in the future. At the level of components and materials, the focus is on the independent functional layers and accessible and reversible connections. In the reuse and recycling calculator, the following properties are scored: avoided material impact, functional independence, technical detachability, physical characteristics and recyclability. The scores of these aspects are normalized following the DGNB guidelines—Ease of recovery and recycling [6] and accumulated into a single score.

### 3.3 *Preservation of Material Supplies—Platform CB'23*

Platform CB'23 stimulates the transition to a circular and sustainable construction economy with a material quantification method. The tool builds on existing methods for assessing sustainability and circularity as much as possible, integrating them into the framework. The method incorporates three aspects: (i) preservation of material supplies, (ii) environmental impacts and (iii) technical and economic value preservation.

The focus of CB'23 tool assessment was on comparison of material flows in a simplified manner, accounting for material input, and output to waste management (lost material, through landfill and incineration) and to reuse and recycling. In this study, the aspect of preservation of material supplies was selected for complementary to previous tools and a mass balance approach. The PDs were modelled in Belgian context for benchmark extraction and end-of-life scenarios for being representative of the current materials and construction methods in an early design stage [5].

**Table 1** Preliminary designs for structure and scenarios for technical installations

| Preliminary designs | Characteristics |
|---|---|
| PD1: Masonry—Traditional | Masonry with mortar—vaulted concrete floor |
| PD2: Masonry—Optimized | Masonry with connectors—concrete floor with ceramic box |
| PD3: Steel—Post-beam | Steel structure—sandwich panel—steel profile floor |
| PD4: Steel framing | Steel framing with aluminum cladding—steel profile floor |
| PD5: Wood framing | Wood framing—masonry finish—wood truss floor |
| PD6: Wood—Post-beam | Caisson with OSB—wood truss floors |
| PD7: Wood SIP—straw | Timber framing—straw-bale finish—Engineering wood floor |
| PD8: Wood—CLT | Cross laminated timber—wood fiber finish—wood truss floor |
| PD9: Modular blocks | Modular blocks—wood fiber finish—modular floor |

### *3.4 Case Study—CBCI Living Lab Ghent*

LL Ghent has the geometry of the typical nineteenth century terraced house typology; two regular storeys with attic under a sloping roof. The front and rear façades have floor-to-ceiling windows which maximize daylight usage. The side walls are typical blind walls to allow the prototype house fit in an urban terraced house context. The LL is planned to be constructed on the Technology Campus Ghent. In order to display its circularity potential, LL is required to be demounted and reconstructed in the nineteenth century belt around Ghent.

In order to achieve a final design that suits for this purpose, a comparative study was conducted with the possible options for PDs as given in Table 1. The PDs were defined according to the literature review and resulted in three main categories: heavy-weight (masonry), light-weight (steel) and bio-based (wood). In all PDs, a thermal transmittance value of 0.15 W/m$^2$ K of the building envelope was defined. Other general requirements such as structural, architectural and mechanical have been achieved according to existing building regulations.

In the next section, the previously given tools were conducted on the LL Ghent in the context of PDs and a comparative study is provided with respective results.

## 4 Results

The results are considered in two perspectives; potential versus current practice. The DfD and BBRI-VCB tool assess the potential of demountability and reuse and recycling. This implies that the results are currently not reflected in the current industrial building processes. On the other hand, CB'23 tool depends on the current technologies and provides actual percentages on material preservation.

**Table 2** Average demountability index for layers and normalized score

| Preliminary designs | Space plan | Skin | Structure | Average | Normalized |
|---|---|---|---|---|---|
| PD1—Masonry (baseline) | 0.29 | 0.85 | 0.38 | 0.51 | 0.52 |
| PD2—Masonry optimized | 0.53 | 0.85 | 0.52 | 0.63 | 0.65 |
| PD3—Steel post beam | 0.43 | 0.89 | 0.77 | 0.70 | 0.65 |
| PD4—Steel framing | 0.43 | 0.88 | 0.80 | 0.70 | 0.65 |
| PD5—Wood framing | 0.48 | 0.85 | 0.80 | 0.71 | 0.66 |
| PD6—Wood post beam | 0.62 | 0.88 | 0.88 | 0.79 | 0.75 |
| PD7—Wood SIP—straw | 0.47 | 0.79 | 0.80 | 0.69 | 0.63 |
| PD8—Wood—CLT | 0.47 | 0.88 | 0.80 | 0.72 | 0.67 |
| PD9—Modular blocks | 0.47 | 0.88 | 0.81 | 0.72 | 0.67 |

Table 2 displays the average and normalized demountability index for PDs. It is shown that the steel and bio-based PD categories (PD3-4, PD5-9) were performing better than the masonry options. The most critical differences were observed at the structure level, especially concerning two main strategies: linear load-bearing stacking and 3D post-beam structures. The latter clearly had an advantage regarding demountability.

Table 3 provides the potential for reuse and recycling of PDs. The critical differences were observed at structure and skin of the PDs. The difference in the skin scores were related to the variety of façade finishes in the line-up. Facades constructed with

**Table 3** Scores for reuse and recycling (out of 20)

| Preliminary designs | Structure | Space plan | | | Skin | | Score (%) |
|---|---|---|---|---|---|---|---|
| | | Wall | Floor | Ceiling | Roof | Façade | |
| PD1—Masonry (baseline) | 0 | 0 | 0 | 0 | 10 | 5 | 5 |
| PD2—Masonry optimized | 0 | 16 | 6 | 9 | 10 | 20 | 50 |
| PD3—Steel post beam | 16 | 16 | 0 | 9 | 14 | 11 | 49 |
| PD4—Steel framing | 5 | 16 | 0 | 9 | 14 | 11 | 40 |
| PD5—Wood framing | 5 | 14 | 0 | 9 | 10 | 5 | 34 |
| PD6—Wood post beam | 9 | 14 | 15 | 9 | 10 | 13 | 62 |
| PD7—Wood SIP—straw | 5 | 14 | 11 | 20 | 10 | 3 | 62 |
| PD8—Wood—CLT | 7 | 14 | 7 | 20 | 10 | 11 | 61 |
| PD9—Modular blocks | 14 | 14 | 7 | 9 | 10 | 11 | 53 |

**Table 4** Scores for preservation of material supplies (kg/m$^2$ GFA)

| Preliminary designs | Total input | Output lost | | Output for next cycle | |
|---|---|---|---|---|---|
| | | Landfilled | Incinerated | Reused | Recycled |
| PD1—Masonry (baseline) | 1219 | 78 | 36 | 53 | 1052 |
| PD2—Masonry optimized | 1189 | 134 | 18 | 53 | 984 |
| PD3—Steel post beam | 659 | 100 | 21 | 53 | 485 |
| PD4— Steel framing | 623 | 106 | 82 | 53 | 382 |
| PD5—Wood framing | 708 | 137 | 101 | 64 | 407 |
| PD6—Wood post beam | 725 | 72 | 86 | 53 | 514 |
| PD7—Wood SIP—straw | 728 | 225 | 24 | 192 | 286 |
| PD8—Wood—CLT | 757 | 70 | 144 | 53 | 489 |
| PD9—Modular blocks | 661 | 80 | 102 | 53 | 425 |

less reversible connections logically resulted in low potential for reuse or recycling, justifying the low scores of the brick facades of PD1 and 5. The structures of PD 3 and 9 performed the best since they are mono-functional and easily dismantled. The bolt connections of PD3 were rewarded slightly more than PD6's connections. PD9 with its 'sliding' connections performed equally well.

Table 4 shows the scores for current practice for PDs regarding preservation of material supplies. Both steel-based designs (PD3-4) used the least amount of material, and performs well from a resource depletion perspective. PD9 was considered as the bio-based PD that performed the best. However, by implementing circular measures at the end of life, the wood SIP straw design had the lowest amount of lost material, depleting materials the least while preserving value for next cycles of construction.

## 5 Discussion

The results of different circularity tools are further discussed in detail in this section. When displayed simultaneously as in Fig. 5, the figures provided the current situation on the preservation of material and the potential for improvement through recycle and reuse. It was considered that, the best options should have the least amount of material in total with lowest amount of materials lost together with a high rate of reuse.

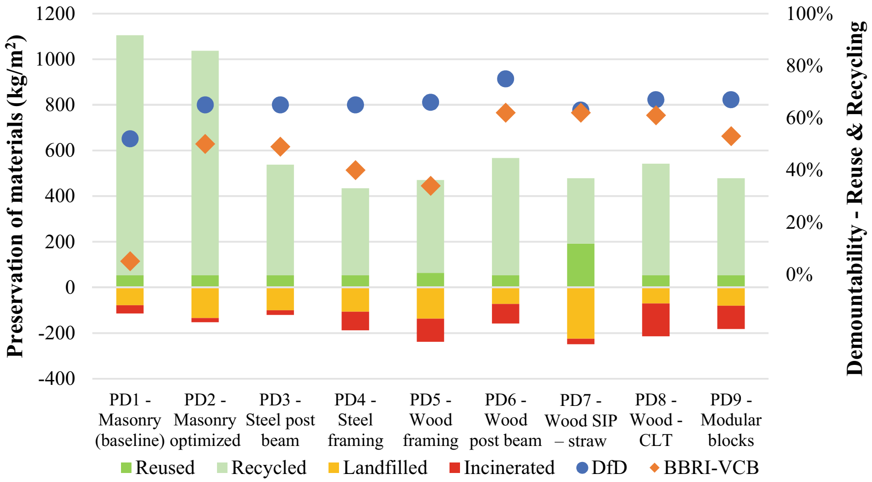


**Fig. 5** Circularity evaluation—potential versus current practice

It was seen that the amount of material input for heavy-weight masonry PDs was significantly high, without room for improvement for reuse and recycle. Light-weight PDs displayed the lowest amount of input with mediocre potential for improvement. Even though bio-based PDs had medium amount of material input, a high potential on reuse and recycling coupled with demountability was observed. PD7—Wood SIP straw performed the best with highest rate of reusability with improvement potential.

It was also observed that demountability and reuse and recycling indexes were not always correlated with each other. It was a clear indication for PD1—Masonry that the low rate of demountability was insignificant as the reuse and recycling potential was so low. With this perspective, it is suggested that improving demountability index would be more meaningful for a design with reuse and recycling potential.

## 6 Conclusion

A selection of existing tools was utilized for circularity assessment of the LL Ghent. The combination of the tools provided promising outcomes. The individual results of the tools would not have provided a comprehensive outlook to the circularity; current practice and potential for improvement for reuse and recycle. A future study for improving the assessment framework will include combining the circularity tools with environmental impact assessment methods.

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## References

1. Bos, M.: Circulair bouwen: Rapport losmaakbaarheid beschikbaar (2019). Retrieved from https://www.w-e.nl/rapport-losmaakbaarheid-bij-circulair-bouwen/
2. BNA: NL/SfB–Tabellen Inclusief gereviseerde Elementenmethode '91 (2005)
3. Brand, S.: How Buildings Learn: What Happens After They're Built. Penguin Books, New York (1995)
4. Braungart, M., McDonough, W.: Cradle to Cradle: Remaking the Way We Make the Things (Waterproof/Durabook ed.). North Point, New York (2002)
5. Platform CB'23: Leidraad 2.0 Meten van circulariteit (2020). Retrieved from https://platformcb23.nl/aan-de-slag/2020
6. DGNB (2018). DGNB System – New buildings criteria set: Technical Quality TEC 1.6 Ease of recovery and recycling. Version 2020 International. DGNB GmbH.
7. Domenech, T., Bahn-Walkowiak, B.: Transition towards a resource efficient circular economy in Europe: policy lessons from the EU and the member states. Ecol. Econ. **155**, 7–19 (2019)
8. Durmisevic, A.: Transformable building structures design for disassembly as a way to introduce sustainable engineering to building design & construction (2006)
9. Durmisevic, A.:. Reversible Building Design. In: Designing for the Circular Economy. 1st edn., pp. 344–359. Routledge (2019)
10. Ecorys (2014). Resource efficiency in the building sector: Final report, DG Environment.
11. EEA: The Circular Economy and the Bioeconomy Partners in Sustainability Report (2018)
12. Ellen MacArthur Foundation (2015). Growth within: a circular economy vision for a competitive Europe, Ellen Mac Arthur Foundation, Cowes, UK.
13. European Commission (EC): Roadmap to a Resource Efficient Europe COM/2011/0571 Final. European Commission, Brussels, Belgium (2011)
14. European Commission (EC): Closing the loop—An EU action plan for the Circular Economy COM/2015/0614 Final. European Commission, Brussels, Belgium (2015)
15. Kralj, D., Markic, M.: Building materials reuse and recycle. WSEAS Trans. Environ. Develop. **5**(4), 409–418 (2008)
16. Lemille,A.: Applying "Circular Thinking" to also eradicate Poverty, Social Businesses at the core of the next economy; Social Business Academia Conference on 10 Nov 2016
17. Lemille, A.: Circular Human Flows [Circular Economy 2.7], Enhancing Humans as an integral part of Circular Economic Flows. Published on Linked on 6 April 2017
18. OVAM (2020). Building catalogue - Change oriented design – Functional Layers. V.U. OVAM, Stationsstraat 110, 2800
19. Revel, D.: Roadmap to a Resource Efficient Europe. In Veille énergie climat (2011)
20. Stephan, A., Athanassiadis, A.: Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. Resour. Conserv. Recycl. **129**, 248–262 (2018)
21. UNEP: Global material flows and resource productivity. an assessment study of the UNEP International Resource Panel. H. Schandl, et al. Paris, UN Environment Programme (2016)
22. Vlaanderen (2018). Spatial Policy Plans for Flanders: Strategic Vision. Department of Environment, Department of Policy Development and Legal Support.
23. Van Vliet, M., Van Grinsven, J., Teunizen, J.:. Circular buildings—Meetmethodiek Losmaakbaarheid. V 2.0. Alba Concepts (2021)

# Landscape Integrated Photovoltaic System for a Solar Island in the Venetian Lagoon

**Elena Lucchi, Sofia Tiozzo Pezzoli, and Antonello Durante**

**Abstract** The paper deals with the refurbishment of La Certosa Island, a protected natural and archeological area in the Venice Lagoon (Italy). According to its original meaning, the Island acts as an innovation laboratory for the application of solar technologies and green infrastructures. The project is based on an integrated model of sustainable development, which offers services like activities related to boating, crafts, tourism, food, and beverage. The existing buildings were covered with colored Building Integrated Photovoltaic (BIPV) systems for an energy production of 184 kWp. The system was perfectly integrated with the landscape and in the historic buildings. The project refers to the entire island, not only to specific buildings, introducing the concept of Landscape Integrated Photovoltaic (LIPV) system. This research presents the urban and building design project, with a risk–benefit assessment of the BIPV roofs and LIPV in the island, developed according to the European standard EN-16883: 2017. Several lessons can be learned from this project. The importance of the public–private partnership for boosting photovoltaic (PV) systems in the territorial redevelopment, and the continuous collaboration among the different stakeholders involved for mitigating their impact. This way, La Certosa Island become a solar Island because of the positive example of BIPV and LIPV application in a protected area.

## 1 Introduction

Renewable Energy Sources (RES) implementation in protected buildings and landscapes is a strategical action to boost industrial innovation, sustainability, energy decarbonization and transition [1, 2]. RES use in Europe is endorsed by the legislation that defined specific targets for increasing their spread, the energy performances

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of buildings, and the reduction of carbon dioxide emissions [3]. These policies and actions also consider cultural heritage. It can contribute to supply-side strategies thanks to the development of RES community [4]. The protection and the enhancement of heritage and natural characters of cities, villages, rural areas, landscapes, and buildings is an important point [5–7]. The use of solar energy, in particular photovoltaic (PV) systems, in architecturally sensitive contexts has controversial issues, mainly related to the visual integration and the aesthetical acceptability [7, 9–11]. On the contrary, technical, energy, and economic advantages are universally recognized [10–12]. For the last ten years, the solar manufacturing industry has been capable to to offer new "*architecturally pleasing*" PV products [12], thanks to the high customization level, and to the increasing of energy performances of colored cells, thin films, homogenized black appearance, crystalline silicon modules, solar tiles, embedded solar tiles, and high-resolution printed images. Moreover, guidelines and handbooks support planning, design, and authorization procedures in these areas with details, practical solutions, and possible approaches [9, 10, 12]. Similarly, several collaborative research projects develop innovative materials and solutions for heritage contexts [10]. PV systems, thanks to their innovative features, are used both at building and landscape scale. At the building level, they are included in the building envelope (e.g. roofs, facades, windows) as building attached or applied PV (BAPV) or building integrated PV (BIPV). BAPV modules are mounted on the building envelope without fulfilling specific integration criteria [11, 13], while BIPV systems provide additional functions to energy production (i.e. mechanical rigidity, structural integrity, primary weather impact protection, noise protection, fire protection, thermal insulation, shading, daylighting, security) [13]. The recent concept of "sustainable energy landscapes" deals with landscape design and planning purposes. It focuses on the relationships between PV systems and spatial and morphological features without compromising values, biodiversity, and food production [14]. The potential of energy generation in these applications is considerably high [14]. The landscape integrated PV (LIPV), particularly, has to face with complex challenges related to the aesthetic appearance, the ecological impact on natural systems, their harmonization on agriculture, and the improvement of infrastructures with energy production [14]. Despite there are several case studies of BAPV and BIPV in heritage contexts [7, 9, 11], LIPV applications refer mainly to the integration of stand-alone PV systems in non-protected rural areas [14]. Only a few examples discuss in detail the integration of PV systems into landscape or conservation areas. No guidelines or standards focus on that [10]. This topic offers new challenges: theories, design parameters, environmental and visual impacts, aesthetic perceptions different from those for traditional PV building integration have to be investigated.

## 2 Aims and Methodology

The paper presents the refurbishment of La Certosa Island, a beautiful natural and protected archeological area in the Venetian Lagoon (Italy). The Island acts as a laboratory and showcase for the application of the best available technologies for green infrastructure and RES production, thanks to the historical vocation of the Island for the innovation related to the production of military materials from nineteenth Century. The end of war industry left the area and its building in a damaged state of conservation. The refurbishment project started in 2010 as an integrated model of sustainable development, offering services like activities related to boating, crafts, tourism, food, and beverage to reply to the territorial needs. The link between innovation and sustainability suggested the application of RES technologies. The energy consumptions of the area are covered by the use PV systems: about 1100 $m^2$ of existing roofs were converted into RES using a BIPV solution with colored PV tiles for 184 kWp. Its innovation consists in the balance between the strictly archeological, natural, and architectural constrains and the preservation of landscape and heritage values of the area, while producing electricity. This project refers to the entire territorial area, not only to specific buildings as happens in similar applications.

The research was structured in the following phases: (i) historical analysis of the site; (ii) urban energy planning; (iii) building energy retrofit, with a focus on the BIPV design; (iv) risk–benefit assessment of the BIPV system, applying the tabular scheme developed according to the European standard EN-16883:2017 [15].

## 3 Historical Analysis of the Site

La Certosa Island is the biggest among the “minor islands” composing the Venetian Lagoon. The area is protected for cultural heritage and archeological interest by the Italian legislation [16]. It is also part of UNESCO sites and is included within the Natura 2000 Network sites. The name derives from the Italian Carthusian monks. Since the medieval ages the island hosted a prestigious monastery; Augustinian monks since 1199 and Carthusian monks from 1424. This monastery was connected to rural and agricultural activities, also thanks to the farmer community of vineyards and orchards. In the Napoleonic period, the area was destroyed, except for a part of the monastic complex that is still conserved and preserved as it was in 1806. Then, the religious community was moved to the mainland. From the XIX Century until the Second World War, the area was used for military purpose: first as storage for military materials and later as fuses, ammunition, and armaments production (named the Pirotecnica della Certosa). The end of the war industry in 1957 left the island in a damaged state of conservation for a long time. Similarly, the hydrography of the Lagoon had several transformations during the Centuries that changed especially the relation between land and water. The contemporary landscape was stabilized in the late 1950s.

A special legislation for Venice [17] gave this island to the Municipality for 99 years, to realize a socio-economic and environmental refurbishment for enhancing the natural landscape, the urban structure, and the historical buildings. This project started considering its natural vocation as "the Gate" of the Lagoon thanks to the presence of the Nautical Center of Venice. Thus, was decided to host sporting, touristic, and recreational activities. In 1996, a retrofit project was developed under the "Vento di Venezia" umbrella, promoted by EU funding and a public–private partnership with the Municipality of Venice and the Magistrato alle Acque di Venezia.

## 4 Urban Energy Planning

The urban project consists of the morphological reorganization, the reuse, and the economic regeneration of the area through the principle of sustainability and low environmental impact. The project includes a marina complex, a public park, a boardwalk, and a pier for the water bus stop. The project aims at making the island a large green area entirely usable a stone's throw from the historic center and equipped with services that do not find expression in the ancient city (i.e. services for the leisure and free time of residents and services for a tourist niche linked to the environment, sport and culture). The interventions include: (i) the redevelopment of the island's building heritage according to the best standards of environmental sustainability; (ii) the creation of equipped paths and the requalification of degraded vegetation while preserving valuable species, the restoration of an agricultural area retracing the traditions of the island's vegetable gardens and vineyards in the pre-nineteenth century; (iii) the development of the current mooring system for pleasure boats entirely on floating docks and the installation of some support equipment; and (iv) a pedestrian crossing system on floating mobile piers to reach the adjacent islands. The extensive process of the Urban Plan is shown in Table 1.

**Table 1** The process of the refurbishment plan

| Year | Activity |
|---|---|
| 1996 | Drafting and approval of the Refurbishment Plan |
| 1996–1998 | Inclusion in the European Community programs |
| 1998–2002 | Design and execution of a first lot of intervention |
| 2003–2004 | Public tender for the existing lots |
| 2005 | Construction of the marina complex |
| 2007 | Design and execution of the urban park |
| 2009 | Public tender for the identification of a partner for the construction of the park and its management |
| 2020 | Installation of the BIPV roofs |

**Table 2** The constrains of the La Certosa Island

| Area | Constrain |
|---|---|
| Venice lagoon | UNESCO Site |
| | Natura 2000 Network sites |
| La Certosa Island | Declaration of cultural interest |
| | Declaration of high public interest |
| | Archaeological risk |
| Buildings: Monastery, Farmer building (Casa dell'Ortolano), old castle (Casello delle Polveri) | Declaration of cultural interest |

The land area is recognized at local level as "transition bond" between the natural and the built environment of the Lagoon. This protected territory is subject to several constraints s that demonstrate the high heritage value of the area (Table 2).

Starting from the analysis of the constrains, the interventions on the building heritage focus on the demolition on reconstruction of the army industry. These buildings are used integrated services for boating, environmental education, tourist-hotel hospitality (hotel, restaurant, shop, and bar), sporting (sailing club), craft, and cultural events (Sect. 5). The ancient remains of the cloister are valued through the creation of cultural and didactic structures. Also, the design project involves the conversion of the abandoned area into an urban park. The lush urban park provides the creation of accessible paths and the conservation of the natural and archeological heritage. The park occupies two-thirds of the twenty-two hectares of the island. The land recovery is based on the conservation of the valuable spontaneous tree essences, through the remediation of waste and weed vegetation. Also, the rural destination allows the recovery of traditional horticultural and wine-growing activities. Rural and natural paths favor the use of equipped areas as well as discourage the use of valuable landscapes. The lowering of some walls of marginalization permits also the creation of terraces and lookout points. In addition, the project involves the expansion of moorings for boats and the upgrading of the infrastructure of support to boating. The presence of a system of pedestrian crossings on mobile piers floats permits to reach the adjacent islands, integrating them to the local public transport with the aim of creating a nautical, agricultural, environmental, and cultural district (see Fig. 1).

## 5 Building Energy Retrofit

The existing buildings in the past were used as storage, warehouse, and industrial construction of the arms industry active on the island until the 1950s. One of these experimentations involved the refurbishment of some non-listed buildings dating back to the 90s by the architects Tobia Scarpa. The interventions focus on the demolition and reconstruction without changing the shapes and increasing the

**Fig. 1** The Certosa Island. *Source* GruppoSTG/VDV srl

volumes of 46 high-damaged buildings (on 67 existing constructions). The intervention was based on the use of natural-based solution and recycled materials from the existing buildings. The project provides the establishment of boating, sport, training, craftsmanship, hospitality, and commercial, and catering activities.

### *5.1 BIPV Design*

Since 2010, because of the need for refurbishment of the area, unusual infrastructures for the lagoon were built notwithstanding the current regulations. With the same approach, some buildings for boatyard were refurbished. They were of large spans and with pitched roofs covered by terracotta tiles. The first design project provided the installation of classic PV single-crystal silicon modules of 60 cells, equipped with a frame, on the best sun-exposed portion of the roof (2010). This project was revised in 2020, proposing a glass/laminated glass BIPV roof without framing systems [18]. Three innovative PV systems integrated into the roof were built, transforming over 1110 m$^2$ of opaque surfaces into an active roof using the BIPV system with colored PV tiles. Also, it was decided that future constructions in the island should include PV modules. The PV roofs installed were made with standard and custom modules. Visual continuity was achieved by adding some completion tiles without silicon cells to the custom-made PV tiles for complete architectural integration of the modules, ensuring a homogeneous view of the roof, especially from far points of view [18]. Overall, 184 kWp of power were installed in combination with a 48 kWh storage system (see Fig. 2).

**Fig. 2** The BIPV roof on a typical building. *Source* GruppoSTG/VDV srl

The PV tile is composed by double laminated glass with PV cells and polyvinyl-butyral (PVB) solar. The front glass is a solar grade glass painted on face two with a ceramic screen-print specifically designed for PV application and giving the terra-cotta color, which will be permanently fixed by the glass tempering process. The internal layer is composed by the monocrystalline PV cells incapsulated in a double PVB solar. This material has higher light transmission than the standard PVB used in the glass sector for favoring the energy production from the PV cells. The back glass is also a tempered glass. This structure makes the PV tile more resistant than single glass panels. An image of the construction phases of a BIPV roof is reported below (see Fig. 3).

**Fig. 3** Construction phases of a BIPV roof. *Source* GruppoSTG/VDV srl

## 6 Risk–Benefit Assessment of the BIPV System

The risk-benefits assessment scheme is developed according to the standard EN-16883:2017 [15] that presents a systematic procedure based on five-levels scale for evaluating the energy efficiency of historic buildings through a sustainable balance between conservation, energy performance, and human comfort issues. The standard aims at balancing heritage conservation, energy performance, and human comfort issues in the energy retrofit and sustainable management of historic buildings. From this general guideline, the Working Group on "Solar Energies" of the International Energy Agency (IEA) Task 59 developed a tabular risk–benefit scheme specifically tailored for the implementation of renewable solar solutions in historic building [19]. This scheme is based on the evaluation of the following categories: (i) technical compatibility, (ii) heritage significance of the building and its settings, (iii) economic viability, (iv) energy performances, (v) indoor environmental quality, (vi) impact on the outdoor environment of the energy solutions, and (vii) aspect of use. According to the standard [15], a five-level assessment scale is proposed to evaluate the solar technology. This scale is divided high and low risks, neutral, high, and low benefits. here, this risk–benefit scheme is applied to the evaluation of La Certosa design project. To have a coherent, transparent, and comprehensive evaluation, the assessment scale is defined by an interdisciplinary team composed by the experts involved in the planning, design, and authorization processes, with the support of BIPV experts. Table 3 shows a synthetical overview of the outcomes of this evaluation.

Overall, the PV system resulted in high technical compatibility thanks to the selection and the installation of PV tiles and fixing systems. PV components were produced, and the system installed according to EU regulations and specific installation guidelines. Hygrothermal, structural, fire, and efficiency reduction risks are negligible for the above reason. There is no hygrothermal risk due to the roof system installed, which is composed of a double layer of strips with a vapor barrier in between. Water channels were carefully designed and fixed with brackets A drainage system that stops the water was also included. PV tile is classified as L1B1 for mechanical resistance, as it has passed the tests required by the UNI EN 12,600: 2004 standard, including the pendulum test. As required by current legislation, the analysis of the fire load development on the roofs was not carried out. However, appropriate corrections on critical points for fire resistance were made (e.g. external direct current cable descents to buildings). The reduction efficiency risk is in line with the premature decay standard for building materials, according to IEC 61215: 2005 and IEC 61730–2: 2012. The PV modules are equipped with fixing components, back drains and water sealing components that allowed a complete replacement of the tiles. Fixing and cabling systems can be easily dismounted or substituted without any significant detrimental effect on the historical building. The PV architectural integration follows a long design process for guarantee a low material, visual, and spatial impact on the building and its surroundings. The roof is composed by two parts: one pitch is covered by the original (but non-historic) brick tiles and the other

**Table 3** Risk–benefit scheme for the assessment of the BIPV system in La Certosa

| Category | Criteria | Description | Level |
|---|---|---|---|
| Technical compatibility | Hygrothermal risk | The detailed study of the system and installation aimed at avoiding the risk of condensation and water accumulation | |
| | Structural risk | The modules were tested for mechanical resistance L1B1 | |
| | Reversibility | The system can be easily dismounted due to the snap-on module coupling systems, which allows returning to the original lath structure when needed | |
| | Reduction efficiency risk | Their production performance reduces to 80% after 25 years | |
| | Fire safety | PV tile without frame has a higher fire safety than a PV module with frame. The roofing system has been designed according to the fire prevention rules | |
| | Design and installation | Accurate design of the roof according to manufactures guidelines and current standards, and faster installation thanks to the snap on module coupling systems | |
| | Thermal bridges | The PV roofs were designed by avoiding thermal bridges | |
| Heritage significance of the building and its settings | Risk of material impact | Reduced impact related to the coverage of only one pitch by PV tiles | |
| | Risks of visual impact | Visual compatibility of the PV tiles based on coplanarity, total coverage of the pitch, absence of frames, color matching, reduction of reflectivity | |
| | Risk of spatial impact | No changes in the geometrical relationships between the building and the surroundings | |
| Economic viability | Capital costs | PV tile: 270 € per unit, 180 €/m² | |
| | Operating costs | No data | |
| | Economical return | No data | |
| | Economic savings | No data | |
| Energy | Energy performance and operational energy demand in terms of primary energy rating | 211 MWh/anno | |
| | Life cycle energy (LCE) demand in terms of use of RES and non-RES primary energy | No data | |
| Indoor environmental (IE) quality | IE conditions suitable for achieving good occupant comfort levels | The PV system might help to maintain a good IE condition if connected to the HVAC systems of these buildings | |
| Impact on the outdoor environment | LCE demand in terms of greenhouse gas emission | No data | |
| | Natural resources | No data | |
| | Influence on the use and the users of the building | No influence with the usage of the building | |

(continued)

**Table 3** (continued)

| | | | |
|---|---|---|---|
| Aspects of use | Consequences of change of use | No major consequences | |
| | Ability of building users to manage and operate control systems | No data | ■ |

*Notes* ■ = High risk ■ = Low risk □ = Neutral ■ = Low Benefit ■ = High Benefit ■ = No data

Source: Elaboration of the authors

one is covered by the PV tiles. This approach is suggested by the Heritage Authorities for minimizing the losses of the original materials and the visual impact from the public area, maintain the original aesthetic image from public views. It has also technical and energy benefits, as the BIPV has the optimal orientation with respect to the sun, maximizing its energy production. In addition, as a portion of the old roofs were destroyed by a tornado, replacement and integration of the tiles were needed. The visual integration is based on the coplanarity, compliance with the roof lines, consistency with the roof pitch shape and dimensions, and color and reflectivity matching. The chromatic design is particularly important for minimizing the visual impact of the PV panels. Thanks to the colored glass, a chromatic effect similar to terracotta color was obtained. This color is typical of the traditional roofing used in the lagoon area and most of the northern and central Italy regions. This solution offered a chance to refurbish the well-exposed roof pitches that resulted in complete chromatic assonance with the surrounding buildings' roofs and the rest of the lagoon. PV modules were visible form the south-east side only, the side from the sea, and brick roofing were visible from the west side only, the side close to the city. This was a design prescription aiming at having uniform visual cones for the most important points of view. Also, the PV panels are visible from the lagoon, as requested by the Heritage Authority for enhancing the innovative character of the Island. This design additionally permits a direct comparison between traditional and PV roofs, particularly useful also from a didactic point of view. Thanks to its features, no changes in the geometrical relationships between the building and the surroundings have been create, preserving the landscape perception. No information is available about the economic viability, apart from capital costs. The investment for the batteries, PV panels, their installation as well as the charge controllers is 180 €/m$^2$ (considering brackets, ducts, and drips). The energy performance of a single-colored module is of 220 W about 10% less than a usual silicon PV module. No LCA of the product has been made. However, the circular economy is at the basis of the project; the old tiles that were removed from the original roofs were recycled for the construction of the new footpaths of the Island. The system was not directly managed by the users, and a system for monitoring the electricity production is planned to be installed along with the other smart management components connected to the island electricity district.

## 7 Conclusions

This project permits to learn some lessons for BIPV application at urban and building level. First, the public–private partnership is important for boosting the use of RES in the territorial redevelopment of unused municipal areas projects considering the sustainable development goals. Thank to this collaboration, the project refers to the entire territorial area not only to specific buildings, as occurs in similar applications. Second, the knowledge of the characters and the meanings of area, traditionally devoted to innovation, was fundamental for developing this project. In fact, BIPV system are visible from the ferries arrival point of view only. This was a design choice that allowed the innovative character of the area to be emphasized with the use of PV. The technical compatibility of BIPV systems implies the absence of structural, hygrothermal, energy, fire, installation, and maintenance risks. Also, reversibility of materials for bonding and mechanical fixings is a fundamental aspect for historic buildings, to dismounting the BIPV system without damaging the original structure [15]. Moreover, a continuous dialogue and a long-term collaboration among the different stakeholders involved in the project (e.g. technicians from the Municipality, designers, environment and heritage conservation bodies, RES industry) improved advanced and coordinated studies for the energy infrastructure, mitigating the impact RES and infrastructure on communities and landscapes. As matter of fact, a proper and consistent design of BIPV systems that respects the heritage significance occurs only through the collaboration of a multidisciplinary team. The collaboration with the Heritage Authorities in the design process particularly was a strategic point for enhancing historical sites and buildings, also protecting their heritage and natural values. The close dialogue between the client and the designers changed the idea of adopting standard PV elements with a frame, favoring the use of colored PV modules without a frame. This allowed to maximize the pickling surface and therefore the power of the system. Economic data in general are not available for privacy policies. Similarly, environmental data (e.g. indoor environmental quality, Impact on the outdoor environment, environmental sustainability, LCA) are rarely considered or published in BIPV design projects. Due to its feature and to the attention of historical, natural, environmental, and architectural data, this BIPV roof can be replicated in further landscape contexts typical of the Italian peninsula. In this way, the solar island is a positive example of LIPV and BIPV application in a protected area.

## References

1. European Commission 2019: The European Green Deal, COM (2019) 640, European Commission, Brussels (2019)
2. European Parliament: Report on the proposal for a regulation of the European Parliament and of the Council establishing the Just Transition Fund, COM(2020)0022–C9-0007/2020–2020/0006(COD), European Parliament, Brussels (2020)
3. European Parliament: Directive 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and

Directive 2012/27/EU on energy efficiency. Off. J. Eur. Union (2018)
4. Potts, A. et al.: Executive summary. In: European Cultural Heritage Green Paper Executive Summary, Europa Nostra, The Hague & Brussels (2021)
5. A Renovation Wave for Europe. Available online at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. Accessed 26 Mar 2021
6. New European Bauhaus. Available online at: https://europa.eu/new-european-bauhaus/index_en. Accessed 26 Feb 2021
7. Serraino, M., Lucchi, E.: Energy efficiency, heritage conservation, and landscape integration: the case study of the San Martino Castle in Parella (Turin, Italy). Energy Procedia **133**, 424–434 (2017)
8. Polo Lopez, C.S., Lucchi, E., Franco, G.: Acceptance of building integrate photovoltaic (BIPV) in heritage buildings and landscapes: potentials, barriers and assessments criteria. In: 8th Euro-American Congress on Construction Pathology, Rehabilitation Technology and Heritage Management, Rehabend 2020, Granada (2020)
9. De Medici, S.: Italian architectural heritage and photovoltaic systems. Match. Style Sustain. **13**, 2108 (2021)
10. Lucchi, E., Polo López, C.S., Franco, G.: A conceptual framework on the integration of solar systems in heritage sites and buildings. In: IOP Conference Series: Material Science and Engineering 949 012113 (2020)
11. Rosa, F.: Building-integrated photovoltaics (BIPV) in historical buildings: opportunities and constraints. Energies **13**, 3628 (2020)
12. Pelle, M., Lucchi, E., Maturi, L., Astigarraga, A., Causone, F.: Coloured BIPV technologies: methodological and experimental assessment for architecturally sensitive areas. Energies **13**, 4506 (2020)
13. Standard EN 50583-1: Photovoltaics in buildings—part 1: BIPV modules, CENELEC, Bruxelles (2016)
14. Scognamiglio A.: Photovoltaic landscapes': design and assessment. a critical review for a new transdisciplinary design vision. Renew. Sustain. Energy Rev. **55**, 629–661 (2016)
15. Standard EN 16883:2017: Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings, Comitè Européen de Normalization (CEN): Bruxelles (2017)
16. Decreto Legislativo 22 gennaio 2004, n. 42 "Codice dei beni culturali e del paesaggio"
17. Legge Speciale per Venezia del 29 novembre 1984, n.798 "Nuovi interventi per la salvaguardia di venezia"
18. Durante, A., Lucchi, E., Maturi, L.: BIPV in heritage contexts award. An overview of best practices in Italy and Switzerland. In: Proceedings of SBE21 Sustainable Built Heritage, online, 14–16 April 2021, SBE Sustainable Built Environment Conference Series
19. Polo López, C.S., Lucchi, E., Leonardi, E., Durante, A., Schmidt, A., Curtis, R.: Risk-benefit assessment scheme for renewable solar solutions in traditional and historic buildings. Sustainability **13**, 5246 (2021). https://doi.org/10.3390/su13095246

# Leaving or Sheltering? a Simulation-Based Comparison of Flood Evacuation Strategies in Urban Built Environments

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**Abstract** When sudden-onset disasters occur in the urban Built Environment (BE), people must quickly leave the dangerous areas to reach safety. Floods in urban BEs surely represent a critical emergency, especially considering users who cannot evacuate upstairs, such as those placed outdoor. Management strategies focused on the evacuation planning could increase the users' safety in a flexible but effective manner. This study compares two evacuation strategies in typological BEs through a simulation-based methodology based on the evacuation process analysis. The first strategy considers that users leave the BE, thus moving away from the source of danger flood. The second strategy adopts gathering areas positioned where the risk is lower, thus sheltering-in-place for the BE users. These strategies are tested considering fluvial flood conditions in four typological BEs, characterized by different layout in terms of streets and squares positions. The simulation-based methodology represents pedestrian evacuation under the two considered strategies depending on the hydrodynamic conditions of the BEs. Comparisons between evacuation time, flows, path length and the users' risk depending on floodwater conditions (in terms of depth and speed) are provided. Results show that sheltering strategies can increase the users' safety in each typological BEs, and mainly in case of the proximity between the square and the river. For instance, the users' risk is generally reduced up to −70%. These findings suggest that effective interventions should be designed to support the users toward "sheltering" areas, by increasing they awareness on the evacuation plan, and implementing wayfinding signs and raised platforms in the BE.

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## 1 Introduction

Floods represent the most important natural hazard in terms of effects on worldwide communities.[1] In the period 2015–2019, only in Italy[2] more than 170 different locations have been affected by floods, causing more than 60 deaths or missings, and almost 21,000 evacuees and homeless. In this context, urban Built Environments (BEs) represent the riskiest scenarios because of the combination between hazard (e.g. position in flood-prone areas, such as near rivers, effects of climate changes), physical vulnerability (e.g. narrow and complex urban fabric, poor infrastructural measures), and exposure (e.g. urbanization/densification growth, high density of exposed users) [1–4].

Different strategies can be applied to reduce the flood risk [5, 6]. Some of them require permanent or long-term solutions, such as physical constructions (e.g.: dikes, drainage and sewer system) or nature-based measures (e.g.: restoration of rivers to their natural courses) that provide continuous protection against floods up to a given return period. Anyway, the implementation of these structural solutions could be difficult in existing BEs because of economic factors, coordination among stakeholders, high application impact in respect of the BEs features (i.e. in historical scenarios), as well as their effects could be limited especially in case of extreme events [7, 8]. Non-structural solutions relating to evacuation management and planning could be implemented in the BE to support structural measures in a flexible and effective manner, thus allowing people to reach areas where they can wait for rescuers' arrival in safe conditions [6, 9–11]. In particular, considering the outdoor context (where the majority of fatalities occur while people attempt to move in floodwaters), two main strategies can be adopted [11–14]: users can leave the flood-prone/affected BE (in the following, "leaving") far from the flood wave, moving on foot or by motor vehicles, and towards target safe havens, or they can gather inside the BE itself (in the following, "sheltering"), especially when safe gathering areas can be identified in outdoor areas of the BE. "Sheltering" strategies can take advantages of gathering areas in streets and squares, also thanking to structural measures (e.g.: raised platforms, benches and urban furniture). Users will remain here and wait for the floodwater decrease and/or the rescuers' arrival [13].

However, in both "leaving" and "sheltering" strategies, the evacuation process can force people to move through areas that are deeply modified by floodwaters and to interact with dynamic conditions that can drastically change in short times [3, 14]. Users could suffer threats because of critical local floodwater depth $D$ [m] and speed $V$ [m/s] values, by: (1) losing stability (i.e. for adults having a mass per height > 50 kg*m, $DV > 1.2$ m/s$^2$ represents the maximum stability threshold) when physical supports are not achievable (e.g. handrails) [15]; (2) being slowed down, thus also increasing the exposure time in risky conditions [16].

[1] https://iddrr.undrr.org/, last access: 09/03/2021.

[2] http://polaris.irpi.cnr.it/report/last-report/, last access: 09/03/2021.

As pointed out by recent works [17], coupling simulation methodologies should be encouraged to consider how users' behavior is affected by the disaster conditions over time and space. In the flood case, such tools should jointly represent floodwater spreading in the BE and users' movements along streets and squares. Each element at risk could be then considered according to microscale approaches, to evaluate the effectiveness of evacuation plans [11]. The influence of BE layout and features on the flood hazard is widely demonstrated, typological BEs have been investigated to describe hydrodynamic aspects and related BE risk-assessment models have been developed [1, 7, 18–20]. Although many flood pedestrian evacuation simulators have been developed [20], previous works seems to generally overlook the correlation between the effectiveness of different evacuation strategies (i.e. "leaving", "sheltering") and such issues, especially considering the outdoor spaces in the BE, such as streets and squares.

In view of the above, this work aims at comparing the effectiveness of "leaving" versus "sheltering" evacuation strategies by means of a microscale simulation-based methodology focusing on the pedestrian evacuation process analysis. The joint evaluation of floodwater spreading in the BE and users' behaviors in the evacuation is performed by considering the BEs features in terms of urban layout, by coupling two existing simulation tools. Thus, various typological BEs layout configurations are tested, and the effectiveness evaluation is mainly performed considering the main parameters affecting the users' movement in outdoor spaces of the BE (i.e., squares and streets).

## 2 Methodology

The adopted simulation approach adopts a microscopic standpoint based on the representation of real-world behaviors in flood pedestrian evacuation depending on the floodwater spreading in the BE (Sect. 2.1). Simulations are performed in several typological BEs representing compact and complex urban scenarios, typical of city centers, to test the differences between "leaving" and "sheltering" evacuation strategies. A behavioral-based approach, that is assessing the impact of the strategies on the evacuation process, is assumed to analyses the simulation results (Sect. 2.2).

### *2.1 Microscale Simulation Approach*

The microscale approach considers the simulation of floodwater spreading in the BE, by means of the open-source software Delft3D (version 4.03.013; www.oss.deltares.nl/web/delft3d—last access: 20/03/2021). The assumed solving mesh is composed of 1 m × 1 m cells, to ensure a detailed description of floodwater levels in outdoor areas, by means of the floodwater depth $D$ [m] and speed $V$ [m/s] values over the time. A time steps of 60 s is assumed for $D$ and $V$ evaluations. Building blocks are simulated as impermeable areas. Thus, no flood discharge can happen into the building ground floors, increasing the effects of the floodwater spreading in outdoor areas and so the risk for users during the evacuation process. *D* and *V* values are then considered to represent the users' movement along squares and streets. First, the evacuation model assumes that the users' speed *Vi* [m/s] are influenced by the local conditions of *D* and *V* values as shown by Eq. 1 [13], where $g = 9.8\ m/s^2$ is the gravitational acceleration.

$$V_i = 0.5\left(D \cdot V^2/g + D^2/2\right)^{-0.1} \quad (1)$$

The *D* and *V* product *DV* [$m^2/s$] is adopted to describe the safety threshold for users' stability, by considering adults' reference values for extreme hazard [15]. Users could still move if locally $DV \leq 1.20\ m^2/s$ or $D \leq 1.20$ m or $V \leq 3.0$ m/s, otherwise casualties occur. The evacuation model also considers that users try to move near unmovable obstacles, such as building walls and fences, having a distance < 3.0 m, since they can look for a direct support of BE elements and well as the floodwater speed at the street sides is lower [13]. Finally, users are not allowed to move upstream or towards the flood flow, while evacuation paths are organized in the model depending on the considered evacuation strategies and their related position in the BE [11].

These modeling assumptions are included in the input setup for pedestrian evacuation simulation performed through the Oasys MassMotion simulator (version 9.5; www.oasys-software.com/products/pedestrian-simulation/massmotion/, last access: 09/03/2021), which has been chosen because it allows replicating user-user interactions from a microscopic standstandpoint, relying on the Social Force Model approach [21].

### *2.2 BEs and Evacuation Analysis for Strategies Comparisons*

The typological BEs considered in this study are represented in Fig. 1. They are based on a riverine context with an orthogonal scheme for the streets network (Fig. 1a).

Then, a square, with the dimension of a building block, is introduced in different positions depending on the distance from the river (Fig. 1b–d). In the following, the typological BEs are named according to the code in Fig. 1. In each typological BE, all the streets perpendicular to the river have a width of 6.0 m and a slope of 0.6%, while streets parallel to the river have a width of 4.0 m and a slope of 0.3%. Cross-sections, the river position and direction (blue rectangle with the white arrow) and the floodwater discharge direction (red arrow) are shown by Fig. 1.The considered BEs consider regular staggered obstacles (i.e. the building blocks) according to previous works on flows patterns in urban scenarios [20]. They can represent a typical Italian context exposed to significant flood risk (i.e. riverine historical BE), in view of the significant risks for this national context shown in Sect. 1, but they

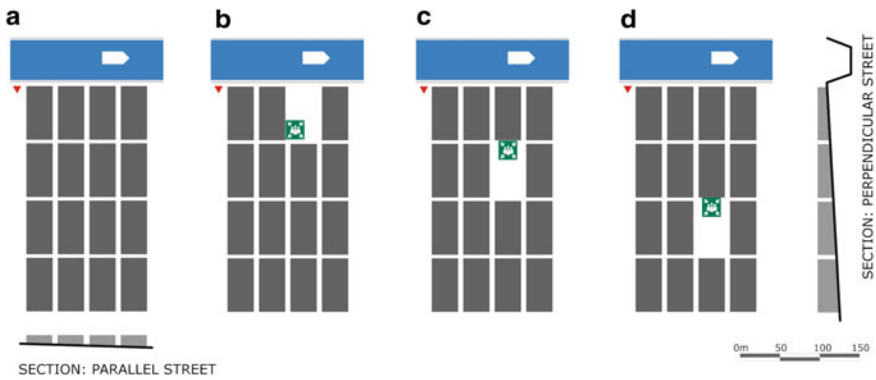


**Fig. 1** Typological BEs for evacuation simulation: the blue area is the river (flow direction by the white arrow), which discharges floodwaters in the BE according to the red arrow. Building blocks are grey rectangles. Gathering areas in the square for sheltering strategies are traced by the related signs. Cross-sections are offered (vertical exaggeration of 10×)

could be also extended to similar BEs of other European contexts [22]. The modelled riverine flood considers a 100yrs maximum flow rate of about 1150 $m^3/s$ [23] and a time of concentration of 6 h, which can be considered as critical for the activation of early warning systems and can increase the necessity to evaluate users' evacuation on foot in the flood-affected BEs. The riverbed has a roughness according to the Manning's coefficient is equal to 0.030 $s/m^{1/3}$, to model natural non-vegetated conditions for a straight river. Streets and squares are modelled to replicate stone paving (0.013 $s/m^{1/3}$). According to a conservative approach, peak flow conditions over the time in the BE are retrieved by the hydrodynamics simulator and then considered to define the $DV$ values in evacuation simulations.

260 users are homogeneously placed outdoor, to represent users who cannot reach a building and vertically evacuate. The users' number is provided by considering low density conditions of passers-by in urban areas (i.e. lower than 0.17 $pp/m^2$) [24]. The simulation time is equal to 20 min, which allows a user to walk across the whole BE using the longest path in critical $DV$ conditions.

The evacuation target choice by the users only depends on the evacuation strategy (the shortest path approach is adopted). In "*leaving*", users move away from the river, since gathering areas are placed in the downstream area of the BE, that is at the end of each perpendicular street (i.e. bottom parts of Fig. 1). Thus, each BE has 3 gathering areas. In "*sheltering"*, according to the hydrodynamic simulations, gathering areas are placed at the middle of each parallel streets, as well as in the areas of the squares where $DV < 0.6 m^2/s$ and so low hazard for the users exist (see the gathering areas signs in Fig. 1) [15]. Building blocks protect gathering areas from the main floodwater flows. Thus, BE B has 12 gathering areas, while the BEs C and D have 11 gathering areas.

The following simulation results are evaluated to compare outcomes from the considered strategies. The percentage of users arrived to a gathering area $P_{safe}$ [%]

is traced depending on [11]: 1) their evacuation time, to show the evacuation curve and to graphically assess the speediness of the process; 2) their path length *PL* [m], to analyses their exposure in the BE and considering the strategy-related position of the gathering areas.

The users' evacuation flow *F* [pp/s] is calculated as the linear regression between the 5th and the 95th percentile of users arrived to a gathering area, thus excluding outliers in terms of initial positions or behaviors [25]. As for the evacuation curve, this value expresses the speediness of the process as a whole. Furthermore, the users flow $F_{50}$ [pp/s] is calculated as the linear regression of the evacuation curves evaluated between the 5th and the 50th percentile of users arrived at a gathering area. It allows to assess if substantial differences in evacuation flows exist between the users who arrived first at the gathering areas and the overall process (described by *K*). The user's floodwater risk-exposure $DV * PL$ [m$^3$/s] is calculated according Eq. 2 and considering the farthest user from a gathering area, to trace a correlation between the user's path and the faced floodwater conditions. In Eq. 2, *p* refers to the part of the evacuation path (a street between two crossroads) of a given length $PL_p$ in which the given $DV_p$ conditions occur. $DV_p$ is averaged on the street length. Finally, differences between the simulation outcomes in the two evacuation strategies are provided in percentage terms, in reference to the "leaving" strategies as the simplest one to be implemented in the BEs.

$$\mathrm{DV} * \mathrm{PL} = \sum_{\mathrm{p}} \mathrm{DV_p} \cdot \mathrm{PL_p} \tag{2}$$

## 3 Results

The results discussion is herein addressed by providing first an overview of the overall differences between the two evacuation strategies, then a specific analysis focusing on each typological BEs. Figure 2 shows the evacuation curve for the two strategies in all the considered typological BEs, while Fig. 3 shows the related cumulative $P_{safe}$ considering the related users' path length *PL*.

As expected, "*Sheltering*" strategies result "faster" than the "*leaving*" ones, thus succeeding in the overall reduction of the exposure time for the whole users' sample, because of the distance to be travelled is shorter, thanks to the widespread distribution of the gathering areas in the BE. For instance, considering typological BEs A, C and D, the median PL (that is for $P_{safe} = 50\%$) decrease from about 150 m in "*leaving*" to about 40 m in "*sheltering*", as shown by Fig. 3. Therefore, the "*sheltering*" strategies can be considered as safer than the "*leaving*" ones because the possibility to use long and risky paths decreases. These results are confirmed by Table 1 outcomes. In fact, evacuation flows *F* are generally higher (at least, double) in "sheltering" than in "leaving", while user's floodwater risk-exposure $DV * PL$ values in "sheltering" are

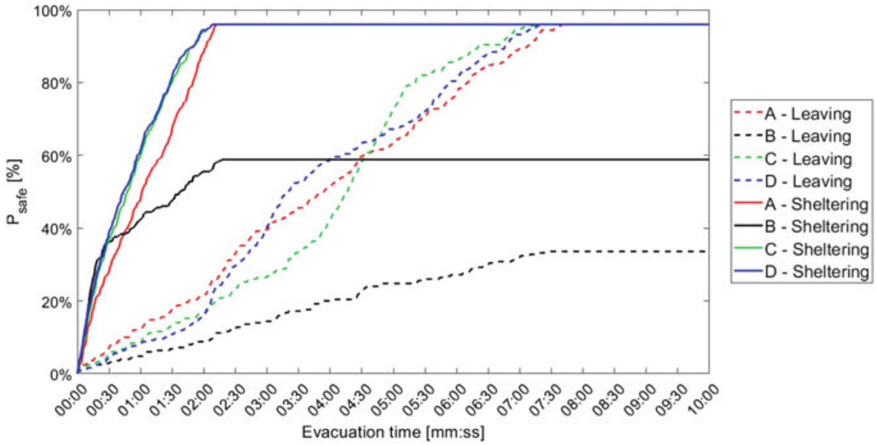


**Fig. 2** Evacuation curves as the percentage of users arrived to a safe area $P_{safe}$ [%] versus the evacuation time. Dashed lines are for the "leaving" strategies, solid lines are for the "sheltering" strategies. The same colors refer to the same typological BE

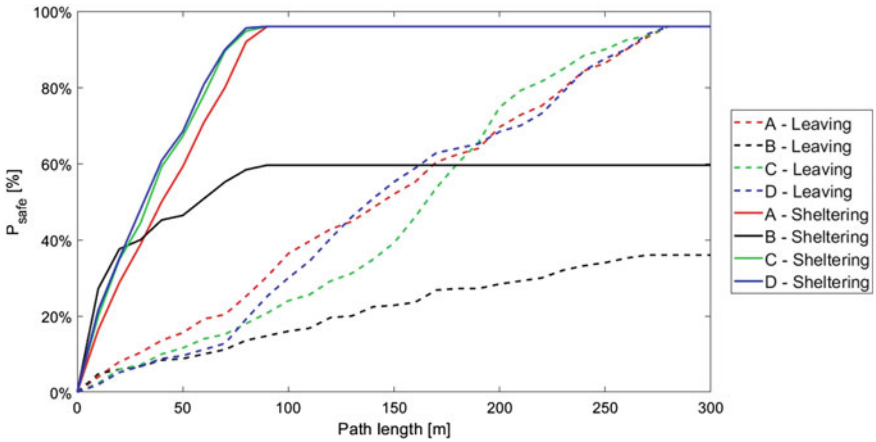


**Fig. 3** Cumulative percentage of users arrived at a safe area $P_{safe}$ [%] versus their path length. Dashed lines are for the "leaving" strategies, solid lines are for the "sheltering" strategies. The same colors refer to the same typological BE

70% lower than those in "leaving" strategies, regardless of the specific typological BEs.

Anyway, the layout features of each typological BE affect both *PL* and evacuation time differences, especially in "*sheltering*", but two groups of conditions of the analyzed BEs can be retrieved. According to the results in Figs. 2 and 3 and Table 1, the typological BEs A, characterized by the compact layout, can be considered as similar to those characterized by the square (C, D) within the BE (see Fig. 1). Here,

**Table 1** Characterization of the evacuation process in the typological BEs considering "leaving" (subscript l) and "sheltering" (subscript s) strategies, in terms of: overall users' flow ($F_l$, $F_s$); users' flow for the 50th percentile of users arrived at a gathering area ($F_{50,l}$, $F_{50,s}$); *DV*PL*. Related percentage variations (Var. columns) are shown

| BEs | $F_l$ [pp/s] | $F_s$ [pp/s] | F Var (%) | $F_{50,l}$ [pp/s] | $F_{50,s}$ [pp/s] | $F_{50}$ Var (%) | DV * PL Var (%) |
|---|---|---|---|---|---|---|---|
| A | 0.53 | 1.82 | + 243 | 0.54 | 1.96 | + 263 | − 72 |
| B | 0.18 | 1.07 | + 494 | 0.20 | 4.71 | + 2255 | − 70 |
| C | 0.57 | 1.98 | + 247 | 0.48 | 2.57 | + 435 | − 73 |
| D | 0.57 | 1.98 | + 247 | 0.66 | 2.84 | + 330 | − 72 |

5% of the users cannot arrive to a safe area because they are placed in the street adjacent to the river, where *DV* rapidly causes body instability [15]. All the other users take advantage of the protection by the built-up areas near the river from direct floodwater spreading within the BE. The comparison between $F$ and $F_{50}$. Table 1 confirms this outcome, especially in "*leaving*", showing a maximum flows difference of about 15%. These results suggest that all the users face quite similar environmental (i.e. DV) conditions in their path, independently from their arrival time, because of the layout effect on floodwater spreading. Adopting "*sheltering*" allows gaining a similar improvement in respect to "*leaving*", as shown by the $F$ percentage variation (about + 250%). Anyway, the "*sheltering*" effectiveness seems to be higher in C, because the square is closer to the river than in D. In C, the gathering area position can more sensibly improve $F_{50}$ values.

The typological BE B is characterized by the risk conditions for some of the people placed in the square and along the outcoming downstream streets. In "*leaving*", these users and the users placed in the street adjacent to the river are significantly affected by body stability loss phenomena causing casualties. "*Sheltering*" can increase the safety of these people. $P_{safe}$ in "*sheltering*" is about − 50% that the value in "*leaving*" because people initially located near the square can reach the adjacent gathering area (see Fig. 1a), which is also protected from the main floodwater stream by the building layout (compare to Sect. 2.2). Anyway, the users initially placed along the street perpendicular to the river on the right-side of the BE still experience instability conditions because of the BE layout effects on floodwater spreading and critical *DV* values. Finally, users who reach a safe area are slowed down by *D* and *V* conditions, as also shown by $F$ and $F_{50}$ values in Table 1 and evacuation curves in Fig. 2. As expected, these effects are more critical in "*leaving*" because of the path length, while "*sheltering*" can significantly increase users' safety, as shown by *DV *PL* variation in Table 1.

## 4 Discussion

Differences between "*leaving*" and "*sheltering*" essentially rely on operational and scenario analysis-related issues.

From an operational standpoint, "*leaving*" can be considered are simpler than "*sheltering*". A low number of gathering areas can be defined to boost the rescuers' actions towards damaged population, and the same evacuation plan could be ideally shared with a large number of users in wide urban areas [11]. From the users' point of view, "*leaving*" can be easier to direct large crowd towards the same target, thus also rely on positive effects of group phenomena in evacuation target selection [13].

From a scenario analysis-related standpoint, either the strategies should consider the microscale hydrodynamic analysis to define safe evacuation paths and gathering areas. Anyway, "*sheltering*" seem to imply a higher level of knowledge of the BE features affecting the floodwater spreading since the conditions of each widespread gathering area should be analyzed in a deep way, according to a simulation-based standpoint [20]. Gathering areas, widespread into the BE, should be placed where limited man-floodwater interactions occur and should consider the effects of their optimal positioning in the BE depending on the users' evacuation safety [13, 15]. In this sense, when *DV* values does not allow to place the gathering area where it is needed, structural solutions such as raised platforms, architecturally-integrated modifications of the BE ground shape and urban furniture should be implemented to physically separate the users from the floodwater and let them wait for the rescuers' arrival. Beside the architectural integration of gathering areas, "sheltering" needs tailored actions to support the users' awareness on the evacuation plan. In addition to communication strategies, wayfinding support could be [6]: (1) physically implemented by means of signs in the urban spaces, to make people aware of BE risk levels and safe areas position also in pre-disaster conditions; (2) provided by means of individual support on portable devices.

Considering the tested typological riverine BEs and hydrodynamic conditions, BEs with a compact layout (A) or with a square not close to the river (C, D) could be take advantage of "leaving" strategy. The same users' number can reach a safe area, even if in a slower manner than "sheltering". On the contrary, "*sheltering*" in BEs characterized by a square close to the river (B) take advantages of multiple safe havens, by increasing the users' number reaching a safe area in safer conditions, thanking shorter distances with respect to exposure values, i.e. *DV*.

## 5 Conclusions

When a flood occurs in an urban Built Environment (BE), users could be forced to evacuate from dangerous areas because primary structural measures failures. Safety issues are widely relevant for BE users placed outdoor, and who cannot move inside a building and vertically evacuate. These people can be forced to change their behaviors and motion features while coping with a BE scenario deeply modified by floodwaters.

This work compares two possible evacuation strategies by mean of a coupled simulation-based method basing on a microscopic representation of the flood evacuation. "*Leaving*" the BE is compared to "*sheltering*", considering river flood occurring in 4 typological BEs: the first has compact layout; the others are characterized by the presence of a square. Findings offer solutions on how to plan gathering areas and safety-paths for users, and show the capabilities of "*sheltering*" in the analyzed contexts. In particular, considering the speediness of the evacuation process and the possibility that people can reach a safe area, the effectiveness of "*sheltering*" seems to mainly increase with the proximity of the square to the river. Anyway, future works should extend the comparison of the evacuation strategies to other typological BEs, as well as to other flood types, to trace common guidelines on how to promote safer evacuation plans.

The role of structural measures to help the users during the evacuation should be investigated, by merging evacuation strategies with support solutions for users' stability in floods (e.g. handrails) and different wayfinding solutions (e.g. signs, personal devices). Furthermore, the architectural implementation of raised platforms for "sheltering" purposes should be also investigated. To this end, future efforts surely should aim at testing those measures in real-world case-studies, by also involving local authorities and public safety stakeholders to promote safety guidelines on evacuation plan.

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## References

1. Paquier, A., Mignot, E., Bazin, P.-H.: From Hydraulic modelling to urban flood risk. Procedia Eng. **115**, 37–44 (2015)
2. Kontokosta, C.E., Malik, A.: The Resilience to Emergencies and disasters index: applying big data to benchmark and validate neighborhood resilience capacity. Sustain. Urban Areas **36**, 272–285 (2018)
3. Chen, L.: A conceptual time-varying flood resilience index for urban areas: Munich City. Water **11**, 830 (2019)
4. Sörensen, J., Persson, A., Sternudd, C., Aspegren, H., Nilsson, J., Nordström, J., Jönsson, K., Mottaghi, M., Becker, P., Pilesjö, P., Larsson, R., Berndtsson, R., Mobini, S.: Re-thinking urban flood management—time for a regime shift. Water **8**, 332 (2016)
5. Bischiniotis, K., de Moel, H., van den Homberg, M., Couasnon, A., Aerts, J., Guimarães Nobre, G., Zsoter, E., van den Hurk, B.: A framework for comparing permanent and forecast-based flood risk-reduction strategies. Sci. Total Environ. **720**, 137572 (2020)
6. Yamashita, S., Watanabe, R., Shimatani, Y.: Smart adaptation activities and measures against urban flood disasters. Sustain. Urban Areas **27**, 175–184 (2016)

7. Rezende, O.M., Guimarães, L.F., Miranda, F.M., Haddad, A.N., Miguez, M.G.: A time-integrated index for flood risk to resistance capacity. Water **11**, 1321 (2019)
8. Plate, E.J.: Flood risk and flood management. J. Hydrol. (2002)
9. Arrighi, C., Pregnolato, M., Dawson, R.J., Castelli, F.: Preparedness against mobility disruption by floods. Sci. Total Environ. **654**, 1010–1022 (2019)
10. Kolen, B., van Gelder, P.H.A.J.M.: Risk-based decision-making for evacuation in case of imminent threat of flooding. Water **10**, 1429 (2018)
11. Lumbroso, D., Davison, M.: Use of an agent-based model and Monte Carlo analysis to estimate the effectiveness of emergency management interventions to reduce loss of life during extreme floods. J. Flood Risk Manage. **11**, S419–S433 (2018)
12. Bernardini, G., Camilli, S., Quagliarini, E., D'Orazio, M.: Flooding risk in existing urban environment: from human behavioral patterns to a microscopic simulation model. Energy Procedia. **134**, 131–140 (2017)
13. Bernardini, G., Postacchini, M., Quagliarini, E., Brocchini, M., Cianca, C., D'Orazio, M.: A preliminary combined simulation tool for the risk assessment of pedestrians' flood-induced evacuation. Environ. Model. Softw. **96**, 14–29 (2017)
14. Opper, S., Cinque, P., Davies, B.: Timeline modelling of flood evacuation operations. Procedia Eng. **3**, 175–187 (2010)
15. Cox, R.J., Shand, T.D.Blacka, M.J.: Australian Rainfall & runoff revision project 10: Appropriate safety criteria for people (2010)
16. Bernardini, G., Quagliarini, E., D'Orazio, M., Brocchini, M.: Towards the simulation of flood evacuation in urban scenarios: experiments to estimate human motion speed in floodwaters. Safety Scie. **123**, 104563 (2020)
17. Lovreglio, R., Ronchi, E., Maragkos, G., Beji, T., Merci, B.: A dynamic approach for the impact of a toxic gas dispersion hazard considering human behaviour and dispersion modelling. J. Hazard. Mater. **318**, 758–771 (2016)
18. Miranda, F.N., Ferreira, T.M.: A simplified approach for flood vulnerability assessment of historic sites. Nat. Hazards (2019)
19. Velickovic, M., Zech, Y., Soares-Frazão, S.: Steady-flow experiments in urban areas and anisotropic porosity model. J. Hydraul. Res. **55**, 85–100 (2017)
20. Mignot, E., Li, X., Dewals, B.: Experimental modelling of urban flooding: a review. J. Hydrol. **568**, 334–342 (2019)
21. Jin, B., Wang, J., Wang, Y., Gu, Y., Wang, Z.: Temporal and spatial distribution of pedestrians in subway evacuation under node failure by multi-hazards. Safety Sci. **127**, 104695 (2020)
22. European Commission: European Overview Assessment of Member States ' reports on Preliminary Flood Risk Assessment and Identification of Areas of Potentially Significant Flood Risk (2015)
23. Giandotti, M.: Previsione delle piene e delle magre dei corsi d'acqua (in Italian—Forecast of floods and low levels of watercourses). Istituto Poligrafico dello Stato **8**, 107–117 (1934)
24. Bloomberg, M., Burden, A.: New York City Pedestrian Level of Service Study-Phase 1. NY, USA, New York (2006)
25. D'Orazio, M., Longhi, S., Olivetti, P., Bernardini, G.: Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire. Autom. Constr. **52**, 16–28 (2015)

# Numerical Assessment of the Impact of Roof Albedo and Thermal Resistance on Urban Overheating: A Case Study in Southern Italy

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**Abstract** Urban heat island (UHI) and global warming effects increase the urban ambient temperature. During recent years, heat mitigation strategies have been implemented through experiments and simulations due to the significant impacts of these phenomena, especially on near-surface air temperature. UHI mitigation may help cities adapt to the future effects of increasing local air temperature, which are crucial especially in tropical cities. The impact of increasing roof albedo as a UHI mitigation strategy coupled to roof renovation with different performance levels was evaluated in the center of Palermo (Italy) as a case study. To this aim, ENVI-met (version 4.4.5) was used. In addition, three different thermal transmittance scenarios and four albedo scenarios (from 0.1 to 0.9) related to roofs were compared to simulate the efficiency of the roofs at the peak hour on the hottest day of a typical summer heatwave in terms of reduction in air temperature. Based on the results, changing the albedo of the roofs in the selected area led to a decrease in air temperature. The most obvious temperature drops of 0.37 °C were recorded in the scenario where the non-insulated roof was applied, while it was around 0.20 °C in other scenarios. Finally, changing roof albedo can have a limited impact on UHI if coupled with high roof thermal resistance.

## 1 Introduction

Climate changes and urban development extremely intensify the Urban Heat Island (UHI) effect [1]. UHI is a phenomenon in which the air temperatures in urbanized areas are elevated related to the surrounding rural areas. The UHI intensity can become 3.5–4.5 °C higher in urban districts compared to surrounding areas and it is assumed to increase by approximately 1 °C per decade [2]. The higher temperature results in locally acute adverse human health, economic, and environmental

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impacts [3]. Cool materials can be used on buildings (walls and roofs) and pavements which include over 60% of the urban surfaces which are considered as common UHI mitigation strategies [4]. Moreover, using high solar reflectance and high thermal emittance materials reduces near-surface air temperature under the sun [5]. In addition, it decreases the heat flow from the roof into the buildings during summer leading to a reduction in energy demand [6]. Since 20–25% of urban surfaces are applied as roof surfaces [7], the present study focused on assessing the urban temperature by using different solar reflectance values for the roof coverings combined with the U-value levels of different roofs by numerical simulations using the ENVI-met software [5].

Moreover reducing thermal transmittance (U-value) of a building envelope is needed based on the actual regulations in refurbishment renovating a roof, even with a cool covering. In this study, the air temperature was quantified by changing the albedos and thermal transmittance of roofs in a selected area in Palermo (Italy). In addition, ENVI-met software was used to evaluate the efficiency of the roofs in a typical heatwave in the Mediterranean climate.

## 2 State of the Art

Using cool materials on the building envelope and open spaces reflecting a significant part of solar radiation and dissipating the heat they have absorbed through radiation is considered as one of the effective solutions to reduce UHI [8].

Based on the literature, increasing 10% of the average urban albedo of surfaces including walls, roofs, pavements, and roadway scan help decrease the ambient temperature from 0.1 to 0.3 °C [9]. However, the range of reducing ambient temperature depends on many parameters such as average height of buildings [10], form [11], local climate conditions [1], and urban geometry [6]. The results indicated that the effectiveness of using high albedo materials is lower than that of vegetation, which is especially related to the shade provided by trees [12]. During the recent decades, numerical simulations by means of ENVI-met software have been conducted to find the relationship between urban fabric and local climate parameters.

ENVI-met is a prognostic model based on fluid dynamics and thermodynamics laws, which is widely used as an instrument to analyze microclimate and compare the performance of different mitigation strategies [13]. Cool roofs and their considerable impact on lowering surface temperatures which decrease the heat gains through the heat transfer, especially with a high U-value (less insulation level), can play a significant role in reducing cooling energy demand [6]. Further, by considering well-insulated layer (low U-value) the heat transfer between roof surfaces and interior of the building is very small [4]. Hence, roofs with an insulation layer and highly reflective envelope can store heat longer and slow heat dissipation rate in indoor buildings [14]. However, there is a growing need for numerical simulation to understand the correlation between the optical properties and insulation level (U-value) of roof coatings and analyze the impact of both insulation and cool roofs on UHI

**Table 1** Main results and input data of papers analyzing the impact of cool roofs on outdoor air temperature at the pedestrian level

| Reference | City | Köppen classification | Roof albedo | Max Ta (°C) | Mean Ta change (°C) | Starting time- Total simulation |
|---|---|---|---|---|---|---|
| [10] | Toronto, Canada | Dfb | 0.3 to 0.7 | 0.5 | 0.17 (area) | 9:00 p.m 24 (h) |
| [15] | Los Angeles, USA | Csb | 0.1 to 0.4 | 0.5 | 0.3 (area) | 4:00 a.m 24 (h) |
| [16] | Avola, Italy | Csa | 0.3 to 0.83 | 1.5 | 1 (area) | 6:00 a.m 24 (h) |
| [6] | Tehran, Iran | BSk | 0.3 to 0.6 | Not mentioned | 0.36 (area) | 4:00 a.m 17 (h) |
| [17] | Nagpur, India | Aw | 0.3 to 0.8 | Negligible | Negligible | 6:00 a.m 24 (h) |
| [18] | Montreal, Canada | Dfb | 0.1 to 0.7 | 0.5 | 0.2 (diurnal) | 4:00 a.m 24 (h) |
| [19] | Rome, Itay | Csa | 0.05 to 0.89 | 1.4 | Not mentioned | Not mentioned |
| [20] | Rome, Itay | Csa | 0,35 to 0.66 | 0.1 | Negligible | 6:00 a.m 72 (h) |
| [12] | Teramo, Italy | Cfa | 0.3 to 0.9 | 0.9 | 0.5 (area) | 6:00 a.m 72 (h) |
| [23] | Ho Chi Minh, Vietnam | Aw | 0.1 to 0.7 | 0.1 | 0.1(area) | 10:00 a.m 36 (h) |
| [11] | Cuiabá, Brazil | Aw | 0.15 to 0.85 | 3.0 | 0.46(area) | 8:00 p.m 48 (h) |
| [24] | Vienna, Austria | Cfb | 0.3 to 0.8 | 0.5 | 0.3(area) | 4:00 a.m 24 (h) |

and cooling energy demand by increasing urbanization. Table 1 indicates the most important conducted studies on cool roofs by ENVI-met.

# 3 Materials and Method

## *3.1 Study Area*

The case study is located in the historical center of Palermo, Italy (38.113° N, 13.361° E), which was selected for its dense urban morphology (Fig. 1a). Indeed, the simulated zone is one of the most densely urban areas of Palermo. The study area

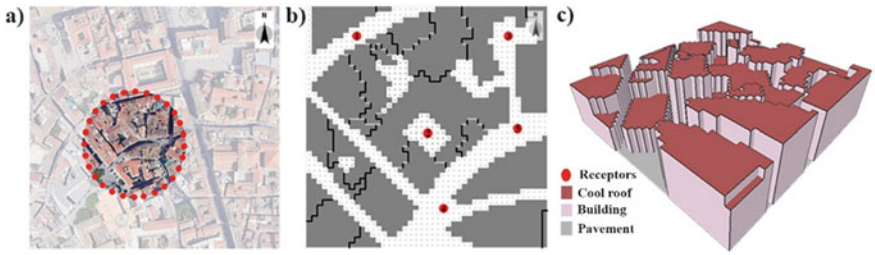


**Fig. 1** **a** Maps (Google Earth 01/2021), **b** plan of the model area in ENVI-met among with receptors location, and **c** 3D perspective of the study area

is composed by wide concrete structures used for the sidewalks. Also, this place has narrow streets with high buildings located in the historical part of Palermo where represents other historical cities in Italy. According to Köppen–Geiger classification, the climate of Palermo stands in (Csa) Hot-Summer Mediterranean climate [15]. The average building height of the model is 9.95 m, and the highest building in the urban context is 15 m.

## 3.2 Modeling Approach in ENVI-Met

The study area was built into a grid of 45 (x) × 45 (y) × 30 (z) m cells and 3 nesting grids to each side with an equidistant horizontal resolution of 1 m. The vertical grid cells have the same height among all implemented scenarios as a standard ENVI-met model (2 m). In addition, it was divided into five sub-grid cells which are considered as 0.40 m. Further, a telescopic grid was not employed.

Accordingly, the construction of buildings, surface cover, and height of buildings for the neighborhood were estimated manually based on Google Earth imagery and used as input data to ENVI-met. Five receptors were inserted in the model area by considering the position of building walls and road width which was calculated in three vertical levels (Fig. 1b). Ambient temperature results were provided at the height of 1.8 m above the ground since it is close to the average human height, at 15 m, represented the altitude of the highest building roof in the selected area and 17 m, which is the top of the roofs to understand quantitative connection between increasing roof albedo and outdoor temperature above the roofs.

## 3.3 Urban Environment and Database Configuration

The optical properties of wall and soil of the buildings were kept the same as the ENVI-met default values for the simulations. The walls of the model were considered concrete (hollow block), the roughness length and other adjustments were kept as the default, and concrete gray was complemented as pavement on all models. Vegetation and pollution were not considered in this study.

Table 2 reports the detail of the roof configuration.

Table 3 shows the recorded initial input data for ENVI-met software. Further, the following meteorological parameters were computed for each of the simulations. The optimal time to start a simulation is at night or sunrise [12]. Hence, the simulations started at 11:00 p.m. on 12 August 2013 and ended at 11:00 p.m. on 14 August.

**Table 2** Physical and optical properties of the roof

| Parameter | Value |
|---|---|
| *Material covering features* | |
| Thickness of the covering material (m) | 0.2 |
| Emissivity (ε) | 0.87 |
| Specific heat (J/kg K) | 880 |
| Thermal conductivity (W/m K) | 0.65 |
| *Insulation layer features* | |
| Absorption | 0.6 |
| Emissivity (ε) | 0.9 |
| Specific heat (J/kg K) | 1470 |
| Thermal conductivity (W/m K) | 0.035 |
| *Slab features* | |
| Thickness of the slab (m) | 0.05 |
| Absorption | 0.6 |
| Emissivity (ε) | 0.9 |
| Specific heat (J/kg K) | 1400 |
| Thermal conductivity (W/m K) | 0.12 |

**Table 3** ENVI-met input data for the simulations

| Parameter | Value |
|---|---|
| Start Simulation (HH:MM: SS) | 23:00:00 |
| Total Simulation (H) | 48 |
| Interval simulation (Min) | 60 |
| Wind speed in 10 m height (m/s) | 1.10 |
| Wind direction (deg) | 210 |
| Max and Min outdoor temperature (°C) | 23 / 37 |
| Initial temperature (°C) | 29.05 |
| Indoor temperature (°C) | 26 |
| Relative humidity at 2 m (%) | 55.71 |
| Roughness length at the measurement site (z0) | 0.015 |

Furthermore, the data were analyzed on 14 August 2013, which was the hottest day of a typical summer heatwave in Italy.

### *3.4 Definition of the Scenarios*

Three different scenarios were implemented in Palermo with a high-density morphology in order to determine the most effective configuration for the roofs to mitigate UHI. First, the reference scenario was simulated with a non-insulated layer (roof U-value 2.32 W/m$^2$ K). Then, two other hypothetical scenarios according to different insulation layer including scenario A (roof U-value 0.25 W/m$^2$ K); and scenario B (roof U-value 0.33 W/m$^2$ K). Further, four solar reflectance levels (0.1, 0.4, 0.6, and 0.9) which are presented in each scenario in terms of low, moderate, and high increased albedo, a total of 12 simulations were considered. The values of the scenarios were developed based on the literature and statistical models which are usually found for roofs [16, 17].

Overall, all components including walls, pavements, and roofs albedo (0.1.0.4, 0.6, and 0.9) were kept unaltered for configuring the scenarios. However, no insulation layer in the reference scenario was replaced by 0.12 m in scenario A and 0.09 m in scenario B.

## 4 Results and Discussion

This section discusses the relationship between scenarios and air temperature (Ta). Ta was taken at the height of 1.8, 15, and 17 m. The variation between reference scenario and other scenarios was comparable since they refer to the simulations with the same input data but with different properties of the roofs. Further, after simulating all three scenarios, Leonardo was used to visualize the results. All results were related to the second day of a heatwave simulation during the summer (August 14th, 2013) to resolve initial uniformity and achieve the numerical stability of the model.

Increasing albedo from 0.1 to 0.9 led to a decrease in peak Ta from 37.30 to 36.93 °C at the pedestrian level in ref-scenario. The variation could be mainly related to high albedo of the roof which reflects a considerable amount of solar energy. In the same situation, Ta changed from 37.30 to 37.10 °C in scenario A, and from 37.30 to 37.10 in scenario B. The lack of any substantial change related to scenarios A and B can be attributed to the urban context whit compact midrise in this study. Further, as shown by other studies [18, 19], the performance of cool roofs is more effective in open low-rise and compact low-rise buildings at the human height level [18]. Comparing the three simulated scenarios at the human level indicated that the highest Ta (37.30 °C) was recorded in the ref-scenario (higher U-value). In addition, the difference in air temperature between the ref-scenario and both scenarios (A and B) for the whole area was 0.17 °C (Fig. 2).

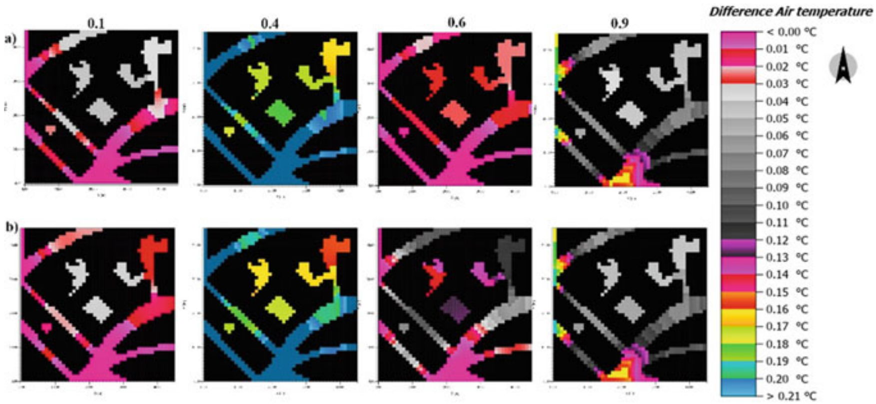


**Fig. 2** Images of air temperature differences between ref-scenario and **a** scenario A and **b** scenario B, with different albedo levels at the pedestrian level at 16:00 on 14 August 2013

Regarding the results at 15 m above the ground, increasing albedo by 0.8 in ref-scenario resulted in falling air temperature from 35.77 to 35.53 °C and Ta changes in scenarios A and B had similar results which altered from 35.76 to 36.6 °C, which may be related to the low differences in U-value. On the other hand, different Ta values between the ref-scenario and these two scenarios were negligible at 15 m above the ground. Further, Ta changes were observed among three scenarios at the hottest hour at 17 m above the ground which by replacing albedo from 0.1 to 0.9, the differences between Ta were 0.5, 0.28, and 0.26 °C in ref-scenario, scenario A, and B, respectively.

Figure 3 displays the air temperature at three height levels above the ground at peak hour in five receptors. At the pedestrian level, the highest temperature values

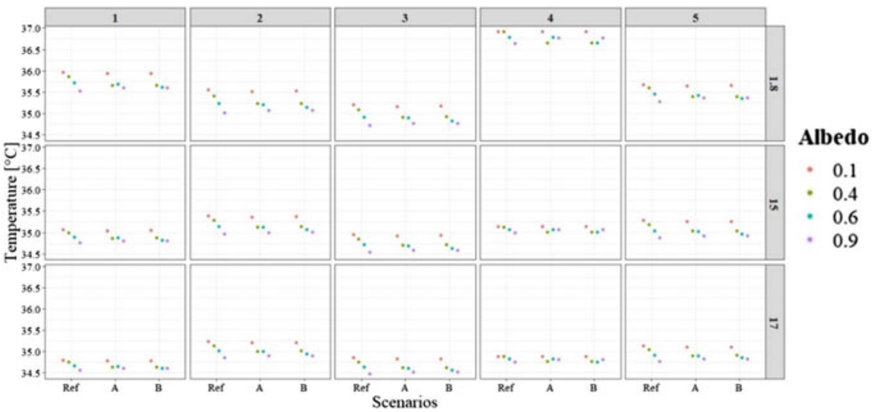


**Fig. 3** A comparison of simulated outdoor air temperature in five receptors at the peak hour (16:00) on 14 August 2013 for three scenarios at three heights (1.8, 15, 17 m)

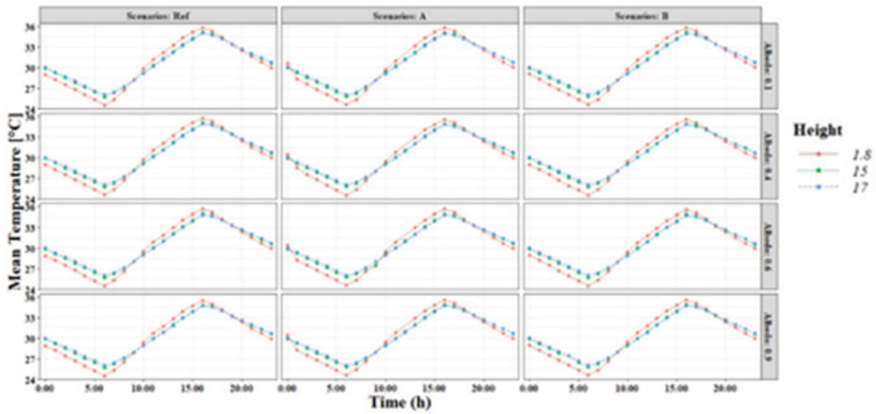


**Fig. 4** Outdoor daily mean temperature trends of receptor data in the scenarios at **a** 1.8 m, **b** 15 m, and **c** above the ground on 14 August 2013

were recorded in receptor four in the south of the selected urban site. Also, the result could be affected by solar radiation conditions. Moreover, the lowest temperature at the human level was recorded in the receptor three and then receptor two, which may be related to a reduction in solar radiation. These temperatures are due to the comparative blockage of surrounding buildings which provide more shade.

Figure 4 represents the related average daily Ta trend in all receptors of three scenarios on the last simulated day (14 August 2013). During the nighttime, while the roof albedo increased from 0.1 to 0.9, the average Ta decreased from 26.8 to 26.73 °C in the ref-scenario. Regarding scenario A, in the same situation, Ta decreased from 26.84 to 26.77 °C and from 26.83 to 26.77 °C in scenario B during the night period. Meanwhile, increasing albedo of roofs was attributed to a decrease in the average Ta from 27.83 to 27.79 °C in ref-scenario at 15 levels, also a reduction in the average Ta from 27.87 to 27.82 °C in scenario A and from 27.86 to 27.82 °C in scenario B at this level. Since the temperature of building components (walls and roofs) by sunset decreases rapidly, thermal storage in urban structures was released into the air at night leading to higher temperatures near the roofs than at the pedestrian level. Meanwhile, nocturnal trends in 17 m indicated no considerable difference between the air temperature recorded at 15 m.

## 5 Conclusion

A series of simulations were conducted to evaluate the impact on urban air temperature related to possible roof retrofit interventions, including an increase in the albedo of the covering and of the whole thermal resistance. To this aim, 12 design scenarios obtained by combining 4 albedo levels and 3 U-value levels were assessed in the

Italian city of Palermo by ENVI-met software. In general, it was shown that a difference in urban air temperature exists when roofs are insulated or not: a mean difference of 0.17 °C was found between the ref-scenario and the renovation scenarios in the whole area. Indeed, if the thermal transmittance of a building envelope is very low, a "thermal decoupling" occurs between the building indoor and outdoor thermal conditions, enhancing the surface temperatures of the building components and slightly rising the surrounding outdoor air.

Simulation results also showed that increasing the albedo of the roofs from 0.1 to 0.9 in the selected urban area can reduce the ambient temperature, especially when no insulation is applied to the roofs. This decrease is higher at 17 m above the ground (0.5 °C), while more limited at the pedestrian level (0.37 °C). This is mainly attributable to the compact midrise urban context analysed in this study.

Changing the albedo from 0.1 to 0.9 in the highly insulated roof scenarios causes a more limited reduction of the air temperature: 0.26 °C at 17 m height and 0.20 °C at the pedestrian level.

These results, consistently with those available in the previous literature [20], confirm that the urban temperature is influenced by the buildings' components transmittance and that the performance of cool roofs is affected by the whole roof thermal transmittance. The adoption of reflective materials in the roofs can be effective in attenuating the higher temperatures reached by the insulated building components, however this topic needs to be further investigated, including several climates and urban contexts, in order to find the best compromise and solutions in terms of building energy performance, urban climate, environmental impacts and users' costs.

## References


1. Battista, G., Evangelisti, L., Guattari, C., Vollaro, E.D.L., Vollaro, R.D.L., Asdrubali, F.: Urban heat island mitigation strategies: experimental and numerical analysis of a university campus in Rome (Italy). Sustain. (Switzerland) **12**(19), 1–18 (2020)
2. Voogt, J.A.: Urban heat island: Causes and consecuences of global environmental change (2002)
3. Corburn, J.: Cities, climate change and urban heat island mitigation: localising global environmental science. Urban Stud. **46**(2), 413–427 (2009)
4. Synnefa, M.S., Akbari, H.: Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. Energy Build. **39**(11), 1167–1174 (2007)
5. Li, X.X., Norford, L.K.: Evaluation of cool roof and vegetations in mitigating urban heat island in a tropical city, Singapore. Urban Climate **16**, 59–74 (2016)
6. Maciel, C.D.R., Kolokotroni, M., Paulo, S.: Cool materials in the urban built environment to mitigate heat islands : potential consequences for building ventilation," pp. 13–14 (2017)
7. Zinzi, M., Agnoli, S.: Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. Energy Build. **55**, 66–76 (2012)
8. Akbari, H., et al.: Local climate change and urban heat island mitigation techniques—the state of the art. J. Civ. Eng. Manage. **22**(1), 1–16 (2016)

9. Santamouris, M.: Cooling the cities—a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol. Energy **103**, 682–703 (2014)
10. Giridharan, R., Lau, S., Ganesan, S., Givoni, B.: Urban Design Factors Influencing Heat Island Intensity in High-Rise High-Density Environments of Hong Kong. Elsevier, Amsterdam
11. Wang, Y., Berardi, U., Akbari, H.: Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. Energy Build. **114**, 2–19 (2016)
12. Farhadi, H., Faizi, M., Sanaieian, H.: Mitigating the urban heat island in a residential area in Tehran: investigating the role of vegetation, materials, and orientation of buildings. Sustain. Cities Soc. **46**, 101448 (2019)
13. Ambrosini, D., Galli, G., Mancini, B., Nardi, I., Sfarra, S.: Evaluating mitigation effects of urban heat islands in a historical small center with the ENVI-Met® climate model. Sustainability (Switzerland) **6**(10), 7013–7029 (2014)
14. Yang, J., et al.: Green and cool roofs' urban heat island mitigation potential in tropical climate. Sol. Energy **173**(April), 597–609 (2018)
15. Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F.: World map of the Köppen-Geiger climate classification updated. Meteorol. Z. **15**(3), 259–263 (2006)
16. Taleghani, M., Sailor, D., Ban-Weiss, G.A.: Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood. Environ. Res. Lett. **11**(2) (2016)
17. Gartland, L.: Heat Islands: Understanding and Mitigating Heat in Urban Areas (2012)
18. Chatterjee, S., et al.: Simulating micro-scale thermal interactions in different building environments for mitigating urban heat islands. Sci. Total Environ. **663**, 610–631 (2019)
19. Middel, A., Selover, N., Hagen, B., Chhetri, N.: Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. Int. J. Biometeorol. **60**(12), 1849–1861 (2016)
20. Di Giuseppe, E., Pergolini, M., Stazi, F.: Numerical assessment of the impact of roof reflectivity and building envelope thermal transmittance on the UHI effect. Energy Procedia **134**(2016), 404–413 (2017)
21. Levinson, R., Akbari, H., Konopacki, S., Bretz, S.: Inclusion of cool roofs in nonresidential title 24 prescriptive requirements. Energy Policy **33**(2), 151–170 (2005)
22. Synnefa, A., Saliari, M., Santamouris, M.: Experimental and numerical assessment of the impact of increased roof reflectance on a school building in Athens. Energy Build. **55**, 7–15 (2012)

# The Value of the Colour Temperature in a Low Light Intensity Design

**Eduardo Espinoza Cateriano, Judit Lopez-Besora, Carlos Alonso-Montolio, Helena Coch Roura, and Isabel Crespo Cabillo**

**Abstract** The study focused on low light intensity spaces. The research helps to find strategies for the reduction of energy consumption. It aims to highlight the role of colour temperature in the lighting design of historic buildings. The case study corresponds to a Roman archaeological site of the Badalona Museum in Barcelona. The lighting design uses three different colour temperatures to differentiate groups of surfaces which play a different role in the visual field. The information panels are lit with white light, the old Roman city has warm white colour light, and the new walkway over the ruins is lit with cool white light. This study evaluates colour temperature value, luminance value and visual task. The present work reveals that the colour temperature allows setting apart and classifying the visual information from low luminance values. The research presented addresses the importance of the colour temperature, as a significant visual perception component, in the inherent low light intensity design proposal to energy conservation.

## 1 Introduction

### *1.1 Research Background*

In spaces with low light intensity design, the colour temperature of the light source can become a tool that helps the observer interpreting information in the visual field. In low light scenes, this is more evident because of the narrow difference between luminance values of surfaces. The use of different colour temperature of light sources is a valuable resource in lighting design as it provides us with visual information.

In 1941, Kruithof [1] published a study of the relationship between illuminance and colour temperature. In that study, he developed a graphic that shows that the

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amount of light needed to enter the comfort zone is inversely proportional to the colour temperature that the light source must-have. In this regard, Lam and Lou [2, 3] tell us that the mind responds negatively to the inconsistent use of different light sources without apparent justification; however, there is a positive response if it helps to differentiate elements in the visual field since it serves to add visual information [4]. When different colour temperatures of light sources are employed in the lighting design, the effect is not disturbing if they are used to illuminate different types of objects and surfaces.

New studies have been carried out to highlight the use of the light source´s spectrum on energy savings. On the one hand, McCluney, Serra and Coch [5, 6] reminds us that the wavelengths emitted by light sources are absorbed, reflected and transmitted by objects. Therefore, a large amount of light in architectural spaces is absorbed and never perceived by users. Thus, Durmus and Davis [7] concluded that 44% of energy consumption can be reduced if the spectrum of the light source is optimized, without altering the colour appearance of the objects. On the other hand, Cuttle [8] warns that light causes photochemical damage, mainly determined by the radiation power, the duration of the exposure and the light source´s spectrum. Subsequently, Abdalla et al. [9] focused on reducing photochemical damage in artwork, suggesting that the filtration of the light spectrum can minimize the energy absorbed by objects by up to 80%, depending on the object´s colour. In museums, lighting allows the visual perception of the exhibited objects, but it also damages the illuminated surfaces. Current regulations recommend not exceeding the illuminance value and reducing the lighting time according to the sensitivity characteristics of the objects. This regulation establishes that objects with high sensitivity must be illuminated with a maximum of 50 lx. Low levels of illumination are usually combined with a low colour temperature. However, recent studies on LED lighting, such as the work of Viénot et al., indicate that the low colour temperature would not be limited to low lighting situations to enhance pleasant sensations.

This document presents a study on the relationship between luminance and colour temperature as a lighting design tool to distinguish between sets of surfaces with different information in the visual field. An exposition area in the Badalona Museum was chosen as a case of study, since the colour temperatures' choice of the lighting design in this museum seems to correspond to the purpose of differentiating the visitors' activities. The research proposes strategies to be considered by in the lighting design of museums or spaces, in general, with low light intensity.

## *1.2 Objective*

The aim is to contribute to energy-saving solutions in the field of electric lighting design [11]. The choice of the colour temperature of light sources and light level depending on the visual activity is key to minimize energy consumption. Colour temperature can be a lighting design tool when luminance values are low, allowing the user to differentiate between surface groups based on activities related to vision.

The objective is to find the best strategies that facilitate the visual task through the balance of light level and colour temperature. The application of the appropriate lighting design could be used, on a local scale, to accommodate both heritage and energy conservation.

## 2 Methodology

For this study, we focus on the correlation between the luminance value, the colour temperature value and the visual task. Therefore, we divided the methodology into three steps:

- Observation: Tour and identification of activities related to vision.
- Measurement: Illuminance, luminance and colour temperature.
- Analysis of results: Relationship between luminance, colour temperature and visual task.

Firstly, the activities related to vision must be identified in the building, for example: walking through the space, looking at the surroundings, reading the information and so on [12].

Secondly, the lighting, coming from several lamps used to illuminate different surfaces, must be measured with a lux meter and luminance meter. Every lamp, with different colour temperature, must be measured with a spectrometer. Furthermore, each activity illuminated with different colour temperature lamps is identified. The comparison analysis serves to group surfaces illuminated with different colour temperature.

Thirdly, several photo sessions to be analysed with lighting software [13] must be taken. In the case of study, a Nikon Digital Reflex Camera with a fisheye lens was used in order to approach the human visual field. The camera with the SIGMA 4.5 mm lens was placed on the tripod at the height of 1.50 m. After that, the camera was programmed to take RAW + JPG shots. Then, three photographs were taken with different exposure times. Each photo from the same series has two steps difference between the extremes and the central. Three pictures with different exposure are enough to obtain digital pictures in High Dynamic Range (HDR) to be analysed [14]. For each photo, a grey sheet was placed next to each information board where luminance and illuminance measurements were taken. The luminance meter and the lux meter were used to get the information in a reference point for calibration in the subsequent analysis of the lighting software. All HDR photos were subject to Aftab Alpha software to reveal the luminance values in a false colour image [15]. The luminance value scale allows us to evaluate the surfaces illuminated with different colour temperature.

Finally, using the luminance value scale and the colour temperature measures, we can study how do both respond to the different purposes of the lighting design.

## 3 Descriptive Study

The case study is located in Badalona city, near Barcelona. The Museum of Badalona covers 3400 $m^2$ of archaeological remains of the Roman city, Baetulo, placed in the basement of a new building. The new building, designed by the architect Camil Pallàs i Arisa, head of the Monuments Conservation Service of the Barcelona Provincial Council, was inaugurated on January 30th, 1966. In the mid-seventies, a process began towards the realization of more strictly museum activities. In 2010 the lighting design project was conceived as an immersion inside the old Roman city. The lighting design was in charge of the architect Jordi Moya and the museographer Joan Mayné [16].

The entry to the archaeological centre has access from the natural lit lobby of the new building. When descending the stairs to the basement floor, the light level drops drastically. The circulation starts across a metal bridge whose surface is illuminated with a cool white light that will guide us through and over the archaeological site. The old Roman city is mostly made up of earth colour brick illuminated by warm white light. The information panels are made of a transparent acrylic board lit by white light inside the structure located over the railing. The new building over the ruins is made up of columns, perimeter walls, and a ceiling, all painted in black.

Three consecutive routes that correspond to the museum design were identified. One hundred points of measurements were defined along the three routes. Thirty-one measurement points were defined on route A, twenty-nine points on route B and forty points on route C. (see Fig. 1). The first and the third route were designed to cross over the ruins. In such a way, the showcases and exhibitors with interior lighting in the second route were discarded from this study because of the high light intensity design. Four measurement points were chosen for this paper.

The museum has electric lighting, avoiding natural light from an overhead opening on route C. All photographs were taken on three consecutive days, from November 19th to 21st of 2020, from 10 to 14 am. Due to the distance of high-level windows from the work plane, artificial light plays a central role in the scenes studied. The lamp model used to illuminate the Roman city is 5 W (50 W) GU10 Warm white Dimmable Spot, LED Philips, placed about 50 cm height over the floor. As users walk over the metal bridge, the lighting intention focuses on keeping the user above the ruins. The walkway bridge is illuminated with a Fortimo LEDFlex 2500 lm/m 9xx G1 lamp placed under the railing. The railing also serves to conduct the light cables to each information panel. The panel is lit by a Fortimo LEDFlex 5 m 2000 lm/m 865 C10 G1 lamp hidden into a metal profile that serves to hold the acrylic board.

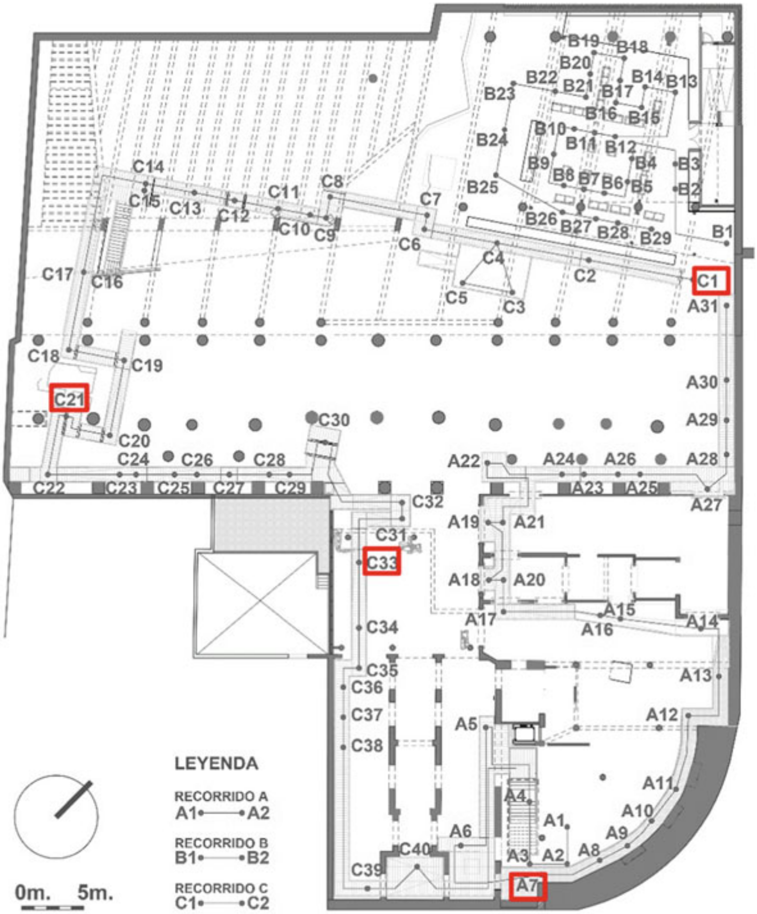


**Fig. 1** Basement floor plan of Badalona Museum

## 3.1 *Experimental Procedure*

In the case study, the experimental procedure was divided into three steps: Observation, measurements and analysis of results.

Observation allows to distinguish four groups of surfaces: The corridors of the visitor's route, the exhibited objects (remains of buildings, mosaics, walkways, showcases, various exhibitors, etc.), explanatory texts and drawings written in information boards, and the museum's container building. In many situations, the visitor sees a scene where elements belonging to more than one of these sets of surfaces with very similar luminance values, even coincident, overlap. This effect makes it difficult to interpret the exposure as it can confuse the scene. However, the lighting design assigns a light source with a different colour temperature for each activity.

The measurements of illuminance, luminance and colour temperature were taken on the four groups illuminated with different lighting intentions. The analysis of results has been done in one hundred series of photos. For this paper, four series of photos were selected to be analysed because of the repeated patterns of luminance found in the museum and the effect of the colour temperature to differentiate surfaces with different visual information. The first photograph shows one of the places where the route invites you to contemplate the Roman city. The second photograph shows us how the path passes over the ruins, clearly differentiated by the light's colour despite having a lower light intensity. The third photograph shows the panel board in front and the Roman city behind. Finally, the fourth photograph illustrates the whole circuit, where the old Roman architecture is warm light illuminated and the modern building that supports the upper levels of the museum is hidden.

## 4 Results

The results in Fig. 2, 3, 4 and 5 correspond to the low light intensity study. On the left side, it can be seen the HDR photo taken with a fisheye lens that shows all surfaces that can be perceived into the visual field. Each HDR photo also shows the colour of surfaces illuminated with different colour temperature. On the right side, the image shows the luminance values in a false colour scale, the mean luminance value, the minimum luminance value and maximum luminance value. The false colour images also show the upper and lower limit of the scale.

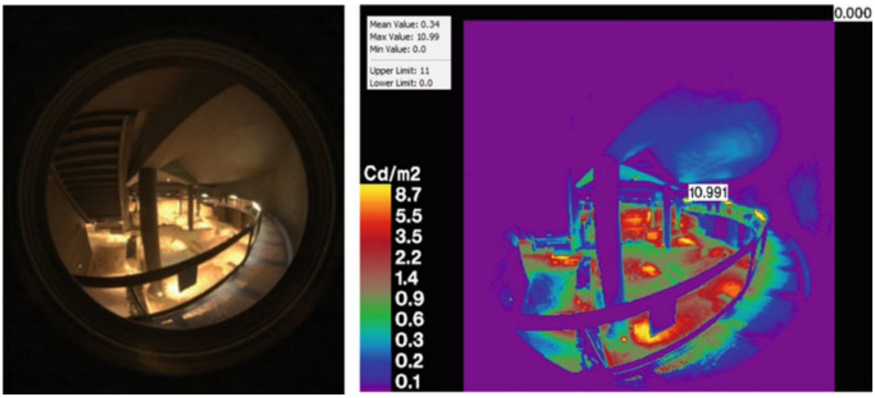


**Fig. 2** Route A, point 7. HDR photo (left side) False colour photo (right side)

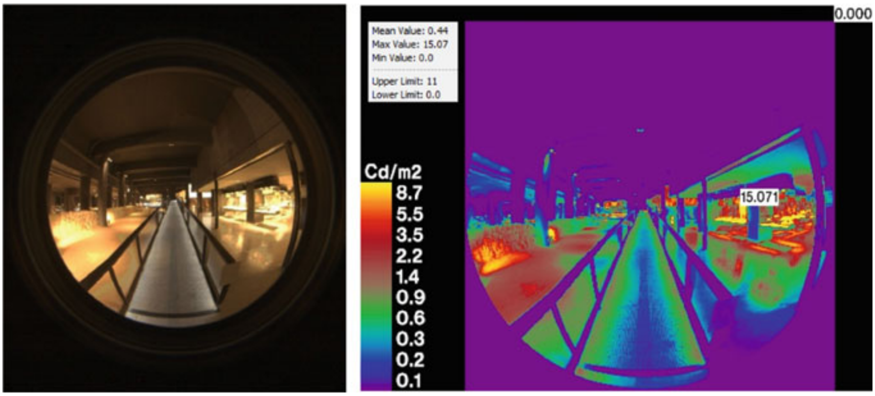


**Fig. 3** Route C, point 1. HDR photo (left side) False colour photo (right side)

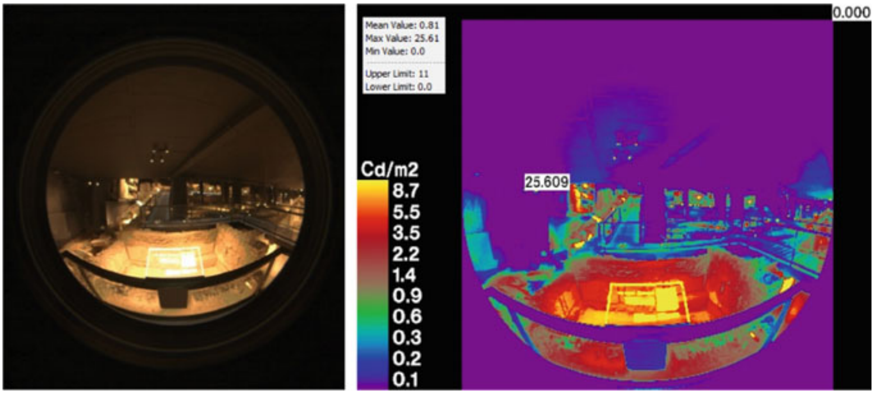


**Fig. 4** Route C, point 21. HDR photo (left side) False colour photo (right side)

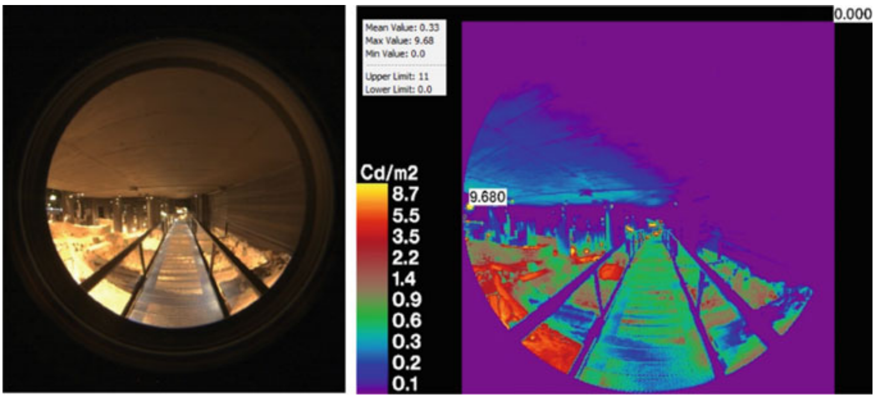


**Fig. 5** Route C, point 33. HDR photo (left side) False colour photo (right side)

The observation in the tour of the Badalona museum allows to identify four user activities related to vision:

- Glimpse the enclosure.
- Go across a walkway.
- Observe the ruins.
- Read the information boards.

These four activities can be grouped into four sets of surfaces as we can see in each figure. The first set of surfaces, made up of the museum container, is painted black and allows glimpsing within the enclosure. Although it is not directly illuminated, it is perceived thanks to the reflection of the other illuminated surfaces. The second set of surfaces, the metal bridge, is illuminated by the light under the black railing. The third group, the Roman ruins, is lit by lamps with a small metal support over the floor. The last set of surfaces, the transparent information board, is illuminated by the light inside the metal support.

Concerning the measurements, on the one hand, it was verified that the light level over the ruins and the pieces found at the remains of Roman city is low enough to avoid damage from radiation. According to the CIE recommendations of exposure limits for different materials, the illuminance limitation and exposure time for low responsivity materials (not very sensitive to light) are 200 lx and 600 000 lx-h/year. On the other hand, the campaign of light measurements shows that the illuminances in the museum route range between 0 and 5 lx, measured on the railing, at 0.9 m above the user's feet. These values are helpful to know that the light intensity in the museum corresponds to the low light intensity study.

Considering the luminance level, a series of photographs has been taken that, once analysed with software that allows obtaining images in HDR and false colour, allows us to see that the scale of luminance values of the surfaces that reflect light is between 0 and 11 cd/m$^2$. However, there are some luminance values over 11 cd/m$^2$ that correspond to the direct light of the source. Furthermore, it is important to notice that the average luminance is between 0.3 and 0.8 cd/m$^2$, according to the photos.

In addition, we can also observe that each of the groups of surfaces is differentiated by a different range of luminance, although sometimes they overlap each other, and by different colour temperatures:

- The first group of surfaces, corresponding to the museum container, show values between 0 and 0.3 cd/m$^2$. They are not directly illuminated.
- The second set, the walkway, has luminance values between 0.3 and 0.9 cd/m$^2$. The colour temperature used is 6500 K.
- The third group, the Roman ruins, has luminance values between 0.3 and 11 cd/m$^2$, but mainly between 0.9 and 8.7 cd/m$^2$. The colour temperature used is 2700 K.
- The fourth family of surfaces, the information panels, present luminance values between 8.7 and 11 cd/m$^2$. The colour temperature used is 4000 K.

## 5 Discussion

The analysis of false colour images reveals that there are different lighting intensities on the main sets of surfaces. The highest luminance corresponds to the illuminated information panel with white light. The medium–high luminance values are found in the vestiges of the Roman city, with warmer light lamps placed close to the ground illuminating the ruins and directional lighting revealing ancient walls and floors. The medium–low luminance values are found in the new walkways, with cooler light lamps illuminating the public path on the floor. The lowest luminance corresponds to the black surfaces of the new building. Walls, columns and ceiling are absorbing the reflections of the different lighting surfaces. Sometimes there are similar luminance overlaps in the same visual scene and this can compromise the legibility of the information. The case study reveals the feasibility of using light sources with different colour temperatures to separate surfaces that may be close or coincident in luminance values.

The results in the Badalona Museum (Figs. 2, 3, 4 and 5), show that the luminance levels on the information panels, the roman ruins and the walkway are higher than the luminance levels in the museum's container building. Even though, the last set of surfaces, the container building, covers almost 50% of the visual field at almost all measurement points. Therefore, the mean luminance value is less than 1 cd/m$^2$.

If scotopic vision starts when the average luminance in the entire visual field is less than 1 cd/m$^2$ [17], we can say that the space corresponds to a low light intensity design where we mainly use rods to see and the perception of colour surfaces starts to be reduced. Considering that an important aspect for visual activities is the colour of surfaces [18], the colour temperature could serve as a tool for lighting design to bring chromatic information into the visual field.

In Figs. 3 and 5, the metal bridge occupies up to 10% of the visual field and it is overlapping the roman ruins that reach up to 40% of the visual field. To differentiate the visual activity of walk and observe the ruins, two different colour temperatures are used. The new walkway presents a lower luminance level than the ancient walls and floor surfaces and it is illuminated with a very cold light in comparison with the warm light of the Roman city. Also, in Figs. 2 and 4, the luminance level on the information panels are higher than the luminance level on other surfaces with reflected light. This set of surfaces represents less than 1% of the visual field. The high luminance corresponds to the need of visual acuity for reading and it is illuminated with white light.

The visual task is linked to the user's activity. The visual information from the surfaces that we see in the museum can be grouped into four different types of activities related to vision: glimpsing the enclosure, walking through the museum, observing the exhibits and reading the museum information. The photographs show that these activities occur simultaneously through the museum tour. Furthermore, the luminance values of the different group of activities sometimes overlap each other.

## 6 Conclusion

The evaluation of the lighting design of this museum allows us to quantify the luminance in spaces with different lighting intentions. Three different set illuminated surfaces have been examined, as well as the building container. Due to the overlap of surfaces illuminated in the visual field, an analysis of the correlation between the luminance values and the colour temperature has been carried out. Current normative specifies to lighting designer the advisable illuminance on the artwork, however, the regulations are more flexible on how to illuminate other surfaces. The chance is left to the lighting designer to choose how to light the rest of the surfaces taking into account the user's activities.

In spaces with low light intensity, when the luminance values of surfaces are very similar, the surface colour is ineffective in distinguishing visual information. In the case that surfaces illuminated for different activities overlap, the colour temperature serves as a tool to give visual information to the user. Therefore, both values, luminance and colour temperature, respond to architectural and lighting design purposes. The goal of lighting design is to achieve the right combination of colour temperature and luminance depending on the activity. Although it is evident that each activity requires a different lighting design, the present work reveals that the colour temperature allows the differentiation of a greater number of activities simultaneously.

According to the results obtained, the comparison of each set of surfaces studied serves to draw a conclusion that, for spaces with low light intensity, the colour temperature helps to set apart and classify the visual information that comes from similar luminance values. In the context of conservation and interpretation of the built heritage where illuminance values are low, we are guided by scotopic vision. Therefore, the visual information provided by the colour surfaces is reduced, and we are guided by the luminance contrast. Colour temperature is a tool in lighting design to return chromatic information diminished by scotopic vision. When luminance values resemble each other, the use of colour temperature is a recommended strategy for zoning different purpose areas in the visual scene. Colour temperature makes it possible to differentiate between surfaces, with low luminance contrast, because of the chromatic contrast of surfaces. The research in low light intensity design contributes to energy-saving solutions in the field of electric lighting.

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## References


1. Kruithof, A.: Philips Techn. Rev. **6**, 65–66 (1941)
2. Lam, W.C.: Perception and Lighting as Formgivers for Architecture. McGraw-Hill Inc., New York (1977)
3. Michael, L.: Light: The Shape of Space. Designing with Space and Light, 1st edn. Wiley, New York (1996)
4. Gibson, J.: La percepción del mundo visual. Infinito, Buenos Aires (1974)
5. McCluney, W.R.: Introduction to Radiometry and Photometry. Artech House Publications, London (1994)
6. Serra, R., Coch, H.: Arquitectura y Energía natural, 1st edn. Edicions UPC, Barcelona (1995)
7. Durmus, D., Davis, W.: Optimising light source spectrum for object reflectance. Opt. Express **23**, A456–A464 (2015)
8. Cuttle, C.: Damage to museum objects due to light exposure. Light. Res. Technol. **28**(1), 1–9 (1996)
9. Abdalla, D., Duis, A., Durmus, D., Davis, W.: Customization of light source spectrum to minimize light absorbed by artwork. In: CIE Lighting Quality and Energy Efficiency Conference, pp. 22–31 (2016)
10. Viénot, F., Durand, M., Mahler, E.: Kruithof's rule revisited using LED illumination. J. Mod. Opt. **56**(13), 1433–1446 (2009)
11. IESNA.: IES Lighting Handbook, 9th edn. Illumination Engineering Society (2000)
12. Mahoney, D.P.: Walking through architectural designs. Computer Graph. World **17**(6), 22–24 (1994)
13. Espinoza, E., Lopez-Besora, J., Isalgué, A., Coch, H., Crespo, I.: Evaluation of three lighting software in the use of different light intensity spaces. In: Littlewood, J., Howlett, R.J., Jain, L.C. (eds.) Sustainability in Energy and Buildings 2020. Smart Innovation, Systems and Technologies, vol. 203, pp. 419–429. Springer, Singapore (2020)
14. Jacobs, A.: High dynamic range imaging and its application in building research. Adv. Build. Energy Res. **1**(1), 177–202 (2007)
15. Miri, M.: Luminance-based HDR photos to help lighting designers in their everyday work. In: 5th Global Lighting Design Conference on Proceedings, Rome, pp. 198–204 (2015)
16. Espinoza, E.: La iluminación para el culto: reflexiones del confort visual en la penumbra (2015). Available: https://upcommons.upc.edu/handle/2117/101100. Last accessed 30 Mar 2021
17. ERCO: Fisiología del ojo. El ojo como sistema óptico. Available: https://www.erco.com/guide/basics/physiology-of-the-eye-2225/es/. Last accessed 30 Mar 2021
18. Lopez-Besora, J., Coch, H., Isalgué, A., Alonso-Montolio, C., Aguilar, A.: The perception of light affected by colour surfaces in indoor spaces. In: CISBAT International Conference Cycle. "CISBAT 2013—International Conference. Cleantech for Smart Cities & Buildings. From Nano to Urban Scale", EPFL, Lausanne, pp. 469–474 (2013)

# A Methodology for Fast Simulation of Energy Retrofitting Scenarios of Social Building Stock

**Vincenzo Vodola, Ernesto Antonini, Jacopo Gaspari, and Lia Marchi**

**Abstract** Retrofitting the built environment is crucial for the achievement of the global sustainable development targets. Therefore, several measures, strategies, and technologies have been developed to pursue this aim and reduce the energy demand of existing buildings. Within this framework, the EU social housing stock represents a relatively small but critical and peculiar share to handle, as the involved variety of economic, social, and environmental issues makes any intervention tough and tricky. This is particularly true in Italy, where about seventy local agencies, which manage over 1 million publicly owned housing assets, are struggling with a shortage of funds to invest and a lack of adequate knowledge of the conditions of their assets. The research we carried out aims at providing managers of large housing parks with a digital tool useful for rapidly forecasting the effects of different refurbishment scenarios. This should allow planning maintenance interventions effectively, according to the available resources. The main result of the study is an algorithm that powers a predictive diagnostic tool by which the current energy behaviour of buildings can be estimated and the effects of different energy retrofitting measures on their overall performance can be simulated.

## 1 Introduction

The building sector represents nowadays one of the major contributors to global related environmental challenges, climate change and resource depletion above all [1, 2]. Buildings account for one third of global energy demand, resulting in 28% of global energy related $CO_2$eq emissions in 2019 [3], of which a large share is due to primary energy consumption related to electricity and fuel demand [4]. The housing sector is the main generator of environmental impacts (62%) of the entire built environment, nevertheless it has a great potential for reduction, estimated in at least 40% [2, 4, 5].

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The energy consumption and emissions reduction are therefore considered a crucial action to achieve the economic and environmental sustainability of the building sector, thus complying with the sustainable targets that institutions have set worldwide [2, 6]. Given that the turn-over of the building stock is very slow, the main challenge is to improve the energy efficiency of existing stock, where in 40 years more than 90% of the EU built environment will consist of constructions already in use today [7, 8].

These concerns drove all the policies on the topic during the last three decades. The EU Energy Efficiency Plan [9] states the greatest energy-saving potential lies in buildings, but this is exploitable only if a comprehensive, rigorous, and deep enhancement of their performance will be realized. Accordingly, the Energy Efficiency Directive 2012/27/EU (EED) [10] and the Energy Performance of Buildings Directive 2018/844/EC (EPDB III) [11] promote the energy efficiency improvement of both new and existing building stock, targeting at reducing of 80–95% the building related Greenhouse Gas (GHG) by 2050. The recent EU Green Deal [12] also highlights the importance of renovating the stock in an energy and resource efficient way.

In this context, social housing represents a peculiar market segment, due to both the fragility of target users and the ownership, which largely belong to Public Bodies or Housing Associations. All of them, while referring to different models and regulations within EU countries, manage large assets, often heterogeneous in terms of location, age, size, and condition [13–15].

As many social housing tenants are low-income and socially impaired, the risk of energy poverty and the limitations in accessing fair energy policies have relevant implications and harder consequences than elsewhere [16–18]. This requires effective measures to reduce energy needed to ensure adequate comfort standards are adopted in order not only to meet environmental requirements but also to make energy costs accessible to tenants.

Due to the heterogeneity of the social housing stock they manage, as well as the financial and regulatory constraints and the resource shortage they often suffer from, owners must select very carefully the buildings to include within their frequent but restricted retrofitting programs, to maximize the effectiveness of each initiative: thus fast and low-cost pre-assessment tools could be of great help [19–21]. The lack of systematically organized information on the buildings often due to data retrieving costs, also represent a strong barrier in adopting suitable management strategies, leading in under-optimization of the scarce resources devoted to refurbishment and energy retrofitting of social housing [22].

### 1.1 Major Issues in Massively Retrofitting the Italian Social Housing Stock

Social housing in Italy represents a critical asset even more than in other EU countries, due to the historic shortage of this stock, furtherly reduced by both the cut in public investments and the sale to tenants of several thousand apartments/year since the 1990s [23]. As a result, the national social housing heritage accounts today for about 900.000 dwellings, less than 3,8% of the whole residential building stock censed in 2007 [24] and it is largely insufficient to face the current demand [14, 25, 26]. This pushes the owners to manage their assets in the most effective way possible, and to make it fully usable through intense maintenance and restructuring activities, since investment resources are not available to suitably increase the stock.

Concerning environmental performances, energy demand of most of these buildings are very high and comfort levels are often poor, largely due to the lack of energy efficiency requirements at the time of construction. This leads to low insulation levels and inefficient technical installations, which push to 250 kWh/m$^2$ year their average energy consumption [27]. High energy-demand frequently causes social issues too, as they feed the energy poverty phenomenon that effective retrofitting interventions could instead reduce [28, 29]. However, the pace of energy improvement is rather slow: the Italian association for social housing (Federcasa) estimates that in 2017 less than 1% of this heritage (6.578 dwellings) had been deeply refurbished, while in 2014 the share was almost double (11.423) [14].

Economic and management issues strongly affect this dynamic, since the entire national stock is held by 74 local agencies [25], mostly being territorial bodies covering a province area, but also single municipality agencies and tenant cooperatives [24]. Each of them runs many thousands of dwellings and have just few, if any, information on current building energy performances, so triggering difficulties in managing such complex and large assets and especially in prioritizing the refurbishment interventions [30].

Furthermore, a lack of information about the expected cost-benefits ratios of the renovation often hampers the tenant acceptance of the planned actions, as the involvement of the owners in multi-property buildings [2, 29, 31]. The tenure fragmentation often exacerbates this situation, as the massive sale of social dwellings done in the late 90 s has led to over 20.000 multi properties buildings, which has highly jeopardized the chances of renovation [23].

It is therefore critical in Italy to make available fast prediction assessments of the potential effects of energy retrofitting in the social housing stock. This aims at enabling owners to create rational intervention plans, thus maximizing the use of limited available capital. Indeed, some Italian housing managers are already performing this kind of application although limited in the extent and effectiveness [22, 30]. As informative systems are gradually spreading among the building sector too, it appears to be as feasible as useful the development of an effective prediction tool easily applicable to any building stock. This goal is especially promising as it is consistent with the Italian program 'Safe, green and social' funded by Next Generation EU plan and devoted to public housing. The program allocates 2 billion Euros for building retrofitting, potentially allowing to renovate one fifth of the entire social housing asset [14].

A fast screening is thus needed to classify the buildings of the owned park by the expected effectiveness of retrofitting intervention that could be performed on each of them, based on the parameters that most affect the decision-making process [22]. Since the forecast must be as rapid and cheap as possible despite detailed data on the stock being potentially unavailable, the process must be based on only very few easily retrieved indicators, namely: the current building energy behavior and the expected outcomes of a set of standard schemes of refurbishment, in terms of both performance and cost.

The paper reports the core conceptual elements of a study originated by the need to predict the effects of energy retrofitting actions within the Italian social housing context, in order to both identify the most effective strategies for each building belonging to the stock and to prioritize interventions over the time in compliance with the owner's policies and available resources.

The goal is to define a digital tool allowing both owners and tenants to predictively compare the effects of possible retrofitting interventions on a building or group of buildings within a certain stock. Furthermore, the tool provides the owner or manager with an easy means to group the buildings based on specific criteria related to energy improvement or intervention costs, or both combined.

## 2 Methodology

The study has been funded by Region Emilia-Romagna within the InSPiRE project (Integrated technologies for Smart buildings and PREdictive maintenance) and it was carried under the umbrella of a broader cooperation between the Department of Architecture and the Interdepartmental Centre for Industrial Research (CIRI_EC) of the University of Bologna with ACER-Bologna, the local Agency for Social Housing.

ACER-Bologna asked the research team to develop a method to forecast the renovation potential of the buildings belonging to the whole building stock it manages, which accounts for about 18.000 dwellings scattered across the Bologna Metropolitan Area (3.770 km$^2$, 55 municipalities, about 1 Million inhabitants). The lack of forecasting capacity prevents them to effectively compare datasets and identify the building renovation potential, mainly due to the inadequacy of the available information on the buildings which proceed from different sources and were collected by various campaigns carried in different periods, making their coverage partial and very heterogeneous. This great variety of data quality drastically threatens the chance to define a reliable catalogue of the stock.

Due to the heterogeneity of the information available on buildings, the already existing dynamic energy tools for urban buildings energy modeling resulted unable to be used. In fact, although validated and effective, the software requires a series of entry data that are not always available in the agency's archives. Thus, aware of obtaining a less precise but faster tool as well as adequate to the manager's skills and knowledge, the research focused on the development of a predictive system starting from the minimum set of data shared by all buildings belonging to the ACER heritage.

Therefore, the key challenges to be addressed can be listed as follows: (i) quantifying the current energy consumption of each building within the stock; (ii) defining a set of suitable retrofitting options based on the most recurrent ones; (iii) estimating the benefits they will produce on the energy needs of each building; (iv) calculating and comparing the costs-energy benefits balance of different retrofitting options.

To this end, the research firstly determined the current building energy needs which must provide the baseline of the simulation. Since the direct quantification of energy consumption is already available only for a few buildings, for most of them the value must be estimated. For this purpose, a minimum dataset has been established which just includes those physical and technical features of the building required to perform the energy simulation.

Afterward, the more recurrent retrofitting measures applied within the observed stock in the last decade have been detected to identify a set of standard intervention schemes and their related expected performance enhancements.

Figure 1 reflects the conceptual and organizational structure underlying the process of the predictive simulation tool. It is built on three main steps:

1. determining the building current features, which are the input data feeding the tool;
2. defining different building retrofit scenarios.
3. applying the refurbishment scenarios to the buildings to obtain the related energy consumption estimates as final output of the process.

The research activities were carried out accordingly.

## 3 Implementation and Outcomes

**Current energy behaviour of the building**. Since appropriate information on the current state of the housing stock is lacking and heterogeneous, it was crucial to identify some key variables allowing rapid estimation of the building energy performance, even when no data were available for accurate calculation. The adopted strategy was to assign each building to a typological class associated with an energy performance range, according to literature. Therefore, the approach provides a double degree of approximation both in assigning a performance profile to the building and in associating it with a level of energy needs (EP).

Once the reference data sources were selected, these approximations were quantified to pre-validate the method. Thus, some buildings of the stock have been selected among those for which the EP official certificates were available. Then, a test was performed on a random selected set of these buildings by comparing the EP assigned

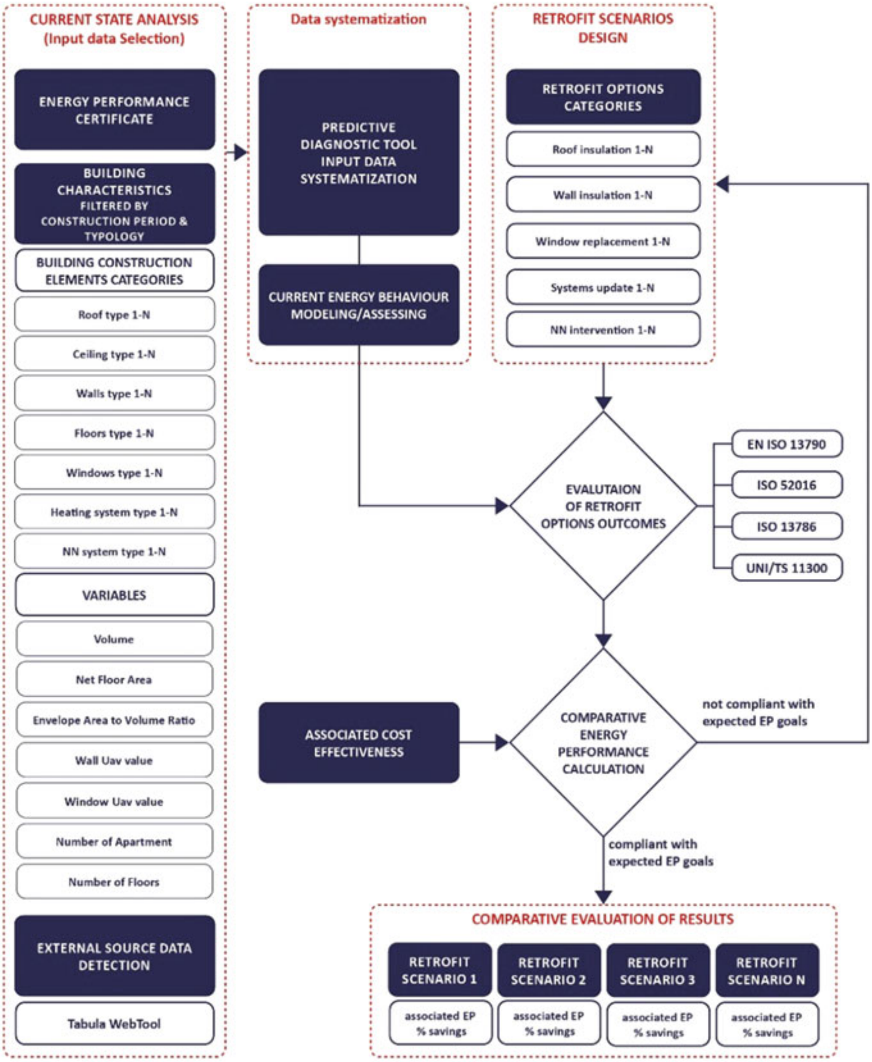


**Fig. 1** Methodology conceptual representation

following the developed method with both the EP from official certificates and the EP resulting from a calculation specifically carried out.

According to the analytical calculations and the values of the energy certificates, the selected buildings had an energy needs ranging between 210 and 225 kWh/m$^2$ per year. The application of the developed method led to a deviation from these results ranging from a minimum of 8 kWh/m$^2$ to a maximum of 40 kWh/m$^2$ per year. Since the buildings belonging to the stock have a high energy consumption and the proposed improvements can easily contribute to largely reduce the energy demand, the deviation of the resulting values was considered negligible and the level of approximation acceptable to the scope. Then, the buildings were assigned to three classes based on the available type of data, namely: buildings with an officially issued EP certificate, buildings without an EP but for which a detailed set of data is available, and buildings with only basic cadastral data. The first class directly associated the buildings with their Energy Performance Certificates (Legislative Decree 63/2013), while for the buildings in the second class the following key indicators have been selected, to be used in estimating current needs for operational energy:

- *Building Volume* (V) [$m^3$], or the volume of heated building zones defined by the building envelope;
- *Net Floor Area* [$m^2$], intended as the walkable surface net of internal and external walls, balconies and/or terraces;
- *Envelope Surface* (S) [$m^2$], as the envelope surface that delimits the volume separating it from the outside or from unheated areas;
- *Envelope Area to Volume Ratio* (S/V) [$m^{-1}$];
- Opaque envelope average *thermal transmittance* (U value) [W/($m^2$K)];
- Window average *thermal transmittance* ($U_w$ value) [W/($m^2$K)].

The energy profile of the third-class buildings was instead defined using TABULA WebTool [32], being otherwise specific ad-hoc calculations too costly and time consuming to the scope. TABULA WebTool was developed in 2011 by TABULA and EPISCOPE research projects, carried within the EU funded Intelligent Energy Europe program and aiming at assessing the energy consumption of the European building stock. A very large and in-depth study on a large sample of residential buildings from different EU countries powers the TABULA tool. This allowed to classify the buildings according to a few simple parameters and to associate for each class a set of energy performance indicators: the climatic area, age, size, geometry, and type are the considered characterization parameters, along with some building's technical features. Entering these parameters, the web tool provides the average values for thermal envelope areas, U-values, supply system efficiency and some other indicators of building energy performance. In order to retrieve the data from the TABULA webtool, the characterization parameters of ACER-Bologna's buildings that need to use this source have been provided and used as a query.

Each of the methods used to esteem the energy behavior of the buildings results in the calculation of an index that expresses the overall energy performance in terms of non-renewable primary energy demand, i.e. the $EP_{gl,\,nren}$. This is the most precise value to assign the energy class and indicates the total energy consumed by the building per square meter of surface each year [kWh/$m^2$y]. Therefore, in order to verify the achievement of a homogeneous value for the entire stock, the obtained indexes were compared and correlated with the building typologies. Buildings of the same type obtained a similar index with each method and also in this case no deviations greater than 40 kWh/$m^2$ per year were detected.

This procedure made available the energy profile of each building in the park. Despite requiring the use of three different methods to quantify the indicators, the verifications show that the three ways output data of comparable reliability and the deviations remain within acceptable limits.

**Improvement scenarios**. Once determined the building energy profile, the tool provides the user with a series of renovation scenarios. To this end, a bundled database is supplied including a set of three retrofitting standard interventions on various technical elements, for which of them two options with increasing levels of performance are available. The proposed intervention schemes are:

- application of insulation layer on the building envelope.
- application of insulation layer on horizontal closures, such as flat and sloping roofs;
- replacement of windows.

While the two performance levels achievable by the schemes, or "refurbishment intensity", are:

- *basic refurbishment*: application of the most commonly used measures to reach the minimum legal requirements regarding energy transmittance (U-value) of the building envelope elements;
- *advanced refurbishment:* adoption of the best available technologies to obtain high energy performance, or an improvement of about 30% compared to the legal minimum requirements.

The user can chose among these options to draft a refurbishment scenario: the tool shows their gap with the present situation in terms of building energy performance and an estimation of the related economic effort, based on the standard cost recorded for each scheme.

**Comparative assessment of the scenarios**. All this makes available a set of different refurbishment scenarios suitable in fueling the core engine of the tool, which operates a comparison among and provides the user the outputs that help its decision process. An iterative process drives the procedure, as users can obtain and compare the estimations of the energy performance achievable by applying the measures included within each scenario, and the related intervention costs. Once the solution has been confirmed as suitable by the user, the final output visualization is displayed (Fig. 2). The process can be repeated until all the comparisons are made and the most efficient and/or cost-effective result is obtained.

## 4 Discussion and Conclusion

The developed tool is a viable and cost-effective answer to a critical decision-making problem the owners and managers of social housing stock face periodically. Even if affected by a certain degree of approximation, a cheap and speedy decision support

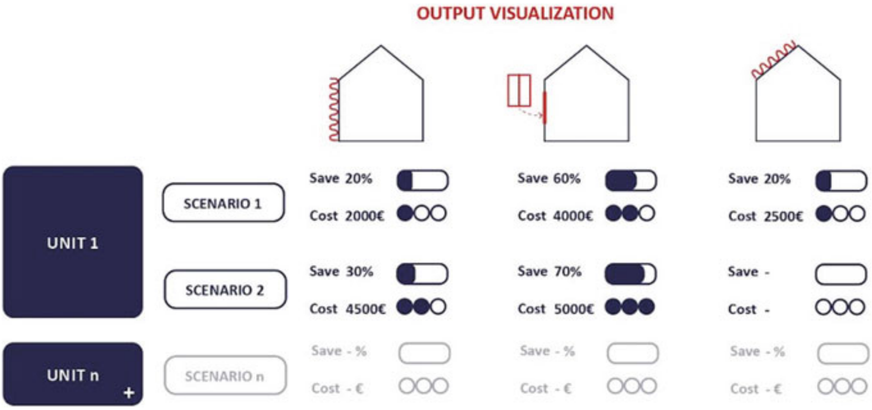


**Fig. 2** Final output visualization

system provides a suitable means for this purpose, as it meets both the lack of knowledge on the current state of the buildings and the strong need in optimizing to optimize the use of scarce funds available for their maintenance. The benefit of a tool providing real-time results with minimal data to input, thus also easy to use for non-specialists, represents a helpful solution for both managers and housing tenants. Hence, the novelty of the proposed methodology does not lie in the technologies adopted but rather in benefits provided to users. An easy access to a predictive simulation can prevent the tenant's mistrust against the manager's energy retrofitting policies and increase the consensus of owners in multi-property assets. This, in addition to the overview survey and the forecasts that the tool allows managers to do on their whole stock, in short time and at very low cost, but reliable enough for a first screening. To demonstrate the potentialities of the proposed method the research, which is still ongoing, is now performing a test campaign on a large sample of cases and developing the IT implementation.

Further improvements of the process deal with the development of faster and more effective data import flows from existing archives and with the enlargement of the possible target users, including energy managers, designers, private real estate holders and managers. In the short term, it is expected the tool will increase the effectiveness of the resources invested in the energy retrofitting of social housing, as well as accelerate intervention programs by planning them more appropriately. In the medium term, this will extend the life span, improve performance, and reduce energy consumption of the housing heritage, thus providing tenants a better quality of life.

## References


1. Fenner, A.V., Kibert, C.J., Woo, J., Morque, S., Razkenari, M., Hakim, H., Lu, X.: Ren. Sust. En. Rev. **94**, 1142–1152 (2008)
2. Yamamoto, G., Graham, P.: Buildings and climate change. Summary for decision makers. United Nations Environment Programme (UNEP)—Sustainable Buildings & Climate Initiative (2009)
3. IEA, 2020. https://www.iea.org/reports/tracking-buildings-2020. Last accessed 20 April 2021
4. McKinsey & Company: Pathways to a Low-Carbon Economy. Version 2 of the global greenhouse gas abatement cost curve (2009)
5. Nejat, P., Jomehzadeh, F., Taheri, M.M., Majid, M.Z.: Ren. Sust. En. Rev. **43**, 843–862 (2015)
6. Artola, I., Rademaekers, K., Williams, R., Yearwood, J.: Boosting building renovation: what potential and value for Europe? In Directorate General for Internal Policies. Policy Department A: Economic and Scientific Policy (2016). http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587326/IPOL_STU(2016)587326_EN.pdf
7. RAEng, Engineering a low carbon built environment, The Discipline of Building Engineering Physics, The Royal Academy of Engineering, London. Available at: http://www.raeng.org.uk/publications/reports. Accessed DATA
8. Russo Ermolli, S., D'Ambrosio, V. The building retrofit challenge. Programmazione, progettazione e gestione degli interventi in Europa, Alinea, Firenze (2012)
9. European Comission: Energy Efficiency Plan 2011, COM(2011) 109 final (2011)
10. Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency: Energy Efficiency Directive (EED)
11. European Commission, 2018/844/EC, Energy Performance of Buildings Directive Directive amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (EPBD III)
12. European Commission, COM/2019/640 final, The European Green, Brussels
13. Musterd, S., van Kempen, R.: Large Housing Estates in European Cities, Opinions of residents on recent developments. Urban and Regional research centre Utrecht (2005). http://www.narcis.nl/publication/RecordID/oai:uva.nl:295944
14. Housing Europe: The state of housing in Europe 2021 (2018). https://doi.org/10.1787/9789264298880-4-en
15. Krapp, M., Vaché, M., Egner, B., Schulze, K., Thomas, S.: Housing Policies in the European Union, Christian Donner, Institut Wohnen und Umwelt GmbH (2020)
16. Boardman, B.: Fuel poverty synthesis: lesson learnt, actions need. Energy Policy **49**, 143–148 (2012)
17. BPIE: Alleviating fuel poverty in the EU. Investing in home renovation, a sustainable and inclusive solution. Building Performance Institute Europe (BPIE) (2014)
18. EPEE: European fuel poverty and energy efficiency, 2009. http://www.fuelpoverty.org/
19. Aranda, J., Zabalza, I., Conserva, A., Millán, G.: Analysis of energy efficiency measures and retrofitting solutions for social housing buildings in Spain as a way to mitigate energy poverty. Sustainability **9**, 1869 (2017). https://doi.org/10.3390/su9101869
20. Tzortzopoulos, P., Ma, L., Soliman Junior, J., Koskela, L.: Evaluating social housing retrofit options to support clients' decision Making-SIMPLER BIM protocol. Sustainability **11**, 2507 (2019). https://doi.org/10.3390/su11092507
21. Amato, A., Calabrese, N., Lavinia, C., Volpe, L.: Riqualificazione energetica del patrimonio immobiliare di edilizia residenziale pubblica. Energia, Ambiente e Innovazione **3**, 87–91 (2020). https://doi.org/10.12910/EAI2020-075
22. Melis, P.: La valutazione della qualità globale degli edifici residenziali nella programmazione degli interventi di riqualificazione alla scala del patrimonio edilizio. Università degli Studi di Cagliari (2010)
23. Antonini, E.: Patrimonio abitativo ed edilizia sociale in Italia. In: Boeri, A., Antonini, E., Longo, D. (eds.), Edilizia sociale ad alta densità: strumenti di analisi e strategie di rigenerazione: il quartiere Pilastro a Bologna. Bruno Mondadori, Milano (2013)

24. Censis. Social Housing e agenzie pubbliche per la casa, Dexia-Crediop. Roma (2008)
25. Federcasa: https://www.federcasa.it/appello-di-federcasa-e-federcostruzioni-in-italia-servono-300mila-nuove-case-popolari/. Accessed on 30 March 2021
26. Reviglio, E.: Rilanciare le infrastrutture sociali in Italia. Rapporto sull'investimento delle infrastrutture sociali in Italia (2020)
27. Boeri, A., Gabrielli, L., Longo, D.: Evaluation and feasibility study of retrofitting interventions on social housing in Italy. Procedia Eng. **21**, 1161–1168 (2011). https://doi.org/10.1016/j.proeng.2011.11.2125
28. Ürge-Vorsatz, D., Eyre, N., Graham, P., Harvey, D., Hertwich, E., Jiang, Y., Majumdar, M., Mcmahon, J. E., Murakami, S., Janda, K., Masera, O., Mcneil, M., Petrichenko, K., Tirado Herrero, S., Jochem, E.: Energy end-use: buildings. In: Global Energy Assessment Writing Team (Ed.), Global Energy Assessment: Toward a Sustainable Future, pp. 649–760. Cambridge University Press (2012). https://doi.org/10.1017/CBO9780511793677.016
29. Gaspari, J.: Cities and buildings efficiency improvement of energy-poor household. In: Urban Fuel Poverty, pp. 211–238 (2019). https://doi.org/10.1016/B978-0-12-816952-0.00009-0
30. SDA Bocconi, Federcasa: Il valore pubblico delle Aziende Casa Logiche di public management per il settore dell'ERP (Fosti, G., Perobelli, E., Saporito, R., eds.). Egea (2019)
31. Economidou, M.: Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings. Buildings Performance Institute Europe (BPIE), Bruxelles, Belgium (2011)
32. Tabula WebTool. https://webtool.building-typology.eu/#bm. Last accessed 20 Apr 2021

# Flood Risk of Open Spaces: From Microscale Factors of Built Environment to Risk Reduction Strategies

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**Abstract** Urban Built Environment can be defined as a network of Open Spaces (including their infrastructures) and buildings, where users live and interact. In case of an emergency, the risk in the Built Environment highly depends on the characteristics of disastrous event, buildings and Open Spaces physical vulnerability, and on users' behavioral patterns and emergency response. Open Spaces represent a fundamental element during the disaster and the immediate aftermath. Floods denote one of the most challenging disasters for Open Spaces safety. In fact, they influence the floodwater spreading in the urban layout, affecting the building damage and the emergency evacuation process. From a critical review of recent advancement in the field, this work addresses the role of Open Space factors in flood risk—considering the composing elements and their interactions—to pursue a microscale approach.

## 1 Introduction

Built Environments (BEs) in our cities are the result of both planned and unplanned developments [1]. These evolution processes affected the components of the BEs and the interactions between the factors determining the overall BEs structure. Broadly speaking, considering a typological and historical–geographical approach to analyse

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the urban BEs [2], four main aspects defining the urban form are relevant to characterize further this complex system: spatial relations of physical features; interrelations between BEs users and BEs physical features; users' fruition models of the BE; formation/transformation/ cyclical changes. The response of a BE to disasters is closely related to these four aspects and urban vulnerability and resilience concepts. Between the components of the BE, urban Open Spaces (OSs) is a paramount element [3], especially if considering Sudden-On set Disasters (SUODs) "triggered by a hazardous event that emerges quickly or unexpectedly".[1] During a SUOD, the network of the urban OSs represents the emergency network for both population's evacuation and rescuers' access to the disaster-affected areas [2, 4, 5]. In this network, areal spaces (e.g., squares, parks, parking areas), which can be used as safe gathering areas for the population, are linked together by linear spaces (i.e., streets), used as evacuation and emergency paths. Both areal and linear spaces can be surrounded by buildings, which can also damage the OSs. Such buildings are characterized by a significant number of exposed people, both indoors and outdoors when the disaster strikes the urban areas [5, 6].

Among the SUODs, flood is one of the most critical for the urban BEs, considering the rising frequency (a consequence of climate-change effects) and severity (due to urbanization growth, which increases the number of exposed people in flood-prone areas) [7, 8]. Therefore, flood risk management requires knowledge of the characteristics of the floods [8, 9]. Floods are often the combination of meteorological and hydrological extreme events. They can be categorized into fluvial floods, pluvial floods, coastal floods, groundwater floods, or floods due to the failure of artificial water systems.

Regardless of the type of flood, the layout, the design and materials, and the supporting infrastructure systems [4, 10] of urban OSs influence floodwater spreading and characterization of the hazard in terms of depth, speed, and solid load. The microscale characteristics of the BE, including physical barriers and surface materials, affect the OSs and the BE in general for damages [11, 12] and to users' safety (i.e., immediate emergency response). This includes the evacuation process and the availability of gathering areas and paths [13, 14]. Increasing the flood resilience of the BE and its community means to promote Disaster Risk Reduction (DRR) actions before the disastrous events, according to criteria of prevention, preparedness, emergency response, and recovery [15]. These 4 criteria correspond to DRR actions aimed at prediction and warning, monitoring, impact assessment, response, and management. These actions refer to a series of structural and non-structural measures against floods [16, 17]. Structural measures are usually engineered measures applied to reduce the flood volume, such as retention ponds, dams, river improvement, urban drainage systems, and levees or dikes. Non-structural measures instead promote strategies based on flood-adapted design and building codes, land-use planning laws and regulations, preparation and evacuation planning, public awareness programs, and flood insurance programs. Both structural and non-structural measures can be reactive (response-oriented) or proactive (risk reduction) [17].

[1] https://www.preventionweb.net/terminology/view/475 (last access: 18/03/2020).

Thereupon, it is essential to describe the interaction systems in the OSs by representing each element at risk. Following a micro-scale risk assessment, adequate safety measures can be implemented to increase the safety and resilience of the BE and its users [5]. Starting from a critical literature review, this paper organizes the microscale building- and OSs-related factors as mitigation strategies related to the hazard, the buildings damages and users' support during the evacuation process.

## 2 Overview of Microscale Factors of Open Spaces Affecting Flood Risk and Mitigation

The urban fabric and surface characterization of the BE influence the flood intensity and spreading in an urban area and the overall safety levels for the BE users, in correlation to their risk perception and awareness [4, 5, 18]. Such issues have a great impact on urban management strategies against the hazard sources [19]. Therefore, the overview of microscale factors is organized considering urban OSs (Sect. 2.2), the delimitating buildings (Sect. 2.1), and the hosted users before and during the emergency conditions (Sect. 2.3).

### *2.1 Open Spaces-Related Factors*

The physical characteristics of urban OSs are of primary importance to enhance resilience and mitigate the BE's flood vulnerability. These characteristics are directly related to the interactions among the constituent components of urban form: street network, plot pattern, and built form. In recent years, the unintended interaction among urban form, flooding events, and human behaviour has been systematically investigated through urban morphometrics [20, 21].

Nonetheless, most of the hydrology-based studies on pluvial flooding conceive the urban form just as the spatial distribution of resistance parameters, providing a reliable description of the flood event, leaving out the understanding of the OSs effect. On one side, most of the proposed parameters do not act as urban form indicators [22]. On the other side, OSs factors remain qualitative rather than quantitative [23]. However, it is worth underlining that attention on the characteristics of the urban form components and their effects on the pluvial flood is rising in the hydrology field. Researchers claim the importance of approaching the modelling with a more accurate scale of analysis, essential for describing the complexity of the BE [4, 24]. In this regard, pushing boundaries in urban morphometrics could be helpful because quantitative, comprehensive, and systematic methods and tools to measure the urban form have been developed [25, 26]. This knowledge helps to characterize the urban spaces with the reliable metrics at the appropriate scale of analysis. In association with well-established statistical parameters, the introduction of OSs metrics in flood modelling could represent a ground-breaking approach in the field. Furthermore, the possibility of developing this approach is demonstrated by introducing novel digital tools for urban flood modelling integrating parameters and spatial data describing the characteristics of the urban space [27].

## 2.2 Building-Related Factors

According to Sect. 2.1, the correlation between buildings and the built form generates the OSs configuration, affecting the urban flood in terms of the specific features of the buildings as obstacles to floodwater spreading [4, 28]. Besides the physical vulnerability involving possible damage to the buildings [11], the quality and quantity of openings, and the wall orientation concerning water flow, are fundamental factors, especially considering the characterization at the ground floor. They influence the collection of floodwaters inside buildings and risk and damage for people, furniture, and goods and chattels placed indoors [6, 12, 28].

Building-related factors are connected to the building typology, as adaptive typologies are designed for areas that are characterized by frequent water presence or flood. The building features allow moving towards passive mitigation solutions when the house is built to adapt to flood events. This is the case of amphibious and floating buildings, or houses with elevated floors [29, 30], which can adapt to flood-prone areas due to construction technology and suitable materials.

Sustainable Urban Drainage systems [10] can be integrated or added to the building to reduce vulnerability to extreme rain events. They can be seen as "active" strategies for risk reduction as they provide runoff retention [31], measured as the percentage of water retained. Indeed, these solutions allow rainwater collection, supporting the infrastructure system to control rainwater volume and peak flow in the street. Green solutions can be applied to buildings' vertical and horizontal envelope, as green walls and roofs [32]. They are an effective support for the sewer systems in case of floods. They allow retaining 45–93% of runoff, depending on the substrates composing the green system and their configuration, roof slope, and rainfall event characteristics [34]. Previous work assessed values reductions up to 90% [35], depending on the rainfall intensity concerning the peak flow control. Moreover, green walls and roofs effectively reduce energy consumption and improve thermal comfort in indoor spaces [36]. The main challenge of green roofs and facades is related to the cost of their construction and maintenance [36], leading to long payback periods. Moreover, the characteristics of the building determine the feasibility of the green features, which are not always suitable for existing BEs. Lastly, rainwater can be stored and retained in buildings with rainwater harvesting systems, which gather rainwater, reduce runoff and peak flows [37], and allow water reuse after being filtered, with environmental and economic benefits [31].

### 2.3 Users-Related Factors

Exposed users undertake emergency behavioural patterns depending on their features and relation with the surrounding BE, the local flooding conditions, and the emergency management system that can support them [5, 13, 14]. Firstly, from a microscale standpoint, considering each user at risk, the individual features mainly concern: (1) individual risk perception, which varies from community to community and depends on 5 types of indicators, that are age and gender, income and occupation, education, and knowledge, past experiences, house ownership and location [18]; (2) characteristics affecting the motion speeds [38] and human body stability [13], that are age, gender, body mass and height, and motion abilities. Secondly, as shown in Fig. 1, different behavioural patterns appear in the three main evacuation steps from this microscale standpoint [14].

In the pre-evacuation phase, users can spend time evaluating the collection of personal belongings to limit their possible damages and then evacuating, basing on [14, 39]: individuals' risk perception, the value of flood-prone assets, pre-disaster activities (depending on the intended use of OSs and buildings), group decisions. Early Warning Systems (EWS) or rescuers-citizen information channels are the main BE-related attributes of references for a prompt evacuation response [40].

Then, the evacuation movement includes all the actions aimed at reaching a safe area to restore safety conditions [5]. The combination between OSs layout (see Sect. 2.1) and floodwaters' spreading affects the evacuation target decision since people spontaneously move towards areas with lower water depths and speed. The building configuration could lead people to move towards the higher stories, in case of

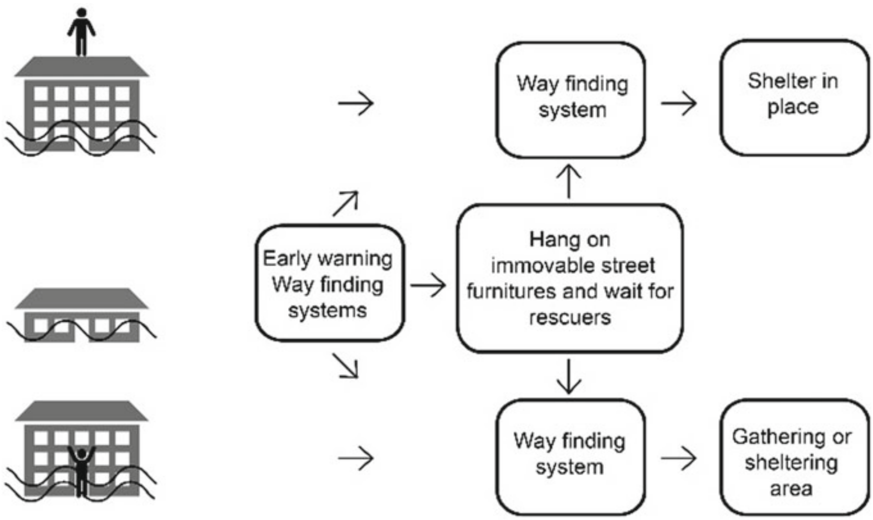


**Fig. 1** Users' evacuation options for multi-storey buildings, single-storey buildings, and outdoor areas

an adequate number of floors, instead of moving towards gathering areas and shelters provided by emergency plans [5]. Users placed outdoors seem to be more vulnerable than those placed inside the buildings since they cannot directly evacuate. In complex buildings, circumscribed OSs, or small urban areas, people can be effectively guided to a “shelter-in-place” area using adequate wayfinding systems [31]. Floodwaters can slow down the evacuation motion process, mainly in undergrounds, ground floors of buildings and OSs, since they can limit the opening of doors, drag people walking along staircases, prevent people from exiting from cars, or cause the loss of human body stability [5, 13, 28, 38]. Handrails or other immovable obstacles can be used to hang on while moving or standing for the rescuers’ arrival, increasing the users’ safety regarding the floodwaters [14]. In the OSs, raised areas can additionally host the evacuees in critical floodwater conditions. Elements dragged by floodwaters in the OSs, including debris and street furniture, represent additional threats for individual safety [4, 14].

Finally, once a safe area is reached, the evacuation stops [14]. People reach safe areas in the emergency plan, as shelters, or gather in the OSs/inside buildings.

## 3 Discussion

The microscale factors discussed in Sect. 2 and the physical elements in the BE can be implemented as structural strategies for DRR applied in the OS, considering their impact on: (i) flood hazard (Table 1), (ii) buildings damages (Table 2), (iii) users’ support pillars (Table 3). For each factor, supporting non-structural strategies [16, 17], advantages and limitations, and literature background are traced by distinguishing which of them relate to OSs and their buildings.

These tables provide an overview of BE’s factors that can generally increase the decision-makers’ risk awareness. Some strategies can boost the individuals and goods safety, such as elevated floors, houses, and harvesting systems. Elevated floor houses are the easiest strategy to shelter-in-place the building occupants but can also be used by outdoor users if the access is ensured to passers-by [5]. However, they have limited reliability in specific contexts, such as historical scenarios. Other structural measures centred on the building preservation could impact on the original features of the OSs, resulting in limited conservation of morphologic and aesthetic elements of the BEs.

Risk reduction interventions are focused on reshaping public outdoor areas in the OS, and local authorities could easily perform them. They provide support to the evacuees’ safety (see Table 3). One of the simplest approaches is implementing unmovable street furniture in the OSs, which could be integrated by risk/wayfinding signage with sensors to support the smart BEs monitoring of EWS, especially in flash flood [14, 31, 40]. They limit the damage caused by floods and debris, and their position in the BE should depend on the hydrodynamics features and the evacuation plan [4, 5, 14].

**Table 1** Microscale factors as structural strategies influencing hazard

| Microscale factor | Non-struct. measures | Advantages/limitations | Refs |
|---|---|---|---|
| **OSs-related** | | | |
| Floodable areas | Urban planning | Control of peak flow/modifications in existing BEs to the ground profile | [41] |
| Permeable paving | Urban planning | Control of peak flow | [41] |
| Raised elements | Urban planning | Decreasing the floodwater speed/obstacles can also hold debris | [4] |
| Street furniture | Urban planning | Obstacles can hold debris; avoiding movable furniture | [4] |
| **Building-related** | | | |
| Green systems | Building codes, flood insurance | Control and reduction of peak flow and volume/not applicable on all existing buildings | [34] |
| Elevated floors houses | Building codes, land-use planning, flood insurance | Possibly restituting soil to permeable paving, thus reducing peak flow/not applicable on all existing buildings | [29] |
| Harvesting systems | Building codes | Reduction of peak flow and volume | [37] |
| Handrails/fences | Building codes supporting public–private interfaces | Obstacles can marginally hold debris | [4] |

**Table 2** Microscale factors as structural strategies influencing building damage

| Microscale factor | Non-struct. measures | Advantages/limitations | Refs |
|---|---|---|---|
| **OSs-related** | | | |
| EWS | Preparation and evacuation planning | Alert timing to perform protection actions for goods and chattels/precise alert depending on the severity of the event | [6, 12, 28] |
| **Building-related** | | | |
| Elevated floor houses | Building codes, land-use planning, flood insurance | Protecting buildings and indoors from damage | [29] |
| Floating and amphibious houses | Building codes, flood insurance | Protecting buildings and indoors from damage | [30] |
| Handrails/fences | Building codes supporting public–private interfaces, flood insurance | Protecting private areas from debris/avoiding movable elements | [4] |

**Table 3** Microscale factors as structural strategies influencing users' support

| Microscale factor | Non-struct. measures | Advantages/limitations | Refs |
|---|---|---|---|
| **OSs-related** | | | |
| Permeable paving | Urban planning | Control of peak flow and floodwater levels causing threats in users' movement/limited effects in some cases, e.g., flash events | [4, 38] |
| EWS | Preparation and evacuation planning | Direct stimuli to evacuation starting/public awareness and plan dissemination campaign needed | [5, 40] |
| Raised elements | Urban planning, evacuation planning | Direct support to people placed outdoors/to be considered in the evacuation plan to support people waiting for rescuers | [14] |
| Street furniture | Urban planning | Benches as raised elements; support to people to hang on them/placed along possible evacuation routes and high hazard areas; avoiding movable furniture | [14] |
| Wayfinding systems | Preparation and evacuation planning | Visible also in non-emergency conditions, direct support to reach a safe area/public awareness, training (e.g., VR) and plan dissemination campaign needed | [31] |
| **Building-related** | | | |
| Elevated floors houses | Building codes, urban planning | Direct safety of people initially placed indoor/impacts are limited to residential areas | [29] |
| Floating and amphibious houses | Building codes, evacuation plan | Direct safety of people initially placed indoor/impacts are limited to residential areas | [30] |
| Handrails/fences | Building codes supporting public–private interfaces | Direct support to people to hang on them/to be considered along possible evacuation routes and high hazard areas; avoiding movable elements | [14] |

Nonetheless, such strategies should be supported by preparedness and risk awareness-increasing non-structural measures to reduce the negative impact of individual's risk attitude and personal experiences in the population's response. Behaviours and personal risk perception can be trained through virtual reality (VR) experiments, where a flood condition is simulated safety [42]. As stated above, users'-OSs interactions significantly affect BEs' safety levels. Thus, risk assessment models and simulation tools should be built on microscale-based interactions to support safety planners in DRR-related activities. Furthermore, they can be integrated into wider-scale analysis on flood sources and spread globally [4–6, 14, 17] according to a Performance-Based Planning [10] standpoint. A plan should perform according to the agreed collective strategy, just like the performance-based design. Simulation-based approaches ensure the effectiveness of the strategies, combining management and structural actions, optimizing the complexity of physical interventions on BEs and OSs and the rescuers' actions [5, 19].

## 4 Conclusions

Flood risk in urban BEs depends on the microscale features of their OS, surrounding buildings, and hosted users. Therefore, the characterization of the composing elements in terms of influence on the flood hazard, building damage, and users' safety is crucial for defining risk reduction strategies. From this assumption, this work adopted a literature-based review to trace a list of microscale risk factors and countermeasures, evidencing how structural/non-structural strategies can be combined to ensure an adequate safety level in the BEs as well as the reliability of the planned solutions.

Real-world BEs can be analyzed according to the proposed risk reduction perspective to determine if typological and recurring conditions can be identified. This approach will boost the definition of the best practices for risk assessment and reduction depending on the specificities of the OSs. From the results of this work, the outline for detecting the composing elements of the BE, their features, and associated measures to provide support in the public decision-making process can be drawn.

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## References

1. Marinaro, C., et al.: Navigating the (in)formal city: Roma, urban life and governance in Rome. Cities (2020)
2. Russo, M., et al.: Morphological systems of open spaces in built environment prone to Sudden-onset disasters. In: International Conference on Sustainability in Energy and Buildings SEB 2020, Split, Croatia (2020)
3. Sharifi, A.: Urban form resilience: A meso-scale analysis. Cities (2019)
4. Mignot, E., Li, X., Dewals, B.: Experimental modelling of urban flooding: a review. J. Hydrol. (2019)
5. Lumbroso, D., Davison, M.: Use of an agent-based model and Monte Carlo analysis to estimate the effectiveness of emergency management interventions to reduce loss of life during extreme floods. J. Flood Risk Manag. (2018)
6. Ferreira, T.M., Santos, P.P.: An Integrated Approach for Assessing Flood Risk in Historic City Centres. Water. (2020)
7. Young, A.F., Jorge Papini, J.A.: How can scenarios on flood disaster risk support urban response? A case study in Campinas Metropolitan Area (São Paulo, Brazil). Sust. Cities Soc. **61** (2020)
8. European Commission: European Overview Assessment of Member States' reports on Preliminary Flood Risk Assessment and Identification of Areas of Potentially Significant Flood Risk (2015)
9. Jha, A.K., et al.: Cities and flooding: a guide to integrated urban flood risk management for the 21st century. The World Bank, GFDRR (2012)
10. Pappalardo, V., La Rosa, D.: Policies for sustainable drainage systems in urban contexts within performance-based planning approaches. Sustain. Cities Soc. (2020).
11. Postacchini, M., et al.: Flood impact on masonry buildings: The effect of flow characteristics and incidence angle. J. Fluids Struct. (2019)
12. Molinari, D., et al.: On the modeling of significance for flood damage assessment. Int. J. Disaster Risk Reduct. (2014)
13. Cox, R.J., et al.: Australian Rainfall and Runoff Revision Project 10: Appropriate Safety Criteria for People (2010)
14. Bernardini, G., at al.: Flooding risk in existing urban environment: from human behavioral patterns to a microscopic simulation model. Energy Procedia (2017)
15. Raikes, J., et al: Pre-disaster planning and preparedness for floods and droughts: a systematic review. Int. J. Disaster Risk Reduct. (2019)
16. UNISDR: UNISDR Terminology on Disaster Risk Reduction (2009)
17. van Berchum, et al.: Evaluation of flood risk reduction strategies through combinations of interventions. J. Flood Risk Manag. (2019).
18. Rana, I.A, et al.: Characterizing flood risk perception in urban communities of Pakistan. Int. J. Disaster Risk Reduct. (2020)
19. Opper, S.,et al.: Timeline modelling of flood evacuation operations. Proc. Eng. 3, (2010).
20. Fleischmann, et al.: Morphological tessellation as a way of partitioning space: Improving consistency in urban morphology at the plot scale. Comput. Environ. Urban Syst. (2020)
21. Dibble, J., et al.: Urban Morphometrics: Towards a Science of Urban Evolution (2015)
22. Kim, B., et al.: Urban flood modeling with porous shallow-water equations: A case study of model errors in the presence of anisotropic porosity. J. Hydrol. (2015)
23. Hossain, M.K., Meng, Q.: A fine-scale spatial analytics of the assessment and mapping of buildings and population at different risk levels of urban flood. Land use policy (2020)
24. Schubert, J.E.,et al.: Building treatments for urban flood inundation models and implications for predictive skill and modeling efficiency. Adv. Water Resour., (2012).
25. Venerandi, A., et al.: Form and urban change—an urban morphometric study of five gentrified neighbourhoods in London. Environ. Plan. B Urban Anal. City Sci. (2017)
26. Dibble, J.,et al.: On the origin of spaces: morphometric foundations of urban form evolution. Environ. Plan. B Urban Anal. City Sci. (2019)

27. Glenis, V., et al.: A fully hydrodynamic urban flood modelling system representing buildings, green space and interventions. Environ. Model. Softw. (2018).
28. Mignot, E., et al.: Measuring the flow intrusion towards building areas during urban floods: Impact of the obstacles located in the streets and on the facade. J. Hydrol. (2020)
29. Xian, S., et al: Optimal house elevation for reducing flood-related losses. J. Hydrol. (2017)
30. Rosso, F., et al.: Adapting towards resilience: analysis of the construction features and dynamic energy performance of amphibious and floating houses. Riv. Tema. **6** (2020)
31. Yamashita, S., et al: Smart adaptation activities and measures against urban flood disasters. Sustain. Cities Soc. **27** (2016)
32. Wang, H., et al: Are green roofs a source or sink of runoff pollutants? Ecol. Eng. (2017)
33. Fassman-Beck, et al.: 4 Living roofs in 3 locations: Does configuration affect runoff mitigation? J. Hydrol. (2013)
34. Ercolani, G., et al.: Evaluating performances of green roofs for stormwater runoff mitigation in a high flood risk urban catchment. J. Hydrol. (2018)
35. Pęczkowski, et al.: Hydrological performance and runoff water quality of experimental green roofs. Water (Switzerland) (2018)
36. Besir, A.B., Cuce, E.: Green roofs and facades : a comprehensive review. Renew. Sustain. Energy Rev. (2018)
37. Palla, A., et al.: The impact of domestic rainwater harvesting systems in storm water runoff mitigation at the urban block scale. J. Environ. Manage. (2017)
38. Bernardini, G., et al.: Towards the simulation of flood evacuation in urban scenarios: experiments to estimate human motion speed in floodwaters. Saf. Sci. (2020)
39. Seebauer, S., Winkler, C.: Should I stay or should I go? Factors in household decisions for or against relocation from a flood risk area. Glob. Environ. Chang. **60** (2020)
40. Bodoque, J.M.,et al.: Enhancing flash flood risk perception and awareness of mitigation actions through risk communication: A pre-post survey design. J. Hydrol. (2019).
41. Barker, R., Coutts, R.: Aquatecture: Buildings and Cities Designed to Live and Work with Water. RIBA Publishing (2016)
42. Carone, M.T., et al.: Can a simulated flood experience improve social resilience to disasters? Prof. Geogr. (2019)

# Low-Cost Architectural Strategies to Reduce Heat Stress in Social Housing for Hot Desert Climates

**Carlos Lopez-Ordoñez, Isabel Crespo Cabillo, Jaume Roset Calzada, and Helena Coch Roura**

**Abstract** Achieving thermal comfort inside buildings in a region with a hot desert climate is challenging, especially in social housing, which is generally not designed or built suitably for these climates. Two well-known architectural strategies for reducing heat stress in these houses are thermal insulation and solar protection by shading. However, under free-running conditions, doubts arise about the effectiveness of these strategies. The social housing of the city of Hermosillo is exclusively single-family housing. The city has a hot desert climate with an average annual temperature of 25 °C and a mean oscillation of 15 °C. During the hot season, there are recurring peaks above 48 °C. This study aims to evaluate three low-cost architectural strategies to reduce heat stress in a single-family social house under free-running conditions; adding thermal insulation to walls and windows, adding sun protection to windows, and solar protection to the roof. The results show that both the use of thermal insulation and solar protections achieve improvements in the indoor thermal conditions of the house. However, when considering the warmer months, the solar protection strategies perform better in reducing indoor heat stress in terms of discomfort hours.

## 1 Introduction

Climate change is taking us to an increase in ambient temperatures and the frequency, duration, and intensity of extreme heat events worldwide [1]. This effect is particularly severe in the desert climate regions. At present, more than 40% of the Earth's surface is considered dryland and concentrates about one-third of the world population; further, approximately 70% of the drylands are located in developing countries. Within the drylands, the arid and hyper-arid regions (deserts) are home to almost 6% of the world's population [2]. The extreme conditions of desert climates pose a series of challenges from an energetic and social development perspective.

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Achieving thermal comfort inside buildings is complicated in regions with extreme climates, such as hot deserts. There are several studies on different strategies to improve the indoor environment in this climate. Some of the strategies are the increment of the reflectance of surfaces [3, 4] and solar protection on both windows and roofs [5, 6]. Other passive design strategies such as evaporative cooling, natural night ventilation, solar chimneys, wind towers, and thermal mass [7] have also been studied. Regarding the use of thermal insulation, these studies usually consider the presence of refrigeration, while the parameters analyzed are usually its placement and thickness [8–10].

This task is even more challenging when it comes to social housing, usually poorly built and equipped, since the owners of these single-family houses are low-income citizens. These houses have characteristics that make them unsuitable for the climate, generally lacking thermal insulation and solar protection. This problem persists despite the existence of different official standards on the energy efficiency of buildings, such as NORM-020-ENER-2011 [11] that establishes the U-values and solar protection factors for different regions of Mexico and is not put into practice by the social housing private developers.

Since a large part of this population cannot afford the installation and the use of air conditioning systems, it is necessary to provide economical and robust solutions to improve the thermal conditions of the house in free-running conditions.

## 2 Objective

This study aims to compare the effectiveness of three common low-cost architectural strategies to improve indoor thermal conditions: thermal insulation and two different approaches to solar protection. In a hot desert climate, solar radiation is the main source of heat gains in buildings, making it a key parameter to consider in achieving indoor thermal comfort [12]. The study is carried in a dispersed and low-density city with a hot desert climate, characterized by almost exclusively single-family houses with a high air conditioning demand during the hot season [13].

## 3 Case Study

### *3.1 Site Description*

This study takes place in Hermosillo (lat. 29 N), a city located in the Sonoran desert in northwestern Mexico (see Fig. 1). This city has a hot desert climate (BWh in the Köppen climate classification), with an average annual temperature of 25 °C, a mean oscillation of 15 °C, and precipitation of 387 mm (Table 1) [14, 15].


**Fig. 1** Location of Hermosillo in relation to Mexico (left), and the urban area of the city (right). Author's elaboration on Google Earth

**Table 1** Monthly data of average maximum temperature (AMT), mean temperature (MT), average minimum temperature (AmT), relative humidity % (RH), and global horizontal radiation (kWh/m$^2$)

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AMT ºC | 24.2 | 25.8 | 28.7 | 32.3 | 36.3 | 39.8 | 39.3 | 38.3 | 37.5 | 33.9 | 28.6 | 24.0 |
| MT ºC | 17.2 | 18.5 | 20.9 | 24.1 | 27.9 | 31.8 | 32.5 | 31.9 | 31.0 | 26.9 | 21.3 | 17.1 |
| AmT ºC | 10.2 | 11.3 | 13.1 | 15.9 | 19.4 | 23.8 | 25.8 | 25.6 | 24.6 | 19.8 | 14.0 | 10.2 |
| HR (%) | 48 | 44 | 40 | 34 | 31 | 34 | 48 | 53 | 48 | 42 | 43 | 49 |
| kWh/m$^2$ | 3.88 | 4.76 | 6.34 | 7.45 | 7.73 | 7.59 | 7.07 | 6.88 | 5.74 | 5.23 | 4.11 | 3.25 |

Although Hermosillo's climate may seem mild on average, it presents extreme climate conditions for more than half the year. During the hot season, which lasts between May and October, the average maximum temperatures range between 34 and 40 °C, and peaks above 48 °C are recurrent. As a desert city, it has high levels of solar radiation. Hermosillo has an annual mean solar radiation of 5.85 kWh/m$^2$ per day. Though, during the hot season, the mean solar radiation is 6.7 kWh/m$^2$ per day.

For the last century in this region of North America, there has been an increase in the average temperature. In Hermosillo, this increase is more noticeable during the hot season. In the last fifty years, there has been an increase of around 2ºC in the average temperature this season (see Fig. 2).

## 3.2 *The Single-Family Social House*

Hermosillo has a high percentage of social housing built in the last three decades, made up exclusively of single-family homes. A worker can acquire a house through a loan granted by the government (INFONAVIT, FOVISSSTE) and pay for it through monthly installments taken from the worker's salary. These houses are classified into

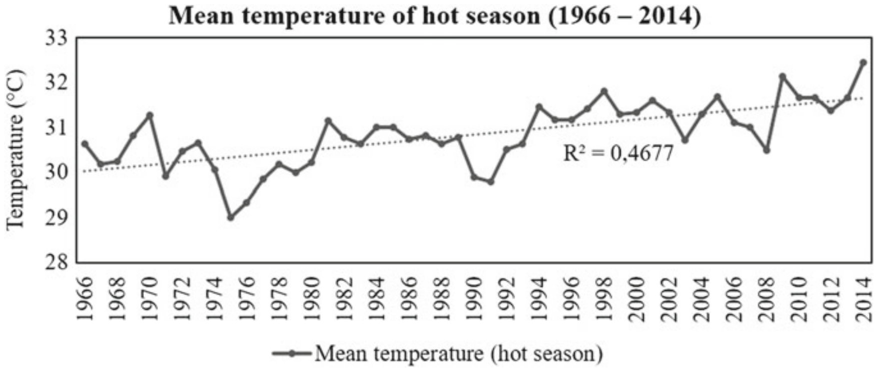


**Fig. 2** Chart that shows the mean temperature change, from 1966 to 2014. There is an increase of almost 2 °C. Authors' elaboration with data from the Municipality of Hermosillo [16]

three basic categories: social-interest, medium-interest, and residential housing. The one with the greatest presence and the largest number of inhabitants is the social-interest housing [17]. These houses are the smallest (25–90 $m^2$) and the construction is cost-effective since they are produced in mass, causing that the quality of the house and an efficient energy design are not a priority, resulting in excessive use of energy with high air conditioning costs [18]. This represents a serious problem for the 41% of the population that lives with less than 3 minimum wages monthly (less than 300 euros), and the 23% receives a monthly income between 300 and 500 euros [19].

The house analyzed in this work is located in a plot 8 × 14 m (112 $m^2$). It has a living area of 51 $m^2$ and an interior height of 2.5 m. Like most houses, it has light colors on its façade and white roof, an outdoor parking space, and a backyard. The lack of vegetation to shade the living areas, the façade and the parking area is a constant in this type of housing (see Fig. 3).

## 4 Methodology

This study assesses the thermal behavior of a single-family social house during the hot season (May 1st–October 31st) in four different cases:

1. Base case (walls of concrete block of 0.15 m thickness, the roof has a 0,12 m of thickness, and consists of precast concrete joists and EPS vaults that act as thermal insulation, and simple 4 mm clear glass for the windows);
2. Case "A": Adding thermal insulation on walls and windows (roof + walls + windows);
3. Case "B": Adding solar protection on windows;
4. Case "C": Adding solar protection over the roof.


**Fig. 3** Photograph of a social housing neighborhood, our model is based in these houses. Photograph taken from Google Earth

The analysis consists of dynamic thermal simulations using DesignBuilder (with EnergyPlus as the calculation engine) [20]. The parameter used to analyze the results is the indoor air temperature. The weather data used from the EPW file is from the Hermosillo International Airport. We evaluated the performance of each intervention based on the number of hours of discomfort and the accumulated degree-hours. These mean the number of hours with an indoor temperature exceeding a temperature value considered "neutral" for people acclimated to this climate (32 °C) [21] and the degrees accumulated for each hour above 32 °C. We quantified these values throughout the hot season and during the two warmest months (July and August).

The geometry, materials, orientation, and the architectonic distribution of the model used for the simulations, respond to the predominant building typology (see Fig. 4). The thermal transmittance, U (W/m$^2$K), of the different elements of the house envelope is as follows: for the Base Case, the walls have a U-value of 2.75 W/m$^2$K;

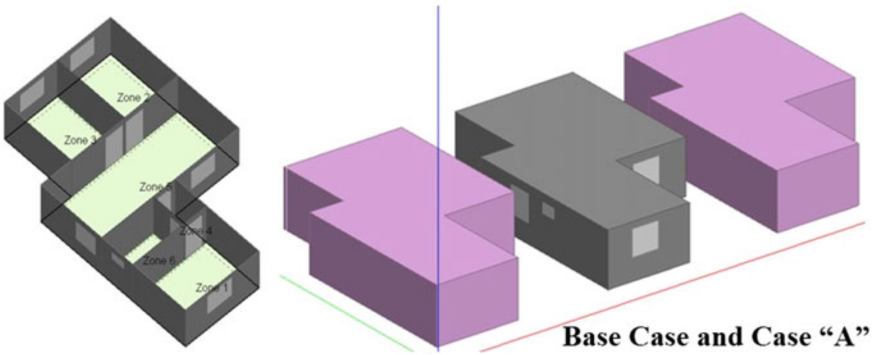


**Fig. 4** Simulation model. It has a north–south orientation, with no adjacency between houses

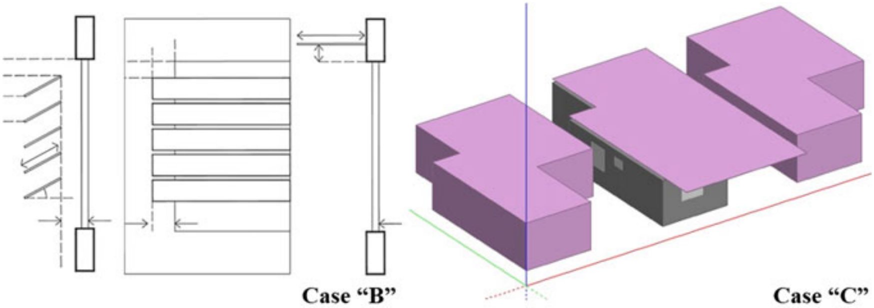


**Fig. 5** Windows solar protection system for Case "B" (used in all windows), and simulation model with a double roof used for Case "C" (shading the roof and south-facing windows)

the roof has a U-value of 1.35 W/m$^2$K; the ground floor U-value is 2.80 W/m$^2$K, and the U-value of the windows is 5,80 W/m$^2$K. For Case A, these U-values are modified in the walls (0.91 W/m$^2$K) by adding a 0.025 m XPS plate (extruded polystyrene); and on windows (3.08 W/m$^2$K) by changing the 4 mm single clear glass to a 6 mm double clear glass + 6 mm air gap. We decided not to insulate the ground floor since its effect is counterproductive in non-conditioned buildings in a hot desert climate [22].

In Case "B", we used a system of gray color metal louvers, overhangs, and side fins to provide solar protection on the windows. In Case "C", for the solar protection of the roof, we added a double roof (a white light metal hat), large enough to protect the concrete roof and south façade windows (see Fig. 5). This system also allows for ventilation between the roofs.

The level of solar protection on windows provided by these two strategies is different. In Case B, with the louvers system, the house receives 209 kWh of direct solar gains throughout the hot season, while in Case C, the windows have a solar gain of 1185 kWh during the same period. Thus, considering that the Base Case receives 1793 kWh, these strategies represent a reduction of 88% and 34% respectively.

We utilized the work that Irene Marincic [23] carried out in Hermosillo during August and September (daily from 8:00 to 19:00) to validate the simulations in this study. They measured and collected hourly data on indoor air temperature, relative humidity, wind speed, and mean radiant temperature from 143 houses and calculated the operating temperature (see Fig. 6). In all cases, the measured values are in a range between 25 and 40 ºC. We used the air temperature ($T_a$) and the operative temperature ($T_{op}$) data to validate our simulations. To do this, we utilized two models of social housing with different living areas (51 m$^2$ and 41 m$^2$), and we simulated their thermal behavior during August and September. To calculate the operative temperature, we used the simplified formula $T_{op} = (T_a + MRT)/2$, where MRT is the mean radiant temperature.

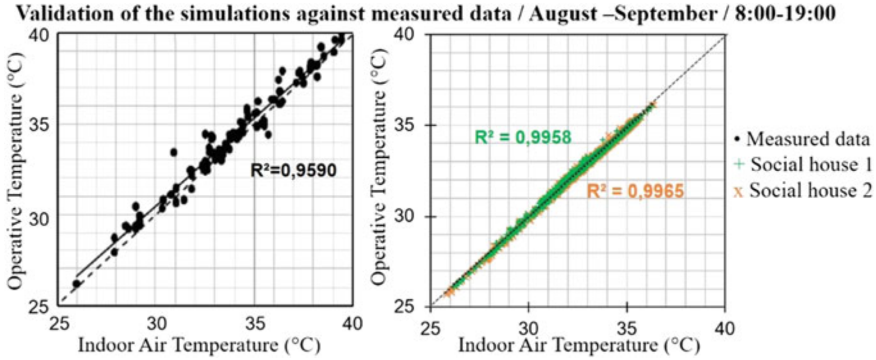


**Fig. 6** Simulation results of two houses ($R^2 = 0.9958$, $R^2 = 0.9965$) contrasted against the data measured in 143 houses ($R^2 = 0.959$) during August and September

The graph on the right shows the mean indoor air temperature and operative temperature data for the two houses. Both houses have similar behavior to the measured data (chart on the left). In these cases, the values obtained through simulations are also in the same temperature range (25–40 ºC).

## 5 Results and Discussion

To ease the discussion the four cases analyzed will be referred to as the base case, case "A" (insulation in roof, walls and windows), case "B" (solar protection on windows), and case "C" (solar protection over the roof). All the cases present the same occupation (4 users, as the only internal gain) and a ventilation rate of 4 ac/h, with an infiltration rate of 0.7 ac/h. It was necessary to analyze the indoor thermal behavior of the four cases during the entire hot season. Figure 7 shows that the three thermal improvement strategies have similar performance, with a seasonal mean

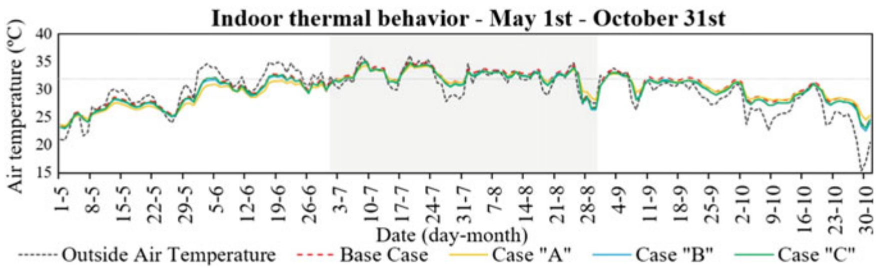


**Fig. 7** Chart with the outside air temperature, the 32 ºC for indoor "neutral" temperature, and the indoor temperature behavior for all cases

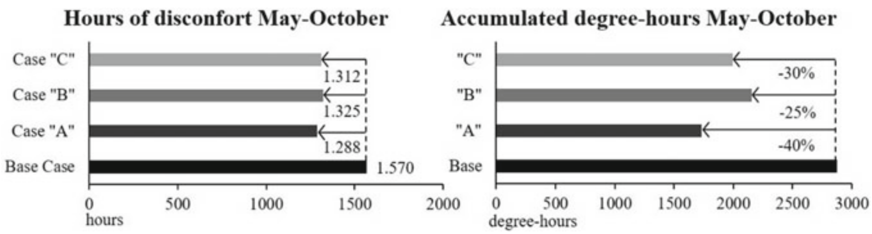


**Fig. 8** These charts show the results of the two comfort indicators for the entire hot season

indoor air temperature of 30.2 ºC. The base case averages an indoor air temperature of 30.5 ºC.

These similarities are more evident during July and August. Figure 8 shows that in the three interventions, the house is out of comfort (hours above 32 ºC) for around 30% (1.288–1.325 h), while the base case is for 37% (1.570 h) of the season. Nevertheless, when analyzing the accumulated degree-hours, the differences among the strategies can be observed. Case "A" represents a reduction of 40% to the base case, the case "B" a 25%, and the case "C" reduces a 30%.

However, when considering only the warmest months (July and August), different results are produced between the three thermal improvement strategies (Fig. 9). The two interventions that increase solar protection, whether on the windows (case "B) or roof (case "C"), manage to decrease discomfort, passing from the 63% (941 h) of the time out of comfort in the Base Case to a 56% (844–851 h) in the refurbished scenario. In contrast, the intervention with higher thermal insulation maintains the initial 63% (938 h) over the neutral temperature of 32 °C.

Nonetheless, when comparing the accumulated degree-hours, the results are different. Case "A" (+ thermal insulation) reduces this indicator by around 28% regarding the base case. Cases "B" and "C" represent a reduction of 20% and 25% each in order.

Based on the results obtained, some doubts about the use of thermal insulation arise. On the one hand, the use of thermal insulation (case "A") reduces the oscillation of the indoor air temperature (see Fig. 10), thus is beneficial when considering the number of accumulated degree-hours (above 32 ºC). However, on the other hand,

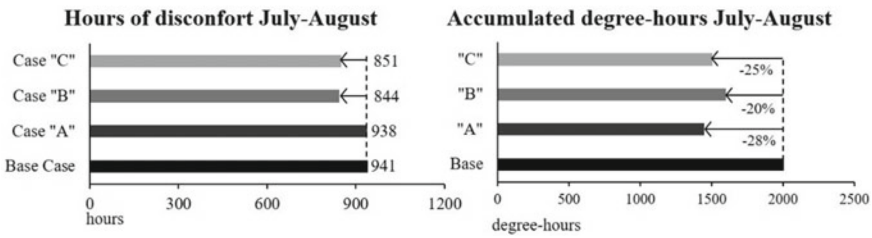


**Fig. 9** These charts show the results of the two comfort indicators for July and August

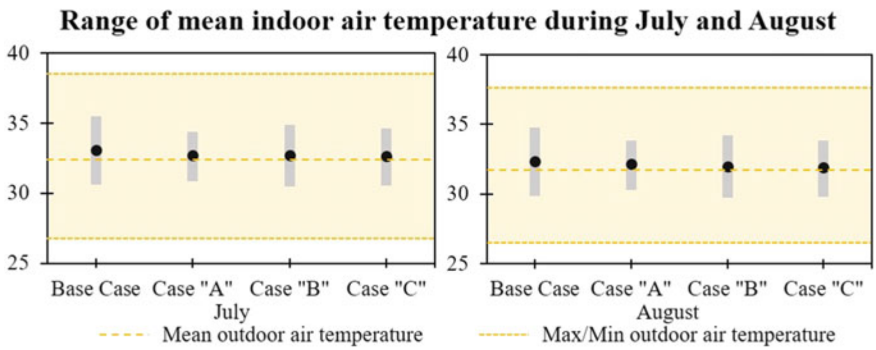


**Fig. 10** These two charts show the range of mean air temperature during the hottest months

thermal insulation does not allow an easy heat dissipation in the house, thus maintaining an indoor air temperature above 32 ºC for more hours. This behavior is more noticeable during the warmest months, though is present in the last 4 months of the hot season (see Fig. 7).

In the case of architectural strategies based on solar protection, it can be said that case "C" with a double roof, has a slightly better performance than case "B" (solar protection on the windows). During the hot season, both have a similar number of hours above 32ºC ("B" 1.325 and "C" 1.312), and a difference of around 5% in the number of accumulated degree-hours in favor of case "C". In July and August, case "B" has 844 h and case "C" 851, but the latter maintains the difference of 5% in the number of degrees accumulated.

## 6 Conclusions

This paper studied the effectiveness of three low-cost architectural strategies to reduce heat stress in social housing under free-running conditions in a hot desert climate.

The methods used to evaluate the strategies' performance (hours of discomfort and accumulated degree-hours) are useful to understand the difference in the thermal behavior of each case. The results obtained indicate that before making a decision, it is necessary to analyze the socio-economic situation and the user's profile of each household.

On the one hand, thermal insulation may not be the best option for a home that can't afford air conditioning. Although the temperature peaks are not as high as in the other strategies, the thermal insulation itself favors maintaining a high indoor temperature. On the other hand, solar protection strategies allow an oscillation of the indoor temperature, reaching higher temperatures, but at the same time, arriving to lower temperatures than a house with thermal insulation. However, if the house is refrigerated, the strategy based on thermal insulation will be the most effective. It will maintain a suitable indoor temperature and lower energy consumption.

The findings of this paper help to prioritize architectural interventions aimed at improving thermal conditions in social housing. Analysis under free-running conditions is essential to decrease the risk of energy poverty in vulnerable populations.

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## References

1. Garcia-Nevado, E., Duport N., Bugeat, A., Beckers, B.: Benefits of street sun sails to limit building cooling needs in a Mediterranean city. Build. Environ. **187**, 107403 (2020)
2. Safriel, U., et al.: Chapter 22: drylands systems. In: Ecosystems and Human Well-being: Current state and Trends, vol. 1. Island Press, Washington, DC (2005)
3. De Boeck, L., et al.: Improving the energy performance of residential buildings: a literature review. Renew. Sustain. Energy Rev. **52**, 960–975 (2015)
4. Alpuche Cruz, M.G., et al.: Influence of absorptance in the building envelope of affordable housing in warm dry climates. Energy Procedia **57**, 1842–1850 (2014)
5. Sherif, A., El-Zafarany, A., Arafa, R.: External perforated window Solar Screens: the effect of screen depth and perforation ratio on energy performance in extreme desert environments. Energy Build. **52**, 1–10 (2012)
6. Galindo Duarte, M., et al.: Sistema De Protección Del Aislamiento E Impermeabilización De Techos Evaluación De Viviendas Del Desierto. Energética **40**, 5–12 (2008)
7. Osman, M., Sevinc, H.: Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan. Sustain. Cities Soc. **47** (2019)
8. Idris, Y., Mae, M.: Anti-insulation mitigation by altering the envelope layers' configuration. Energy Build. **141**, 186–204 (2017)
9. Calderón, R., et al.: Electrical consumption and $CO_2$ reduction using saving systems and thermal insulation applied to dwellings in arid lands of Mexico. Información Tecnológica **22**(2) (2011)
10. Friess, W.,A., et al.: Wall insulation measures for residential villas in Dubai: a case study in energy efficiency. Energy and Build. **44**(1) (2012)
11. Normas Oficiales Mexicanas en Eficiencia Energética -Edificaciones-, https://www.gob.mx/conuee/acciones-y-programas/normas-oficiales-mexicanas-en-eficiencia-energetica-edificaciones/. Last accessed 8 June 2021
12. Coch, H.: Bioclimatism in vernacular architecture. Renew. Sustain. Energy Rev. **2**(1–2), 67–87 (1998)
13. Wegener, M., Lopez-Ordoñez, C., Isalgue, A., Malmquist, A., Martin, A.: How much does it cost to go off-grid with renewables? A case study of a polygeneration system for a neighborhood in Hermosillo, Mexico. In: Littlewood, J., Howlett, R., Capozzoli, A., Jain, L. (eds.) Sustainability in Energy and Buildings. Smart Innovation, Systems and Technologies, vol 163. Springer, Singapore (2020)
14. Servicio Meteorológico Nacional (SMN): Normales Climatológicas, Hermosillo II (DGE). https://smn.conagua.gob.mx/es/informacion-climatologica-por-estado?estado=son. Last accessed 30 March 2021
15. LEMA, Estación Meteorológica, https://lema-arq.unison.mx/. Last accessed 20 Nov 2020

16. IMPLAN Hermosillo, http://www.implanhermosillo.gob.mx. Last accessed 30 March 2021
17. Lopez-Ordoñez, C.: Planificación urbana en ciudades dispersas de clima desértico: La densificación vertical como estrategia para la mejora ambiental. El caso de Hermosillo (México). Universitat Politècnica de Catalunya, Barcelona (2020)
18. Marincic, I., Ochoa, J.M., Alpuche, G.: Passive house for a desert climate. In: Brebbia, C.A., Pulselli, R. (eds.) Eco-Architecture V. Harmonization Between Architecture and Nature 2014, pp. 13–24. WIT press, Southampton (2014)
19. INEGI. https://www.inegi.org.mx/. Last accessed 30 March 2021
20. DesignBuilder Software Ltd, https://www.designbuilder.co.uk/. Last accessed 30 March 2021
21. Marincic, I., Ochoa, J.M., Del Rio, J.A.: Confort térmico adaptativo dependiente de la temperature y la humedad. ACE Architecture, City and Environment **07**(20), 27–46 (2012)
22. Lopez-Ordoñez, C., Crespo Cabillo, I., Roset Calzada, J., Coch Roura, H.: The role of thermal insulation in the architecture of hot desert climates. In: Littlewood, J., Howlett, R., Capozzoli, A., Jain, L. (eds.) Sustainability in Energy and Buildings. Smart Innovation, Systems and Technologies, vol. 163. Springer, Singapore (2020)
23. Gomez-Azpeitia, L., Bojorquez-Morales, G., Ruiz, R.P., Marincic, I., Gonzalez, E., Tejeda, A.: Extreme adaptation to extreme environments in hot dry, hot sub-humid and hot humid climates in Mexico. J. Civil Eng. Archit. **8**(8), 929–942 (2014)

# Field Performance of HVAC System Under Healthy and Faulty Conditions During the Summer: Preliminary Development of a Simulation Model Based on Artificial Neural Networks

**Antonio Rosato, Sergio Sibilio, Francesco Guarino, Mohammad El Youssef, Evgueniy Entchev, and Luigi Maffei**

**Abstract** The dynamic behaviors of the heating, ventilation and air-conditioning (HVAC) system serving the integrated test room of the SENS i-Lab of the Department of Architecture and Industrial Design of the University of Campania Luigi Vanvitelli (Aversa, south of Italy) has been experimentally characterized by means of a series of tests performed during the summer under fault free and faulty operation (5 typical faults have been investigated) upon varying the boundary conditions. An artificial neural network-based model of the HVAC system has also been developed in the MATLAB environment and validated in contrast with the measured data with the aim of producing operation data to assist further research in control, fault detection and diagnosis of HVAC units. Finally, the validated artificial neural network has been coupled with a dynamic TRNSYS simulation model and used to assess the impact of the selected faults on both energy performance as well occupant indoor thermo-hygrometric comfort.

## 1 Introduction

Heating, ventilation and air-conditioning (HVAC) systems in the developed countries account for 10–20% of the total energy share in buildings and for 50% of the energy demand in commercial buildings. It is well acknowledged that the existence of faults (deviations from normal or expected operation) in HVAC systems impacts building energy consumption, occupant comfort, maintenance cost, and equipment life cycle. A study conducted on more than 55,000 HVAC units showed that 90% of them runs with one or multiple faults [1]. Yu et al. [2] highlighted that (i) typical faults of HVAC

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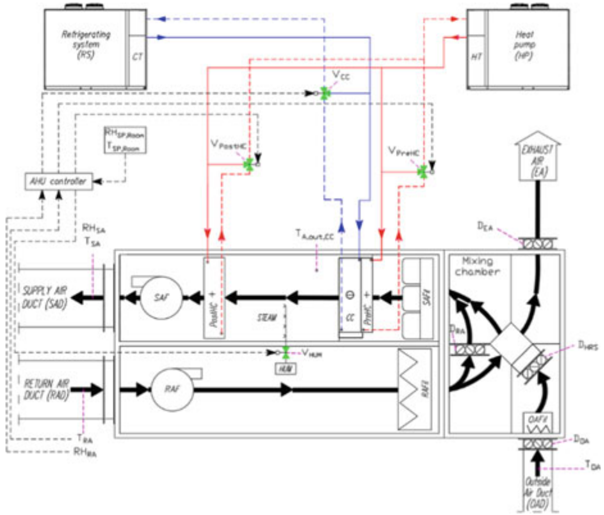
systems are responsible for 25–50% of energy waste in buildings located in the United Kingdom, and (ii) this inefficiency could be strongly decreased below 15% thanks to early detection and identification of faulty operation. Yan et al. [3] estimated that the identification and diagnosis of faults in HVAC units can lead to potential savings of about 30%. Generally, a reactive maintenance or a preventive maintenance for HVAC units is adopted; both approaches are characterized by a number of critical points [4, 5] that can be overcome by means of automatic fault detection and diagnosis (AFDD) [2]. AFDD methods can detect as well as predict the presence of the defects; ideally, AFDD approaches could also diagnose the type of problem and/or identify its location, giving instructions for undertaking corrective actions. Advanced methods of fault detection are based on system and process modelling to generate fault symptoms, while fault diagnosis methods use causal fault-symptom relationships. The methods used for performing an AFDD analysis can be classified in quantitative model-based, qualitative model-based and data driven-based. In the last few years, the data-driven approach for the AFDD analysis gained more and more interest and vendors are beginning to use data driven methodologies for addressing AFDD tasks [6]. Data-driven based AFDD tools need a proper amount of data for the development of models and cannot extrapolate beyond the range of training data (typically derived from HVAC recommissioning or simulated data) [6]. Even if several scientific works focusing on data-driven AFDD methods are available in the literature [4, 6], most of them are based on the ASHRAE RP-1312 data set dated 2010 [6]; few studies supply detailed information about how the faults experimentally implemented in a real HVAC system or modeled [6, 7]; fewer studies describe how their simulated faulty operation data are validated [6, 7]; nearly all studies only consider one HVAC operation condition with changing weather conditions [6]; not many studies quantitatively examine how various faults and fault severities impact energy consumption, user comfort, maintenance cost and equipment life cycle [6]. In this paper the dynamic behaviors of the heating, ventilation and air-conditioning (HVAC) system serving the integrated test room of the SENS i-Lab of the Department of Architecture and Industrial Design of the University of Campania Luigi Vanvitelli (Aversa, south of Italy) has been firstly experimentally characterized by means of a series of tests performed during the summer under fault free and faulty operation (5 typical faults have been investigated) upon varying the boundary conditions. In the MATLAB [8] environment an optimal artificial neural network-based model has also been trained, tested and validated in contrast with the measured fault free and faulty data to assist further research in control, fault detection and diagnosis of HVAC units. Finally, the optimal artificial neural network has been coupled with a dynamic simulation model developed in TRNSYS environment [9] and then used to assess the impact of the selected faults on both energy performance as well as indoor thermo-hygrometric comfort.

## 2 Description of the Experimental Set-Up

The SENS i-Lab is an innovative, multi-sensorial and multi-purpose laboratory consisting of an integrated test room served by a HVAC system, including an air-handling unit (AHU), able to control the indoor air temperature, relative humidity, velocity and quality. The integrated test room is characterized by a floor area of 16.0 $m^2$, with a height of 3.6 m; it is composed of four vertical walls, a horizontal ceiling as well as a horizontal floor; it is located inside a large open space of the department. Figure 1 reports the schematic of the AHU together with its main components.

Table 1 describes the main characteristics of the AHU components. The heat carrier fluid is a mixture of water and ethylene glycol (90/10% by volume). The model ANL 050HQ [10] is used as electric heat pump (HP), while the model ANL 050Q [10] is adopted as refrigerating system (RS). A 75 L cold thermal energy tank (CT) as well as a 75 L hot thermal energy storage (HT) are coupled with the refrigerating unit and the heat pump, respectively, in order to store the cold/hot heat carrier fluid. The AHU is fully equipped in order to monitor, control and record the key parameters of the system. The main characteristics of the sensors are reported in Table 2. The AHU is operated according to a specific control logic. In particular, the following parameters are manually set (and eventually modified during the test) by the end-users: (i) the desired targets of both indoor air temperature ($T_{SP,Room}$) and relative humidity ($RH_{SP,Room}$) to be achieved inside the test room; (ii) the deadbands $DB_T$ and $DB_{RH}$ for both $T_{SP,Room}$ and $RH_{SP,Room}$, respectively; (iii) the flow rate of both the return air fan ($OL_{RAF}$) and the supply air fan ($OL_{SAF}$); (iv) the opening percentages of the return air damper ($OP_{DRA}$), the outside air damper ($OP_{DOA}$), the exhaust air damper ($OP_{DEA}$); (v) the activation of the static heat-recovery system damper ($OP_{DHRS}$). Once the previous parameters are manually set by the end-users, the opening percentages of the valves ($OP_{V\_PreHC}$, $OP_{V\_PostHC}$, $OP_{V\_CC}$ and $OP_{V\_Hum}$) are automatically managed in the range $0 \div 100\%$ by PID (proportional-integral-derivative) controllers in order to achieve the desired targets inside the test room. However, alternatively the end-users can also manually force (at the beginning or during the test) the opening percentages of the valves ($OP_{V\_PreHC}$, $OP_{V\_PostHC}$, $OP_{V\_CC}$ and $OP_{V\_Hum}$) for research purposes. The refrigeration system operates in order to maintain a temperature $T_{CT}$ of 7 °C inside the cold tank, while the heat pump is activated with the aim of achieving a temperature $T_{HT}$ of 45 °C inside the hot tank. The air flow rate moved by the supply air fan can be varied between 0 ($OL_{SAF} = 0\%$) and 1080 $m^3/h$ ($OL_{SAF} = 100\%$), while the air flow rate of the return air fan is in the range from 0 ($OL_{RAF} = 0\%$) up to 1460 $m^3/h$ ($OL_{RAF} = 100\%$); the maximum electric consumption of the SAF and RAF are, respectively, 1.22 kW and 0.48 kW. The parameters $OP_{DRA}$, $OP_{DOA}$ and $OP_{DEA}$ can be varied in the range 0–100%, where 100% means that the damper is fully open. The parameter $OP_{DHRS}$ can be set to 100% (the heat recovery does not occur) or 0% (the heat recovery from return air flow takes place). Even if the AHU is equipped with a pre-heating coil, this component has been always manually de-activated during the tests.




3-way valve of cooling coil ($V_{CC}$)
3-way valve of post-heating ($V_{PostHC}$)
3-way valve of pre-heating coil ($V_{PreHC}$)
Cold tank (CT)
Cooling coil (CC)
Cross flow static heat recovery system (HRS)
Damper of heat recovery system ($D_{HRS}$)
Exhaust air dumper ($D_{EA}$)
Heat pump (HP)
Hot tank (HT)
Humidifier (Hum)
Humidifier valve ($V_{Hum}$)
Outside air duct (OAD)
Outside air dumper ($D_{OA}$)
Outside air filter (OAFil)
Post-heating coil (PostHC)
Pre-heating coil (PreHC)
Refrigerating system (RS)
Return air duct (RAD)
Return air dumper ($D_{RA}$)
Return air fan (RAF)
Return air filter (RAFil)
Supply air duct (SAD)
Supply air fan (SAF)
Supply air filter (SAFil)

**Fig. 1** Schematic of the air-handling unit (AHU) serving the integrated test room

**Table 1** Characteristics of main AHU components

| | | |
|---|---|---|
| Supply (SAF)/Return (RAF) air fan | Nominal supply/return air flow rate ($m^3$/h) | 600/600 |
| Cross flow heat recovery system (HRS) | Nominal Efficiency (%)/ Nominal recovery capacity (kW) | 74.7/3.1 |
| Pre-heating coil (PreHC) | Nominal heating capacity (kW) | 4.1 |
| | Nominal heat carrier fluid/air flow rate ($m^3$/h) | 0.710/600 |
| Colling coil (CC) | Nominal cooling capacity (kW) | 5.0 |
| | Nominal heat carrier fluid/air flow rate ($m^3$/h) | 0.860/600 |
| Humidifier (Hum) [11] | Nominal steam capacity (kg/h)/Nominal power (kW) | 5.0/3.7 |
| Post-heating coil (PostHC) | Nominal heating capacity (kW) | 5.0 |
| | Nominal heat carrier fluid/air flow rate ($m^3$/h) | 0.860/600 |
| Heat Pump (HP)/Refrigerating System (RS) [10] | Nominal capacity (kW) | 14.0/13.4 |
| | Nominal input power (kW) | 4.75/4.48 |
| | Nominal heat carrier fluid flow rate ($m^3$/h) | 2.41/2.31 |

**Table 2** Characteristics of the sensors used for the AHU monitoring

| Model | Monitored parameter | Measuring range | Accuracy |
|---|---|---|---|
| Siemens QFM2160 [12] | Return air temperature $T_{RA}$ | 0 ÷ 50 °C | ± 0.8 K |
| | Return air relative humidity $RH_{RA}$ | 0 ÷ 100% | ± 3% |
| Siemens QFM2160 [12] | Supply air temperature $T_{SA}$ | 0 ÷ 50 °C | ± 0.8 K |
| | Supply air relative humidity $RH_{SA}$ | 0 ÷ 100% | ± 3% |
| Siemens QAM2161.040 [12] | External air temperature $T_{OA}$ | −50 ÷ 50 °C | ± 0.75 K |
| Siemens QAM2161.040 [12] | Air temperature $T_{A,out,CC}$ at outlet of the CC | −50 ÷ 50 °C | ± 0.75 K |
| TSI 7575, 982 IAQ [13] | Air temperature outside the room $T_{BEA}$ | −10 ÷ 60 °C | ± 0.50 K |
| | Air relative humidity outside the room $RH_{BEA}$ | 5 ÷ 95% | ± 3% |

## 3 Experimental Tests

Nine experiments have been carried out to investigate the HVAC system behavior during steady-state and transient operations under summer conditions; in particular, 4 tests (n. 1, 2, 3, 4) have been performed under healthy conditions, while the remaining

5 tests (n. 5, 6, 7, 8, 9) have been carried out while artificially introducing 5 specific typical faults by manually forcing the operation of related HVAC components. Table 3 describes the operating conditions of the normal and faulty operation tests. The experiments have been performed by measuring the parameters indicated in Table 2 every 1 min. During all tests the following parameters have been maintained constant: $T_{SP,Room} = 26$ °C, $RH_{SP,Room} = 50\%$, $DB_T = 1$ °C, $DB_{RH} = 5\%$, $OP_{DRA} = 100\%$, $OP_{DOA} = 20\%$, $OP_{DEA} = 20\%$ and $OP_{DHRS} = 100\%$. In addition, during the faulty operation tests specific conditions have been forced in order to artificially simulate 5 specific faults: in particular, during the test n. 5 the velocity of supply air fan has been fixed at 20% (fault 1), during the test n. 6 the velocity of return air fan has been fixed at 20% (fault 2), during the test n. 7 the opening percentage of the valve regulating the flow entering the post-heating coil has been always closed (fault 3), during the test n. 8 the opening percentage of the valve regulating the flow entering the cooling coil has been always closed (fault 4) and during the test n. 9 the opening percentage of the valve regulating the flow entering the humidifier has been always closed (fault 5).

The experimental data under normal and faulty operation highlighted that the percentages of time during which the indoor air temperature is within the given deadband (1 °C) around the given target (26 °C) are equal to 69.8%, 57.0%, 71.3%, 69.1%, 0%, 36.1%, 13.4%, 0% and 86.6%, for the tests 1–9, respectively. In addition, the percentages of time during which the indoor air relative humidity is within the given deadband (5%) around the given target (50%) are equal to 98.4%, 84.9%, 83.5%, 88.3%, 16.2%, 80.6%, 88.1%, 90.6% and 65.4%, during the tests 1–9, respectively.

## 4 Artificial Neural Network-Based Models

In this paper the MATLAB (The MathWorks Inc.) Neural Network Toolbox [8] has been used for the development of twelve artificial neural network (ANN)-based simulation models of the HVAC system. An ANN is a type of artificial intelligence that mimics the behavior of the human brain; it can learn and reproduce the behavior of data time series without requiring explicit mathematical representations [14]. The artificial neural networks ANN1-ANN12 have been developed with the 10 inputs and 5 outputs, while differing in terms of hidden layers and neurons in each hidden layer (Table 4).

The following ten variables have been set as inputs of all ANNs: (1) difference between return air temperature and related target, (2) difference between return air relative humidity and related target, (3) supply air temperature at previous minute, (4) supply air relative humidity at previous minute, (5) outside air temperature, (6) opening percentage of valve regulating the flow entering the post-heating coil at previous minute, (7) opening percentage of valve regulating the flow entering the cooling coil at previous minute, (8) opening percentage of valve regulating the flow entering the humidifier at previous minute, (9) velocity of the supply air fan, and (10) velocity of the return air fan. The following five parameters have been set as outputs

**Table 3** Boundary conditions of experimental tests under normal (tests 1–4) and faulty operation (tests 5–9)

| Test n | $T_{SP, Room}$ (°C) | $RH_{SP,Room}$ (%) | $T_{OA}$ (°C) | $OL_{RAF}$ (%) | $OL_{SAF}$ (%) | $OP_{V\_PostHC}$ (%) | $OP_{V\_CC}$ (%) | $OP_{V\_Hum}$ (%) | Duration (h) | Date (dd/mm/yyyy) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 26 | 50 | 20.6 ÷ 26.7 | 50 | 50 | 0 ÷ 100 | 0 ÷ 100 | 0 ÷ 100 | 2.87 | 29/05/2020 |
| 2 | 26 | 50 | 29.1 ÷ 35.2 | 50 | 50 | 0 ÷ 100 | 0 ÷ 100 | 0 ÷ 100 | 1.43 | 28/07/2020 |
| 3 | 26 | 50 | 25.3 ÷ 32.0 | 50 | 50 | 0 ÷ 100 | 0 ÷ 100 | 0 ÷ 100 | 3.13 | 23/07/2020 |
| 4 | 26 | 50 | 28.6 ÷ 35.3 | 50 | 50 | 0 ÷ 100 | 0 ÷ 100 | 0 ÷ 100 | 2.70 | 21/07/2020 |
| 5 | 26 | 50 | 30.4 ÷ 34.9 | 50 | 20 | 0 ÷ 100 | 0 ÷ 100 | 0 ÷ 100 | 5.05 | 31/07/2020 |
| 6 | 26 | 50 | 32.1 ÷ 38.8 | 20 | 50 | 0 ÷ 100 | 0 ÷ 100 | 0 ÷ 100 | 4.12 | 03/08/2020 |
| 7 | 26 | 50 | 33.8 ÷ 38.4 | 50 | 50 | 0 | 0 ÷ 100 | 0 ÷ 100 | 2.23 | 16/09/2020 |
| 8 | 26 | 50 | 29.4 ÷ 35.8 | 50 | 50 | 0 ÷ 100 | 0 | 0 ÷ 100 | 2.83 | 16/09/2020 |
| 9 | 26 | 50 | 28.7 ÷ 38.2 | 50 | 50 | 0 ÷ 100 | 0 ÷ 100 | 0 | 2.98 | 18/09/2020 |

**Table 4** Structure of the investigated artificial neural networks

| | ANN1 | ANN2 | ANN3 | ANN4 | ANN5 | ANN6 | ANN7 | ANN8 | ANN9 | ANN10 | ANN11 | ANN12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of hidden layers | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| Number of neurons in each hidden layer | 10 | 20 | 30 | 40 | 50 | 60 | 10 | 20 | 30 | 40 | 50 | 60 |

of all ANNs: (1) supply air temperature, (2) supply air relative humidity, opening percentages of the valves regulating the flow entering (3) the post-heating coil, (4) the cooling coil, and (5) the flow exiting the humidifier. Each ANN has 1 input layer with 10 neurons and 1 output layer with 5 neurons. The hyperbolic tangent sigmoid transfer function (tansig) has been used in the hidden and output layers of each ANN. Levenberg-Marquart back-propagation training algorithms (trainlm) have been used as training function to update the weight and bias values at any case. The experimental data measured during the tests described in the Sect. 3 have been used for training, testing and validating the ANNs. Two different datasets have been randomly extracted from the entire database (1641 data points in total): the first dataset (1149 points) has been used for training purposes, while the second one (492 points) has been considered for testing and validating the networks. The values predicted by the ANNs have been compared to the entire experimental dataset to assess the accuracy of the ANNs by means of the following metrics (the average error $\overline{\varepsilon}$, the average absolute error $|\overline{\varepsilon}|$, the mean square error MSE, the root mean square error RMSE, the coefficient of determination $R^2$):

$$\varepsilon_\mathrm{i} = \mathrm{g}_{\mathrm{pred,i}} - \mathrm{g}_{\mathrm{exp,i}} \tag{1}$$

$$\overline{\varepsilon} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \varepsilon_i/\mathrm{N} \tag{2}$$

$$|\overline{\varepsilon}| = \sum_{\mathrm{i}=1}^{\mathrm{N}} |\varepsilon_\mathrm{i}|/\mathrm{N} \tag{3}$$

$$\mathrm{MSE} = \frac{1}{N}\sum_{\mathrm{i}=1}^{\mathrm{N}} (\varepsilon_\mathrm{i} - \overline{\varepsilon})^2 \tag{4}$$

$$\mathrm{RMSE} = \sqrt{\sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{(\varepsilon_\mathrm{i} - \overline{\varepsilon})^2}{\mathrm{N}}} \tag{5}$$

$$\mathrm{R}^2 = 1 - \left[\sum_{i=1}^{N} \frac{\left(g_{exp,i} - g_{pred,i}\right)^2}{\left(g_{exp,i} - \overline{g}_{pred}\right)^2}\right] \tag{6}$$

where N is the total number of data points, while $\mathrm{g}_{\mathrm{pred,i}}$, $\mathrm{g}_{\mathrm{exp,i}}$ and $\overline{\mathrm{g}}_{\mathrm{pred}}$ are, respectively, the predicted values at time step i, the measured values at time step i, and the arithmetic mean of the predicted values. Table 5 summarizes the values of $\overline{\varepsilon}$, $|\overline{\varepsilon}|$, MSE, RMSE and $R^2$ associated with the performance of all ANNs developed in this study. The results reported in this table highlight that (i) all ANNs are able to accurately reproduce the operation of the HVAC system and (ii) the ANN characterized by the best performance is the ANN5.

**Table 5** Errors between the ANN-based model predictions and measurements

| Errors | Outputs | ANN1 | ANN2 | ANN3 | ANN4 | ANN5 | ANN6 | ANN7 | ANN8 | ANN9 | ANN10 | ANN11 | ANN12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\bar{\varepsilon}$ | $T_{SA}$ (°C) | -0.03 | -0.02 | 0.00 | -0.04 | -0.02 | -0.01 | -0.01 | -0.02 | -0.03 | -0.02 | -0.03 | -0.04 |
| | $RH_{SA}$ (%) | 0.16 | 0.01 | 0.31 | 0.01 | 0.00 | 0.01 | 0.24 | 0.13 | -0.01 | 0.14 | 0.25 | 0.80 |
| | $OP_{V\_PostHC}$ (-) | -0.01 | 0.00 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.03 | -0.01 |
| | $OP_{V\_CC}$ (-) | -0.02 | 0.03 | 0.01 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.01 | 0.03 | 0.03 | 0.01 |
| | $OP_{V\_Hum}$ (-) | -0.02 | 0.02 | 0.00 | 0.00 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.02 | -0.01 | -0.07 |
| $\overline{\lvert\varepsilon\rvert}$ | $T_{SA}$ (°C) | 0.50 | 0.29 | 0.38 | 0.27 | 0.22 | 0.23 | 0.39 | 0.39 | 0.26 | 0.26 | 0.28 | 0.37 |
| | $RH_{SA}$ (%) | 2.22 | 1.69 | 1.87 | 1.68 | 1.50 | 1.56 | 2.15 | 1.97 | 1.71 | 1.61 | 1.69 | 2.15 |
| | $OP_{V\_PostHC}$ (-) | 0.08 | 0.03 | 0.06 | 0.04 | 0.02 | 0.04 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 | 0.07 |
| | $OP_{V\_CC}$ (-) | 0.12 | 0.06 | 0.11 | 0.09 | 0.05 | 0.06 | 0.07 | 0.09 | 0.08 | 0.08 | 0.08 | 0.09 |
| | $OP_{V\_Hum}$ (-) | 0.19 | 0.05 | 0.11 | 0.09 | 0.06 | 0.10 | 0.08 | 0.16 | 0.08 | 0.08 | 0.13 | 0.22 |
| MSE | $T_{SA}$ (°C) | 0.46 | 0.17 | 0.27 | 0.16 | 0.10 | 0.15 | 0.29 | 0.33 | 0.15 | 0.14 | 0.15 | 0.26 |
| | $RH_{SA}$ (%) | 10.43 | 6.87 | 8.58 | 6.74 | 6.18 | 6.30 | 9.35 | 8.74 | 6.97 | 6.51 | 6.58 | 9.02 |
| | $OP_{V\_PostHC}$ (-) | 0.25 | 0.23 | 0.24 | 0.19 | 0.14 | 0.27 | 0.28 | 0.29 | 0.20 | 0.36 | 0.23 | 0.29 |
| | $OP_{V\_CC}$ (-) | 0.35 | 0.31 | 0.48 | 0.48 | 0.28 | 0.44 | 0.50 | 0.44 | 0.54 | 0.64 | 0.49 | 0.34 |
| | $OP_{V\_Hum}$ (-) | 0.72 | 0.26 | 0.40 | 0.45 | 0.29 | 0.41 | 0.38 | 0.57 | 0.33 | 0.33 | 0.60 | 0.88 |
| RMSE | $T_{SA}$ (°C) | 0.68 | 0.41 | 0.52 | 0.40 | 0.32 | 0.38 | 0.54 | 0.57 | 0.38 | 0.38 | 0.39 | 0.51 |
| | $RH_{SA}$ (%) | 3.23 | 2.62 | 2.91 | 2.60 | 2.49 | 2.51 | 3.05 | 2.95 | 2.64 | 2.55 | 2.55 | 2.90 |
| | $OP_{V\_PostHC}$ (-) | 0.50 | 0.48 | 0.49 | 0.43 | 0.37 | 0.52 | 0.53 | 0.54 | 0.45 | 0.60 | 0.48 | 0.54 |
| | $OP_{V\_CC}$ (-) | 0.59 | 0.56 | 0.69 | 0.69 | 0.53 | 0.66 | 0.71 | 0.66 | 0.73 | 0.80 | 0.70 | 0.58 |
| | $OP_{V\_Hum}$ (-) | 0.85 | 0.51 | 0.63 | 0.67 | 0.53 | 0.64 | 0.62 | 0.75 | 0.57 | 0.58 | 0.77 | 0.94 |
| $R^2$ | $T_{SA}$ (-) | 0.992 | 0.997 | 0.995 | 0.997 | 0.998 | 0.997 | 0.995 | 0.994 | 0.997 | 0.997 | 0.997 | 0.995 |
| | $RH_{SA}$ (-) | 0.973 | 0.982 | 0.978 | 0.983 | 0.984 | 0.984 | 0.976 | 0.977 | 0.982 | 0.983 | 0.983 | 0.978 |
| | $OP_{V\_PostHC}$ (-) | 0.985 | 0.986 | 0.986 | 0.989 | 0.992 | 0.984 | 0.983 | 0.983 | 0.988 | 0.979 | 0.986 | 0.983 |
| | $OP_{V\_CC}$ (-) | 0.982 | 0.984 | 0.975 | 0.975 | 0.985 | 0.977 | 0.974 | 0.977 | 0.972 | 0.967 | 0.974 | 0.982 |
| | $OP_{V\_Hum}$ (-) | 0.962 | 0.986 | 0.979 | 0.977 | 0.985 | 0.978 | 0.980 | 0.970 | 0.983 | 0.983 | 0.968 | 0.954 |

## 5 TRNSYS Model

In the dynamic simulation software TRNSYS [8] (i) a system is decomposed into components' models (named "Types") each of which is described by a FORTRAN subroutine, (ii) the user assembles the Types by linking component inputs and outputs and by assigning component performance parameters and (iii) the program solves the resulting non-linear algebraic and differential equations to determine system response at each time step. In this study a model in TRNSYS environment has been developed in order to simulate, with a time-step equal to 1 min, the return air temperature and relative humidity ($T_{RA}$, $RH_{RA}$) as well as the electric energy consumptions (not measured) of (i) the heat pump (HP), (ii) the refrigerating system (RS), (iii) the humidifier (Hum), (iv) the supply air fan (SAF) and (v) the return (RAF) air fan. This TRNSYS model has been coupled with the ANN5 by means of the TRNSYS Type 155; in particular, the Type 155, recalling the artificial neural network ANN5, has been linked with both the Type 56, simulating the loads of the integrated test room, as well as the Type 661, modeling a "sticky" controller where the outputs are set to the input values from the previous time step. The Type 941 has been adopted to model and simulate the performance of both the refrigeration system and the heat pump; this Type is able to calculate and provide as outputs the cooling/heating power, the power absorbed as well as the temperature of both heat carrier fluid and air according to the performance map suggested by the manufacturer [10]. The air flow rate as well as the energy electric consumption of supply/return air fans have been taken into account based on separate experimental measures as a function of the fans' velocity. The operation as well as the energy consumption of the humidifier has been simulated with the Type 641. The 3-way valves have been modeled with the Types 647/649, while the Type 2 has been used for modeling the on/off differential controllers.

## 6 Assessment of Faults' Impact

In this section the experimental performances of the HVAC system operating under faulty conditions (tests 5–9 of Table 3) have been compared with those predicted by the ANN5 coupled with the TRNSYS model in the cases of the HVAC system is operating under the same boundary conditions while artificially removing the faults.

This means that the test 5 (with the fault 1) has been compared with the simulation case where the velocity of supply air fan has been fixed at nominal value of 50%, the test 6 (with the fault 2) has been compared with the simulation case where the velocity of return air fan has been fixed at nominal value of 50%, the test 7 (with the fault 3) has been compared with the simulation case where the values of $OP_{V\_PostHC}$ vary according to the automatic control logic, the test 8 (with the fault 4) has been compared with the simulation case where the values of $OP_{V\_CC}$ vary according to the automatic control logic, and the test 9 (with the fault 5) has been compared with the simulation case where the values of $OP_{V\_Hum}$ vary according to the automatic control logic. These comparisons have been performed in order to assess the impact of each fault on the capability to achieve the desired indoor conditions as well as the overall electric energy consumption. Table 6 compares the thermal/hygrometric comfort times (i.e., the percentage of time during which the target of indoor air temperature/relative humidity is within the given deadbands) of the simulation tests without faults with respect to those associated to the experimental tests when only one of the 5 faults (describe in the previous Sect. 3) is occurring. Table 6 also shows the electric energy consumptions of the heat pump ($EE_{HP}$), the refrigerating system ($EE_{RS}$), the humidifier ($EE_{Hum}$), the supply air fan ($EE_{SAF}$), the return air fan ($EE_{RAF}$) as well as the overall electric energy consumption ($EE_{TOT}$), with and without faults. With respect to the case without faults, Table 6 indicates that the occurrence of the fault 1 (test 5) strongly reduces both the thermal comfort time (72%) and the hygrometric comfort time (61%), while lowering the overall electric energy consumption (36%) thanks to reduced consumption of the heat pump (97%), humidifier (100%) and

**Table 6** Comfort time and electric energy consumption with/without faults

| Type of test | | Comfort time (%) | | Electric energy consumption (kWh) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Thermal | Hygrometric | $EE_{HP}$ | $EE_{RS}$ | $EE_{Hum}$ | $EE_{SAF}$ | $EE_{RAF}$ | $EE_{TOT}$ |
| Test 5 | Fault 1 (exp.) | 0.0 | 16.2 | 0.28 | 19.64 | 0.00 | 0.17 | 0.44 | 20.53 |
| | w/o fault (pred.) | 72.3 | 76.9 | 10.31 | 17.39 | 2.71 | 1.30 | 0.44 | 32.15 |
| Test 6 | Fault 2 (exp.) | 36.1 | 80.6 | 0.29 | 16.68 | 9.00 | 1.04 | 0.12 | 27.13 |
| | w/o fault (pred.) | 50.6 | 91.9 | 6.42 | 13.72 | 6.60 | 1.04 | 0.35 | 28.12 |
| Test 7 | Fault 3 (exp.) | 13.4 | 88.1 | 0.22 | 7.96 | 2.65 | 0.56 | 0.19 | 11.58 |
| | w/o fault (pred.) | 54.7 | 92.8 | 3.54 | 8.38 | 4.13 | 0.56 | 0.19 | 16.80 |
| Test 8 | Fault 4 (exp.) | 0.0 | 90.6 | 0.22 | 0.85 | 1.48 | 0.71 | 0.24 | 3.50 |
| | w/o fault (pred.) | 55.6 | 95.9 | 2.43 | 10.43 | 2.90 | 0.71 | 0.24 | 16.72 |
| Test 9 | Fault 5 (exp.) | 86.6 | 65.4 | 1.75 | 10.85 | 0.00 | 0.76 | 0.26 | 13.62 |
| | w/o fault (pred.) | 87.3 | 84.5 | 6.34 | 11.31 | 1.29 | 0.76 | 0.26 | 19.96 |

supply air fan (87%); the occurrence of the fault 2 (test 6) slightly decreases both the thermal comfort time (14%) and the hygrometric comfort time (11%), while slightly reducing the overall electric energy consumption (4%) thanks to the lower consumption of both the heat pump (96%) and return air fan (66%); the occurrence of the fault 3 (test 7) strongly reduces the thermal comfort time (41%) and slightly decreases the hygrometric comfort time (5%), while lowering the overall electric energy consumption (31%) due to the reduced consumption of both the heat pump (94%) and the humidifier (36%); the occurrence of the fault 4 (test 8) significantly decreases the thermal comfort time (56%) and slightly reduces the hygrometric comfort time (5%), while lowering the overall electric energy consumption (79%) thanks to the reduced consumption of the heat pump (91%), the refrigerating system (92%) and the humidifier (49%); the occurrence of the fault 5 (test 9) reduces the thermal comfort time by a slight amount (1%) and significantly decreases the hygrometric comfort time (19%), while reducing the overall electric energy consumption (32%) due to the lower consumption of both the heat pump (72%) and the humidifier (100%).

## 7 Conclusions

Data-driven based AFDD tools need a proper amount of data to be developed and applied on HVAC devices. In this study, a simulation model based on ANNs of a typical HVAC system has been developed in contrast with fault free and faulty experimental data. The results demonstrated that the model is able to accurately reproduce fault free and faulty operation of the HVAC unit upon varying the boundary conditions and, therefore, it represents a useful tool for producing operation data to assist further research in control, fault detection and diagnosis of HVAC systems by applying techniques from statistical decision, artificial intelligence and soft computing. The study also highlighted the relevant impact of the 5 typical faults, denoting that they can cause a drop of thermal comfort by 72%, decrease hygrometric comfort by 61% as well as reduce overall electric energy consumption by 79%.

## References


1. Proctor, J.: Residential and small commercial center air conditioning, rated efficiency isn't automatic. In: Proceedings ASHRAE Winter Meeting. Anaheim, CA, USA (2004)
2. Yu, Y., Woradechjumroen, D., Yu, D.: A review of fault detection and diagnosis methodologies on air-handling units. Energy Build. **84**, 550–562 (2014)
3. Yan, K., Zhong, C., Ji, Z., Huang, J.: Semi-supervised learning for early detection and diagnosis of various air handling unit fault. Energy Build. **181**, 75–83 (2018)
4. Guarino, F., Filomena, V., Maffei, L., Sibilio, S., Rosato, A.: A review of fault detection and diagnosis methodologies for AHU. Glob. J. Energ. Tech. Res. Updat. **6**, 26–40 (2019)
5. Rosato, A., Guarino, F., Filomena, V., Sibilio, S., Maffei, L.: Experimental calibration and validation of a simulation model for fault detection of HVAC systems and application to a case study. Energies **13**(15), 3948 (2020)

6. Piscitelli, M.P., Mazzarelli, D.M., Capozzoli, A.: Enhancing operational performance of AHUs through an advanced fault detection and diagnosis process based on temporal association and decision rules. Energy Build. **226** (2020)
7. Wen, J., Li, S.: Tools for Evaluating Fault Detection and Diagnostic Methods for Air-Handling Units. ASHRAE 1312-RP (2010)
8. MathWorks, https://it.mathworks.com/products/matlab.html. Last accessed 26 March 2021
9. TRNSYS, http://www.trnsys.com. Last accessed 26 March 2021
10. AERMEC Datasheet, https://download.aermec.com/docs/schede/ANL-021-203-HP_Y_UN50_03.pdf?r=14395. Last accessed 26 March 2021
11. CAREL datasheet, https://www.carel.com/documents/10191/0/%2B030220621/92fca658-a251-49ee-9979-b8829fcba49f?version=1.0. Last accessed 26 March 2021
12. SIEMENS Datasheet, https://www.downloads.siemens.com/download-center/Download.aspx?pos=download&fct=getasset&id1=24897. Last accessed 26 March 2021
13. TSI Datasheet, https://www.tsi.com/getmedia/d2a8d1d1-7551-47fe-8a0f-3c14b09b494b/7575_QTrak_A4_UK_5001356-web?ext=.pdf. Last accessed 26 March 2021
14. Entchev, E., Yang, L., Ghorab, M., Rosato, A., Sibilio, S.: Energy, economic and environmental performance simulation of a hybrid renewable microgeneration system with neural network predictive control. Alex. Eng. J. **57**(1), 455–473 (2018)

# Impact of Occupants' Behavior Uncertainty on Building Energy Consumption Through the Karhunen-Loève Expansion Technique: A Case Study in Italy

**Gianluca Maracchini, Elisa Di Giuseppe, and Marco D'Orazio**

**Abstract** In Europe, the building sector is liable for 40% of the entire energy consumption (EC) and 35% of the total greenhouse emission. Building energy performance simulation (BEPS) tools are fundamental to assess the EC of both new buildings and energy retrofit intervention, and to verify the reaching of the requirements set by the national building energy standards. However, the results obtained from these tools are often unreliable due to the different assumptions that must be made in case of data input uncertainty, generating a "*performance gap*" between observed and predicted EC. Occupants' behavior (OB) is one of the most difficult parameters to be estimated since affected by high uncertainty that may strongly affect the numerical results. However, the most recent BEPS tools neglect the existing uncertainty by modeling the occupant behavior through deterministic hourly-defined profiles. For this reason, in this work, the impact of OB uncertainties on EC is evaluated by applying a Karhunen-Loève Expansion (KLE) on deterministic hourly defined profiles. A typical Italian residential building is modeled and calibrated on EC data. Then, occupancy behavior-related profiles, such as heating setpoint, internal thermal loads, and windows opening, are randomly perturbed using the KLE technique. The results demonstrate that the heating setpoint patterns uncertainty has the highest impact on EC. Moreover, the more the energy performance of the building, the higher the impact of heat gains and losses caused by OB.

## 1 Introduction

In Europe, 40% of the overall energy consumption (EC) and about 35% of the total greenhouse gas (GHG) emissions can be traced back to the building sector. Due to the low energy performance of 75% of the EU building stock, half of this energy is used for heating the households, whose energy demand is expected to increase by more than 20% in the next 10 years [1]. In this framework, improving the energy

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performance of the building sector represents a great opportunity to significantly reduce the overall EU energy consumption and greenhouse emissions, and then to meet the EU sustainability and energy efficiency objectives [2, 3].

Building energy performance simulation (BEPS) tools are fundamental allies for the practitioners to compare different energy retrofit interventions and to verify the reaching of the requirements set by the national building energy standards. However, due to the difficulty in characterizing all the input required for building energy models (BEMs), a large discrepancy between actual and simulated energy performance (called "energy performance gap") is often obtained for both new and existing buildings (up to 250%) [4]. Several studies found the occupants' behavior (OB) to be one of the main responsible for the energy performance gap in residential buildings. A different occupants' behavior in terms of use of thermostats, electric appliances, lighting, domestic hot water appliances, and windows, may indeed lead to very different building energy performance levels, even for the same building, which may be lower or higher than that forecasted by building energy models (BEMs) [5–8]. The numerical modeling of the occupant behavior may facilitate the understanding of the impact of OB uncertainty on building energy use. However, despite the increasing power of the actual computer, which makes it feasible to conduct in a reasonable time frame parametric BEPS with thousands of simulations and stochastic input, the more recent BEPS tools model the occupant behavior through deterministic hourly-defined profiles [9]. This approach has the main advantage of being simple and easy to understand for most common applications. However, it does not consider the uncertainty related to the occupants' interaction with building operation, leading to evaluate the energy performance related to only one possible scenario that could be different from the reality.

## 2 Literature Review

For this reason, over the past 20 years, researchers and practitioners paid increasing attention to evaluating the impact of OB on building energy use, using both scenario analyses [10, 11] and stochastic OB models [5, 6, 12–14]. These works mainly focus on office buildings, while a fewer number of works concern residential ones. These works generally investigate how different OB may affect the building EC. In [5], for example, the robustness of EC prediction of a high-performance residential building in Quebec City, Canada, is estimated by using multiple realistic OB profiles. In some cases, however, the OB can be known. For example. It can be derived from the occupsnts' questionnaire. In this context, it can be interesting to evaluate how a certain degree of uncertainty on OB patterns (due to the method of estimation adopted) may affect the numerical outcomes. At this aim, O'Neill and Niu proposed an interesting approach to consider both the spatial and temporal OB uncertainties of a known OB pattern [6]. This approach is based on the application of a Karhunen-Loève expansion (KLE) sampling technique and was applied to a US DOE prototype BEM for considering the uncertainty of HVAC setpoint and internal thermal loads patterns. However, in their work, the authors assume a very small range of uncertainty of OB, and completely neglect the uncertainty related to some very important OB such as windows opening [15]. Moreover, an application to a real residential case study is still missing in the literature. To overcome these issues, this paper presents a contribution to this topic by extending the application of this technique to a real, multi-family building placed in the Italian Marche region (Ancona). Different from [6], calibrated simulations are used to increase the reliability of the numerical outcomes, and OB uncertainties related to internal loads (IL), heating setpoint (HS), and window opening (natural ventilation, NV) patterns are considered. In addition, since the impact of OB on EC may change to vary building energy performance levels, both pre- and post-energy retrofit scenarios are considered. In this way, the impact and robustness of EC prediction of a real case study with respect to the uncertainty on specific OB patterns are estimated.

## 3 Methodology

This work can be subdivided into three main phases. Firstly, a BEM of a real residential building is purposely created, accurately collecting information about OB through questionnaires. Then, the BEM is calibrated on real EC data to increase the reliability of the numerical results. Finally, UAs on OB have been carried out considering both pre- and post-retrofit scenarios, with the twofold aim of estimating the impact of OB uncertainties on EC before and after energy renovation, and of evaluating the energy prediction robustness with respect to the OB uncertainty.

### *3.1 Numerical Modeling of the Case Study*

To numerically estimate the impact of occupants' patterns uncertainties on building heating demand, a typical Italian multi-family building built between 1970 and 1975 has been considered in this study. The building is placed in the hot-summer Mediterranean climates of Ancona, Italy (according to Köppen climate classification [16]), and consists of six stories and 12 dwellings, with a floor area for each story of 280.8 $m^2$ (Fig. 1a). The first floor is unheated and below the ground level. All the other floors have three dwellings each, excepting for the first and the last floor, which have one and two dwellings, respectively. A dwelling belonging to the third story was selected for calibration and UA (Fig. 1b). The apartment is occupied by four persons, i.e. a couple with one son, and consists of two bedrooms, a bathroom, a kitchen, and a living room, for an overall area of 80.4 $m^2$. An EnergyPlus BEM has been created through the graphical interface DesignBuilder ver. 6.1 [17]. Literature and Italian Standards (where typical values for Italian multi-family houses built between 1970 and 1975 are reported) allowed to estimate the building properties as well as some OB data, e.g. maximum internal thermal loads [18]. Due to the inherent

**Fig. 1** **a** Six-story multi-family building; **b** case study apartment at the third level used for numerical simulations

uncertainties on as-built data, a range (min, max) of variation has been assumed for each relevant property, as summarized in Table 1, which also defines the search space for the calibration process. In Table 1, also the values assumed in the post-renovation scenario are reported. In this scenario, all envelope elements and heating systems are upgraded according to the Italian Law on buildings' energy performance [19].

To accurately characterize the patterns representing the interactions between occupants and building systems (internal loads, ILs, heating system operation, HS, and windows opening/natural ventilation, NV) detailed questionnaires have been submitted to the occupants of the considered flat. The gathered data are then translated into averaged daily profiles (see Fig. 2), to be used as a starting point for both BEM calibration (Sect. 3.2) and UA (Sect. 3.3). Regarding the ILs, the schedule indicated in Fig. 2a is multiplied by a maximum value, whose range of variation due to uncertainty is indicated in Table 1. Concerning the heating system, since in the apartment two different thermostats are present, i.e., one for the sleeping area and one for the living one, two different heating activation profiles are defined according to the

**Table 1** Uniform ranges of variation of BEM properties in the as-built scenario and deterministic values in post-retrofit scenarios

| Property | As built | Post-retrofit |
|---|---|---|
| Exterior walls U-value [W/m$^2$ K] | 0.65–1.30 | 0.32 |
| Internal walls (between apartm. and stairs) U-value [W/m$^2$ K] | 0.65–1.30 | 0.32 |
| Internal walls (between apartm. rooms) U-value [W/m$^2$ K] | 1.40–2.60 | Calibrated value |
| Windows U-value [W/m$^2$ K] | 1.80–3.70 | 1.20 |
| Windows SHGC [–] | 0.65–0.85 | 0.35 |
| Infiltration rate [h$^{-1}$] | 0.30–0.50 | Calibrated value |
| CoP [–] | 0.60–0.75 | 0.85 |
| Heating setpoint (sleeping area) [°C] | 18–20 | Calibrated value |
| Heating setpoint (living area) [°C] | 18–20 | Calibrated value |
| Maximum internal thermal load [W/m$^2$] | 3–12 | Calibrated value |
| Maximum windows opening area fraction [–] | 0.05–1.00 | Calibrated value |

*SHGC* Solar Heat Gain Coefficient; *CoP* Coefficient of Performance

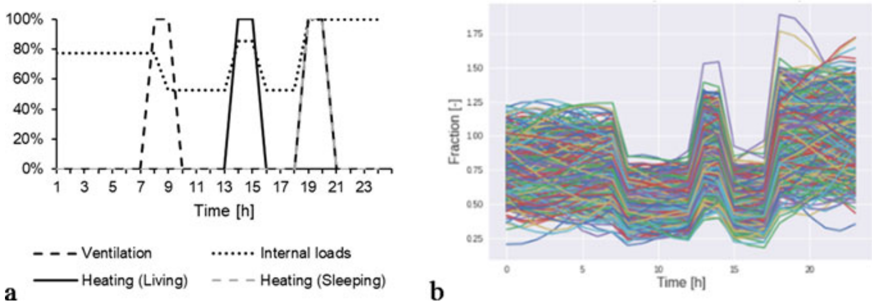


**Fig. 2** **a** Average occupants' schedules derived from occupants' questionnaires; **b** exemplary application of KLE technique on the internal thermal loads averaged profile

occupants' information, each of which multiplies a constant HS (ranging between 18 and 20 °C, see Table 1). Finally, concerning the NV, the schedule in Fig. 2a indicates the time when the windows are opened by the occupants to ventilate the apartment. During this time, the entering NV flowrate from windows is computed as the combined effect of both the airflow driven by wind $Q_W$ and the airflow due to stack effects $Q_S$, according to the ASHRAE book of fundamentals [20]. The opening area of the window is considered as unknown and then will be defined in the calibration phase (see Table 1).

### 3.2 Model Calibration

In the literature, the impact of OB on EC is often addressed by using not calibrated or validated BEMs [6, 12], which, however, may lead to inaccurate numerical predictions [4]. For this reason, in this work, a BEM calibration is carried out to increase the accuracy of the numerical analyses. In particular, an automated calibration tool purposely developed by the authors has been used for BEM calibration. The tool is written in the python language and implements the Non-dominated Sorting Genetic Algorithm (NSGA-II) for the optimization process, which is one of the most used multi-objective optimization algorithm adopted for BEM optimization and automatic calibration [21–24]. The comparison between measured and simulated EC is carried out considering the heating period from the 1st of November 2016 to March 24th, 2017. To ensure successful calibration, the actual climate conditions are also considered in the simulations, with main weather data (outdoor air temperatures, relative humidity, horizontal global solar radiation, wind speed, and direction) recorded through a local weather station placed about 1 km away from the building. The search space for the calibration process is defined by the ranges of variation indicated in Table 1. The optimization algorithm searches the set of input data that minimizes the error between simulated and measured monthly heating EC, as requested by the ASHRAE guideline 14 [25]. The error is computed through two error functions, which are the Coefficient of Variation of the root mean square error (CVRMSE) and the Normalized Mean Bias Error (NMBE). According to the ASHRAE guideline 14, the model can be considered as calibrated if the obtained CVRMSE and NMBE are lower than 15% and within ±5%, respectively [25].

### 3.3 Uncertainty Analyses

The impact of OB uncertainties on building EC and the robustness of the BEM energy prediction with respect to the estimated OB are evaluated in this study by carrying out three distinct "local" uncertainty analyses (UAs) on the calibrated BEM. In each UA, one of the averaged OB patterns shown in Fig. 2a is varied, i.e. the internal load pattern (IL-UA), the heating setpoint pattern (HS-UA), and the natural ventilation pattern (NV-UA). For each UA, a Karhunen-Loève Expansion (KLE) sampling technique is applied to create different patterns starting from the averaged ones. This technique has been already applied in the literature to evaluate the impact of OB on EC, but, to the authors' knowledge, this is the first time that this technique is adopted to perform IL-UA and NV-UA, and, more in general, OB UA on calibrated BEMs [6]. Similar to the Fourier analysis, a KLE allows representing a stochastic process as an infinite linear weighted combination of orthogonal functions. In this way, the dimension of the stochastic processes is reduced by converting time-dependent uncertainty into time-independent stochastic parameters. In synthesis, the KLE can be represented through Eq. (1), where $\mu_x(t)$ is the mean value at the time t (assumed equal to 0 in this work), $\psi_i$(t) is a temporal basis function, $\lambda_i$ and $y_i$ are the eigenvalues and eigenfunctions of the covariance function C($\times 1$, $\times 2$) that, by definition, is bounded, symmetric, and positive definite. The eigenfunction $y_i$ is a time-independent stochastic parameter expressed as Gaussian variables with a zero mean. The most used correlation function types are Gaussian, exponential, and turbulent functions [26]. In this study, the exponential covariance function defined in Eq. (2) is adopted, where $c$ is a variance scaling parameter.

Each KLE provides a set of 24 random coefficients that, applied to the averaged occupants' profiles $X(t)$, allow obtaining a new hourly schedule $X^*(t) = X(t) \cdot (1 + x(t))$ (see Fig. 2b). In this work, 1000 KLE are considered for UAs since sufficient to ensure the convergence of the result. The c parameter in the covariance function (Eq. 2) corresponds to the CoV of each normally distributed hourly value. For this reason, due to the high uncertainty in the estimation of ILs and NV profiles, a high value of c, equal to 20%, has been assumed for IL-UA and NV-UA. Differently, a smaller c value (2.5%) has been assumed for the HS-UA to have plausible values for hourly HS, i.e. a maximum variation of ±1 °C with respect to the calibrated value.

$$x(t) = \mu_x(t) + \sum_{i=1}^{\infty} \sqrt{\lambda_i}\psi_i(t)y_i \tag{1}$$

$$C(x_1, x_2) = ce^{-\left(\frac{x_1 - x_2}{5}\right)^2} \tag{2}$$

## 4 Results

In this section, the results of the model calibration and UAa are reported. Concerning model calibration, a CVRMSE and NMBE equal to 13.57 and −3.56%, respectively, have been obtained. These values are lower than the threshold set in the ASHRAE guideline 14, equal to 15 and ±5%, respectively [25]. Thus, the obtained model can be considered as calibrated, i.e. sufficiently reliable and representative of the energy performance and actual use of the building. The calibrated values for each BEM property are reported in Table 2.

The results of the IL-UA, HS-UA, and NV-UA are reported in Fig. 3, where also a comparison between calculated and measured monthly EC is shown. As expected, for each UAs, the yearly EC can be considered as normally distributed, with the same mean value of about 4300 kWh. Some differences between IL-UA, HS-UA, and NV-UA can be observed in terms of CoV, equal to 4.4, 5.5, and 3.3%, respectively (corresponding to standard deviations equal to 189.2, 236.5, and 141.9 kWh, respectively). Thus, in the pre-retrofit scenario, the HS has the highest impact on the building EC, followed by IL and NV. To evaluate how the OB uncertainty impacts on EC vary in a post-retrofit scenario, the same three UAs are repeated considering the same case study with improved energy performance (see Table 1). As expected,

**Table 2** Calibrated values for the pre-retrofit scenarios

| Property | Calibrated value |
|---|---|
| Exterior walls U-value [W/m$^2$ K] | 0.66 |
| Internal walls (between apartm. and stairs) U-value [W/m$^2$ K] | 0.67 |
| Internal walls (between living and sleeping zone) U-value [W/m$^2$ K] | 1.43 |
| Windows U-value [W/m$^2$ K] | 1.96 |
| Windows SHGC [–] | 0.65 |
| Infiltration ACH [h$^{-1}$] | 0.31 |
| CoP [–] | 0.75 |
| Heating setpoint (living area) [°C] | 18.1 |
| Heating setpoint (sleeping area) [°C] | 20.0 |
| Maximum internal thermal load [W/m$^2$] | 7.37 |
| Maximum windows opening area fraction [–] | 0.06 |

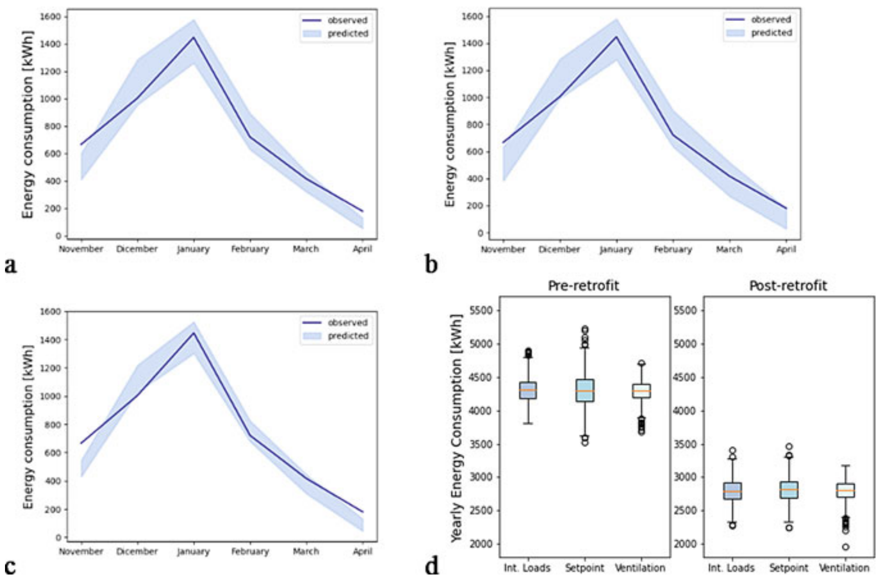


**Fig. 3** Monthly EC for the three UAs in pre-retrofit scenario: **a** IL-UA, **b** HS-UA and **c** NV-UA; **d** box plot of yearly EC in pre- and post-retrofit scenarios

for all the three UAs a decrease of the mean building energy consumption of about 35% is obtained (with a mean value of yearly EC of about 2800 kWh, see Fig. 3). Comparing UAs, even in this case, the highest variation in terms of EC is obtained for the HS-UA, followed by IL-UA and NV-UA. In particular, the standard deviations of the yearly, normally distributed ECs are equal to 168.5, 187.0, and 154.0 kWh for IL-UA, HS-UA, and NV-UA, respectively. Despite these values are lower than those obtained in the pre-retrofit scenario, in relative terms the EC variability is higher than those in the pre-retrofit case due to the decrease of the mean EC value, with CoVs equal to 6.0, 6.6, and 5.5%, respectively. The increase in CoV values is different among different UAs, with the highest increase obtained for the NV (+67%), followed by the ILs (+36%) and HS (+20%). This indicates an increased impact of OB in the post-retrofit scenario, especially for NV-related activities.

## 5 Discussion

This works allowed to investigate the impact of different OB uncertainties on the EC of a real existing residential building located in Italy in both pre- and post-retrofit scenario. Results demonstrated that the HS uncertainties have always a higher impact on EC, followed by IL and NV. In particular, the high variability assigned to IL and NV patterns ($c = 20\%$, see Sect. 3.3) produces a low variation on EC in both pre- and post-retrofit scenarios (CoV equal to 4.4 and 3.3%, for the first scenario, and 6.0 and

5.5% for the second one), denoting a very low impact of IL and NV uncertainties on EC. Conversely, the low variability assigned to the HS variation (c = 2.5%), leads to larger CoVs (5.5 and 6.6% for the pre- and post-retrofit scenario, respectively), denoting a high impact of the HS pattern on EC in both pre- and post-retrofit scenario. These results are similar to those obtained in similar works. In particular, in [6] it was found that HS has a higher impact than that obtained for ILs. However, it should be noted that it is very difficult to compare the results among different studies because they vary greatly in many factors such as building characteristics, type of use, OB patterns, and location. However, it can be said that correctly defining the HS profile is very important to obtain realistic ECs for both high and low energy performance existing buildings.

Comparing the results in pre- and post-renovation scenarios, it can be observed that the higher the thermal performance of the building, the higher the relative impact of OB on EC, with the highest increase obtained for NV, followed by ILs and HS. This is because heat gains and losses due to IL and NV, respectively, remain quite constant among different scenarios, while the overall EC significantly decreases in the post-renovation one, resulting in a higher increase of CoVs. This result indicates the importance of considering IL and NV uncertainties for higher-performance buildings.

The main limitation of this work lies in the use of a local UA approach. Thence, further studies will be carried out to evaluate the overall EC variation by varying together all the occupants' patterns. Moreover, more climatic locations and building use/type scenarios could be considered.

## 6 Conclusion

In this paper, the impact of OB patterns uncertainties on the EC of a typical Italian building is quantified in both pre- and post-retrofit scenarios through calibrated simulation and OB UAs, the latter obtained by using a KLE technique applied to OB patterns. The results indicate that, in both scenarios, the HS patterns uncertainty has the highest impact on the building EC if compared with IL and NV uncertainties. However, in relative terms, increasing the thermal performance of the building leads to a higher increase of the impact of both IL and NV on EC if compared to the HS impact increase. Further studies will evaluate the global impact of OB uncertainties on building EC, also considering different climatic locations and building characteristics.

## References

1. International Energy Agency (IEA): Outlook for energy demand—World Energy Outlook 2020—Analysis (2020)
2. Di Giuseppe, E., Maracchini, G., Gianangeli, A., Bernardini, G., D'Orazio, M.: Internal insulation of historic buildings: a stochastic approach to life cycle costing within RIBuild EU Project. In: Sustainability in Energy and Buildings, pp. 349–359 (2020). https://doi.org/10.1007/978-981-32-9868-2_30
3. Di Giuseppe, E., D'Orazio, M., Du, G., Favi, C., Lasvaux, S., Maracchini, G., Padey, P.: A stochastic approach to LCA of internal insulation solutions for historic buildings. Sustainability **12**, 1535 (2020). https://doi.org/10.3390/su12041535
4. Cuerda, E., Guerra-Santin, O., Sendra, J.J., Neila, F.J.: Understanding the performance gap in energy retrofitting: measured input data for adjusting building simulation models. Energy Build. **209**, 109688 (2020). https://doi.org/10.1016/j.enbuild.2019.109688
5. Rouleau, J., Gosselin, L., Blanchet, P.: Robustness of energy consumption and comfort in high-performance residential building with respect to occupant behavior. Energy **188**, 115978 (2019). https://doi.org/10.1016/j.energy.2019.115978
6. O'Neill, Z., Niu, F.: Uncertainty and sensitivity analysis of spatio-temporal occupant behaviors on residential building energy usage utilizing Karhunen-Loève expansion. Build. Environ. **115**, 157–172 (2017). https://doi.org/10.1016/J.BUILDENV.2017.01.025
7. Braulio-Gonzalo, M., Bovea, M.D., Jorge-Ortiz, A., Juan, P.: Contribution of households' occupant profile in predictions of energy consumption in residential buildings: a statistical approach from Mediterranean survey data. Energy Build. **241**, 110939 (2021). https://doi.org/10.1016/j.enbuild.2021.110939
8. Carlucci, S., De Simone, M., Firth, S.K., Kjærgaard, M.B., Markovic, R., Rahaman, M.S., Annaqeeb, M.K., Biandrate, S., Das, A., Dziedzic, J.W., Fajilla, G., Favero, M., Ferrando, M., Hahn, J., Han, M., Peng, Y., Salim, F., Schlüter, A., van Treeck, C.: Modeling occupant behavior in buildings. Build. Environ. **174**, 106768 (2020). https://doi.org/10.1016/j.buildenv.2020.106768
9. O'Brien, W., Gaetani, I., Gilani, S., Carlucci, S., Hoes, P.J., Hensen, J.: International survey on current occupant modelling approaches in building performance simulation†. J. Build. Perform. Simul. **10**, 653–671 (2017). https://doi.org/10.1080/19401493.2016.1243731
10. Kotireddy, R., Hoes, P.J., Hensen, J.L.M.: A methodology for performance robustness assessment of low-energy buildings using scenario analysis. Appl. Energy. **212**, 428–442 (2018). https://doi.org/10.1016/j.apenergy.2017.12.066
11. Cvetković, D., Nešović, A., Terzić, I.: Impact of people's behavior on the energy sustainability of the residential sector in emergency situations caused by COVID-19. Energy Build. **230** (2021). https://doi.org/10.1016/j.enbuild.2020.110532
12. Carlucci, S., Causone, F., Biandrate, S., Ferrando, M., Moazami, A., Erba, S.: On the impact of stochastic modeling of occupant behavior on the energy use of office buildings. Energy Build. **246**, 111049 (2021). https://doi.org/10.1016/j.enbuild.2021.111049
13. Fajilla, G., Chen Austin, M., Mora, D., De Simone, M.: Assessment of probabilistic models to estimate the occupancy state in office buildings using indoor parameters and user-related variables. Energy Build. **246**, 111105 (2021). https://doi.org/10.1016/j.enbuild.2021.111105
14. Abuimara, T., O'Brien, W., Gunay, B., Carrizo, J.S.: Towards occupant-centric simulation-aided building design: a case study. Build. Res. Inf. **47**, 866–882 (2019). https://doi.org/10.1080/09613218.2019.1652550
15. Chen, S., Zhang, G., Xia, X., Chen, Y., Setunge, S., Shi, L.: The impacts of occupant behavior on building energy consumption: a review. Sustain. Energy Technol. Assessments **45**, 101212 (2021). https://doi.org/10.1016/j.seta.2021.101212
16. Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F.: World map of the Köppen-Geiger climate classification updated. Meteorol. Zeitschrift. (2006). https://doi.org/10.1127/0941-2948/2006/0130

17. Cockcroft, D.: DesignBuilder building simulation. www.designbuilder.co.uk. (2021)
18. Carnieletto, L., Ferrando, M., Teso, L., Sun, K., Zhang, W., Causone, F., Romagnoni, P., Zarrella, A., Hong, T.: Italian prototype building models for urban scale building performance simulation. Build. Environ. **192**, 107590 (2021). https://doi.org/10.1016/j.buildenv.2021.107590
19. Ministero dello Sviluppo Economico, Decreto Interministeriale 26.06.2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici, 2015.
20. ASHRAE 55, Ashrae Handbook Fundamentals, 2017. https://doi.org/10.1039/c1cs15219j.
21. Deb, K., Pratap, A., Agarwal, S., Meyarivan, T.: A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Comput. (2002). https://doi.org/10.1109/4235.996017
22. Martínez, S., Eguía, P., Granada, E., Moazami, A., Hamdy, M.: A performance comparison of multi-objective optimization-based approaches for calibrating white-box building energy models. Energy Build. **216**, 109942 (2020). https://doi.org/10.1016/j.enbuild.2020.109942
23. Ramos Ruiz, G., Fernández Bandera, Gómez-Acebo Temes, T., Sánchez-Ostiz Gutierrez, A.: Genetic algorithm for building envelope calibration. Appl. Energy **168**, 691–705 (2016). https://doi.org/10.1016/j.apenergy.2016.01.075
24. Ramos Ruiz, G., Fernández Bandera, C.: Analysis of uncertainty indices used for building envelope calibration. Appl. Energy **185**, 82–94 (2017). https://doi.org/10.1016/j.apenergy.2016.10.054
25. ASHRAE Standards Committee: ASHRAE Guideline 14-2014 Measurement of Energy and Demand Savings (2014)
26. Phoon, K.K., Huang, S.P., Quek, S.T.: Simulation of second-order processes using Karhunen-Loeve expansion. Comput. Struct. **80**, 1049–1060 (2002). https://doi.org/10.1016/S0045-7949(02)00064-0

# Towards a Multi-risk Assessment of Open Spaces and Its Users: A Rapid Survey Form to Collect and Manage Risk Factors

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**Abstract** The Built Environment (BE) with its users is increasingly prone to SUdden-Onset Disasters (SUODs), such as earthquakes and terrorist attacks, and SLow-Onset Disasters (SLODs), such as those related to pollutions and heatwaves. In this regard, historical centers represent vulnerable contexts due to their morphological complexity, construction peculiarities, and user-related characteristics. Therefore, risk assessment studies emphasize the importance of characterizing the BE from a holistic perspective to identify risk factors that interfere with disaster response. In particular, Open Spaces (OSs) (e.g., streets, squares) play a key role in increasing the overall BE resilience as elements that ensure the safety of BE users in emergency phases. This research is aimed at providing a quick OSs survey form to collect and manage the main risk factors according to a multi-risk approach. The form focuses on the critical users-BE interactions due to the OSs modifications during disasters and has been applied to 8 case studies in Italian historical city centers. Results show how the form can assess the OSs complexity and trace the main morphological, constructive, use-related, and context risk factors affecting the safety of OSs and their users. Promoted in the context of the Italian research project (PRIN) BE S2ECURe, the research succeeds in defining a quick methodology for risk factors collection, which can also support planners and local administrations in promoting effective mitigation strategies.

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## 1 Introduction

The resilience of the Built Environment (BE) and the safety of its users in case of disasters depend on the whole system of connections of urban elements (i.e., infrastructures, open spaces, buildings) and social factors (i.e., users behaviour, risk awareness, and preparedness) [1–3]. In addition, the physical form of the city contributes to understanding how the configuration of the urban environment and the relationships between urban elements influence overall resilience [4]. Therefore, BE risk assessment must encompass a holistic and multi-risk perspective, especially in relation to historic city centers with a high concentration of exposed users [1, 5, 6]. The BE characterization at the meso-scale, which relies on the analysis of interconnections and features of buildings blocks and Open Spaces (OSs), contributes to the definition of the risk level of the entire urban system and the safety of users during disasters [7]. The dislocation of OSs, divided into Linear Spaces (LSs, e.g., streets) and Areal Spaces (ASs, e.g., squares), and their specific morpho-typological characteristics and spatial configuration in the urban layout influence the emergency management phase [2, 7, 8]. LSs are links among ASs, that act as outdoor gathering areas where users affected by SUODs can wait for rescue. Moreover, both the indoor functions of the OS facing buildings and the outdoor space uses can be catalysts for time-varying human presence, resulting in different exposure levels in both SUdden Onset Disasters (SUODs) (e.g., earthquakes) and SLow Onset Disasters (SLODs) (e.g., air pollution and heatwaves) [3]. Thus, the combined impacts of SUODs and SLODs on emergency response must be evaluated considering the interactions between all BE characteristics [9, 10].

The present work aims at providing a first step towards the creation of multi-risk scenarios by defining a quick survey form with morphological, geometrical, constructive, and use factors influencing BE response to disasters. It ensures an easy and rapid application even by low trained technicians and non-expert decision-makers, like local administrators, to identify critical conditions requiring more specific risk assessments. Indeed, the proposed form acts as a preliminary checklist to collect data and determine the relevance of the case study with respect to multi-risk assessments. In this context, the research is a fundamental step in the framework of the Project BE S$^2$ECURe—"(make) Built Environment Safer in Slow and Emergency Conditions through behavioUral assessed/designed Resilient solutions" (supported by MIUR—the Italian Ministry of Education, University, and Research), aimed at developing methods, tools, and guidelines to assess the resilience of the BE according to a multi-risk approach [11].

## 2 Methodology

The OS multi-risk factors survey form was developed from a literature review of BE characteristics that influence hazard, vulnerability, and exposure of both SUODs (e.g., earthquakes and terrorism) and SLODs (e.g., air pollution and heat-waves) [12] (Sect. 2.1). Subsequently, the form has been applied to 8 significant case studies among Italian historical centers. The application process allowed both to verify the completeness of the form and analyze characteristics recurrence (Sect. 2.2).

## 2.1 *Definition of the Survey Form of Multi-risk Assessment of Open Spaces*

The survey form is composed of five sections representing different macro-areas of the OSs features and relies on the identification of its frontier (e.g., buildings facing the OS) and content elements (e.g., elements contained within OS) [7]. Each section consists of main "parameters" subdivided into detailed "sub-parameters" (Fig. 1).

The first section focuses on OS morpho-typological characteristics identification [7]. Based on OS morphological approaches [8, 13–15]. Six categories of AS configurations and four categories of LS are proposed in relation to evacuation aspects during SUODs (e.g., number and location of escape routes [13, 16], functional aspects related to usual traffic level and accessibility [8, 17]) and SLODs-related factors (e.g., orientation and solar exposure, natural ventilation and pollutant concentration) [18].

The second section focuses on geometrical-spatial characteristics [19] that hinder OS Frontier and OS Content from being seamless. Indeed, porches and special buildings in OS frontier can be linked to structural weaknesses due to typical failure mechanisms. Moreover, height differences and micro vulnerabilities (e.g., canopy, monuments) [20] can influence users' reactions in the evacuation process, while water and green area can mitigate the increasing temperatures and air pollution. OS permeability and spatial organization (e.g., access number and type, number of continuous built front, structural aggregates, and structural units) influence the evacuation process and ventilation.

The third section focuses on constructive characteristics. Specifically, the structural performances of the building fronts define OS's extrinsic vulnerability to SUODs. Indeed, the overturning of façades due to both earthquake and terrorist attacks determines the occlusion of the facing OSs, thus affecting the users' safety. The pavement material, lying, and finishing contribute to OS's intrinsic vulnerability influencing the accessibility and hence the evacuation process during an emergency [21, 22]. Moreover, façade finishing influences the solar and energy performance, concerning SLODs [18].

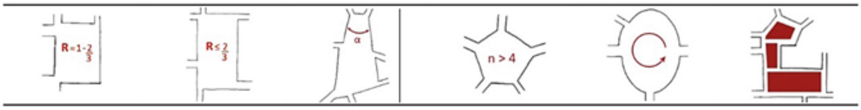
The fourth section relates to the exposure factors in terms of characteristics of use by defining potential crowding levels over time, vehicular and pedestrian accessibility, and the type of users [22]. Moreover, it outlines which aspects may hinder or facilitate the SUODs evacuation process in relation to the number of users, their behaviours, and individual vulnerability [1, 23, 24]. In particular for a terrorist attack, the intended uses of OS and OS facing buildings suggest the evaluation of the "exposed value" and determine the risk class depending on the type of target (i.e., soft or hard target) [25].

The fifth section focuses on context characteristics linked to the OS site [12]. These factors are related to the climatic zone, which contributes to the definition of SLODs hazard level (e.g., maximum temperatures, solar radiation, natural ventilation) [35] and the potential type of SUODs. Moreover, the types of infrastructural networks

**SECTION 1: MAIN TYPE**

***AREAL SPACE:***

| 1.Tending to quadrangle | 2.Elongated with parallel sides | 3.Tending to triangular and funnel-shaped | 4.Trapezoidal and polygonal | 5.Tending to circular, ovoid and ellipsoid | 6. Composite |
|---|---|---|---|---|---|




***LINEAR SPACE:***

| 1. Passage | 2. Traditional street | 3. Main street | 4.Gateway/Mobility street |
|---|---|---|---|

**DIMENSIONS:**

| | |
|---|---|
| Area ($m^2$) | Orientation |
| H max built front (m) | Sea level (m) |
| H min built front (m) | |

N

**draw a scheme of the OS with the main dimension and accesses location*

**SECTION 2: CHARACTERISTICS OF GEOMETRY AND SPACE**

| *FRONTIER* | | | | *CONTENT* | | | |
|---|---|---|---|---|---|---|---|
| SA (Structural Aggregates) | | | | Special building | | | |
| Aggregated (SU≥1) | ☐ | Isolated (SA=SU) | ☐ | | | | |
| SUi (Interferent Structural Unit) | | | ☐ | Church | ☐ | City Hall | ☐ |
| CBF (Continuous Built Front) | | | ☐ | Theatre | ☐ | School | ☐ |
| Access | | | | Museum | ☐ | Other: .................... | ☐ |
| Vehicular | ☐ | Pedestrian | ☐ | Canopy | | | ☐ |
| Controlled /with obstacles | | | ☐ | Fontaine | | | ☐ |
| Special building | | | | Monuments (i.e. obelisk, statues) | | | ☐ |
| Church | ☐ | City Hall | ☐ | Dehors | | | ☐ |
| Theatre | ☐ | School | ☐ | Height difference | | | |
| Museum | ☐ | Other: .................... | ☐ | Upward (i.e. stairs, ramps, containment walls) | | | ☐ |
| Porches | | | ☐ | Downward (i.e. stairs, ramps, balconies) | | | ☐ |
| Water / Green area | | | ☐ | Archaeological sites | | | ☐ |
| Height difference | | | | Water / Green area | | | ☐ |
| Upward (i.e. stairs, ramps, containment walls) | | | ☐ | Underground park | | | ☐ |
| Downward (i.e. stairs, ramps, balconies) | | | ☐ | Underground cavities | | | ☐ |

**Fig. 1** Rapid survey form to collect and manage risk factors (both pages)

## SECTION 3: CONSTRUCTIVE CHARACTERISTICS

| *FRONTIER* | | *CONTENT* | |
|---|---|---|---|
| Homogeneity of built environment age | | Pavement materials (i.e. marble, travertine…) | |
| Yes ☐ | No ☐ | Pavement lying (i.e. compact, disjointed, big slabs, small tiles, cobblestones…) | |
| Homogeneity of constructive techniques | | | |
| Yes ☐ | No ☐ | Pavement finishing (i.e. smooth, coarse, irregular…) | |
| Façade finishing (e.g. albedo coefficient...) | | | |
| Urban furniture/obstacles | | Urban furniture/obstacles | |
| Benches ☐ | Flowerpot ☐ | Benches ☐ | Flowerpot ☐ |
| Bumps ☐ | Railings ☐ | Bumps ☐ | Railings ☐ |
| Poles ☐ | Traffic barriers ☐ | Poles ☐ | Traffic barriers ☐ |
| Bike Rack ☐ | Other: .................... ☐ | Bike Rack ☐ | Other: .................... ☐ |

## SECTION 4: CHARACTERISTICS OF USE

| | | | |
|---|---|---|---|
| Daily crowding | | Strategic buildings | |
| Morning ☐ | Afternoon ☐ | City Hall and administrative buildings ☐ | Operational headquarters for emergency management ☐ |
| Evening ☐ | Night ☐ | Law enforcement offices ☐ | Healthcare facilities ☐ |
| Special uses of open space | | Sights | |
| Concerts ☐ | Theater ☐ | Overall Areal o Linear Space ☐ | Church ☐ |
| Parking ☐ | Festivals ☐ | City Hall ☐ | Theatre ☐ |
| Other: .................... | ☐ | Museum ☐ | Other: .................... ☐ |
| Accessible to | | Sensitive targets | |
| Vehicle ☐ | Pedestrian ☐ | High profile people ☐ | Symbolic buildings ☐ |
| Bike /Scooter ☐ | Other: .................... ☐ | Tourists or crowd of them | ☐ |

## SECTION 5: CONTEXT CHARACTERISTICS

| | | | |
|---|---|---|---|
| Climate classification [DPR 412/1993] | | Hazard assessment | |
| A ☐ | B ☐ | Earthquake ☐ | Landslide ☐ |
| C ☐ | D ☐ | Tsunami ☐ | Wildfire ☐ |
| E ☐ | F ☐ | Mass Movement (dry) ☐ | Chemical ☐ |
| Infrastructural network | | Volcanic activity ☐ | Explosion/fire ☐ |
| | | Storm/tornado ☐ | Transport accident ☐ |
| Primary urbanization ☐ | Uncovered pipes ☐ | Extreme temperature ☐ | Terrorist attack ☐ |
| High tension wire ☐ | Other: .................... ☐ | Flood ☐ | Miscellaneous accident ☐ |

**Fig. 1** (continued)

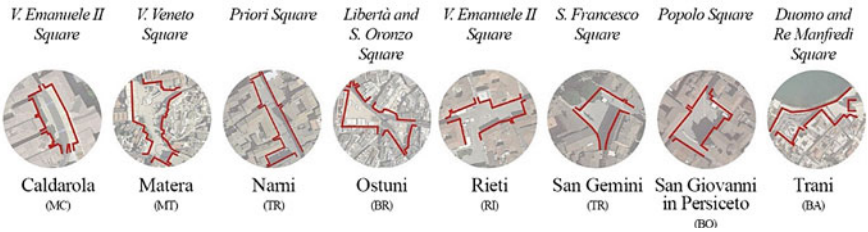



**Fig. 2** Areal spaces of eight case studies for the application of the survey form

that may be susceptible to damage (e.g., explosions or fires to primary infrastructures triggered by the collapse of adjacent structures during SUODs) are taken into account.

### *2.2 Application to Eight AS Case Studies*

In view of the territorial application context of the BE S$^2$ECURe project and of the wide variety of construction culture of the Italian historical centers, the survey form has been applied to 8 case studies (ASs) to evaluate the efficacy of the procedure regarding the complexity of their morphological configurations (Fig. 2).

The case studies are representative of various layout configurations of OS in the Italian territory by different geographical locations, types, dimensions, and populations. The eight squares belong to medium-sized cities (between 5,000 and 50,000 inhabitants) and small cities (less than 5,000 inhabitants), which represent more than 90% of the total Italian municipalities and about 70% of the national resident population [36]. These ASs are located in cities representing different historical-architectural and construction traditions, with various geometric, spatial, and uses-related features.

## 3 Results

The application to real case studies confirms the accuracy of the survey form parameter for describing unambiguously and completely the characteristics of an OS. The data collected by the application on the eight ASs are analysed for each survey form section, distinguishing between data referring to frontier and content of OS (Fig. 3).

Considering Sect. 1 of the form, two squares belong to the "tending to quadrangle" morphological category (San Gemini and San Giovanni in Persiceto-SGP), one to the "elongated with parallel sides" one (Caldarola), one to the "tending to triangular" category (Ostuni, which is composed of two spaces tending to the triangle shape), and four to the "composite" category (Rieti, Narni, Matera, and Trani). For Sect. 2 of the form, the SA median value is 6, with a maximum of 9 for Ostuni

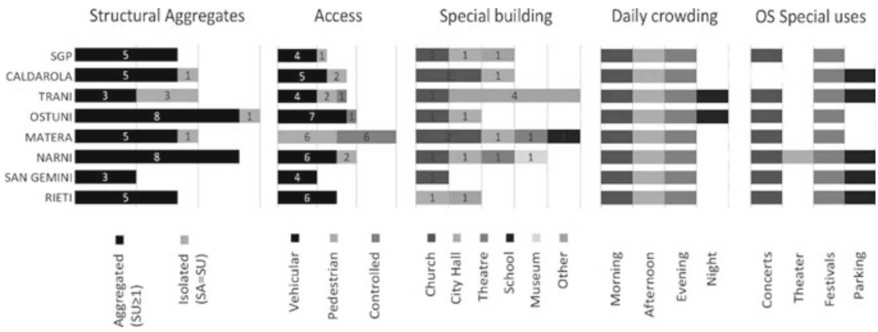



**Fig. 3** Charts of the data of the eight case studies: relation between the number of Structural Aggregates SA and interferent Structural Units—SUon the AS frontiers; number and type of accesses to AS; types of special buildings on the AS fronts; crowding data with respect to time stages; special and temporary uses of the AS

and a minimum of 3 for San Gemini. The access parameter, differentiated by types (pedestrian, vehicular and controlled access), has a median value of 7 accesses per square, with a minimum of 4 for San Gemini and a maximum of 12 for Matera. The median value of special buildings is 3, with a minimum of 2 for Rieti, San Gemini, and Ostuni, and a maximum of 7 for Matera. Considering Sect. 3 of the form, all the cases present a non-homogeneity of construction techniques and BE age, except for Caldarola. With regard to the pavement features, there is an equal number of cases with compact and non-compact lying, with a prevalence of cases with an irregular finishing (6 out of 8). Considering Sect. 4 of the form, a homogeneous trend of OS use during the day and afternoon is noticed for all the cases, with the exception of Trani and Ostuni which are also characterised by significant evening use. AS main special function is related to festivals and concerts, while theatre performances are present in only one case. The strategic building's median value is 1, with a maximum of 3 for San Giovanni in Persiceto. The tourist attractions parameter has a median of 2, with a maximum of 5 for Narni and Matera. Finally, considering Sect. 5 of the form, significan multi-hazard conditions are noticed, as well as hazard-affecting factors (i.e. infrastructural). In particular, the median value of hazards is 6, with a minimum of 5 for Matera and a maximum of 7 for Caldarola.

According to the survey form capabilities in describing the complexities of historical risk-prone OSs, the risk factors recurrence analysis has been used to select the most relevant ASs cases. By performing this analysis, in which the factors are not weighted to highlight the risk factor repository nature rather than risk assessment, it was possible to find the most significant case studies for a deeper investigation in view of multi-risk scenario creation. Figure 4 shows the total number of retrieved risk factors divided by section for each case study. Thus, the value points out the overall complexity of the characteristics of the AS. In general, the sum of the parameters is around a range between 65 and 75 (median = 68). The trend highlights that the AS complexity is mainly defined by the characteristics of geometry and space, where the high presence of frontier elements emerges. The second element of complexity is

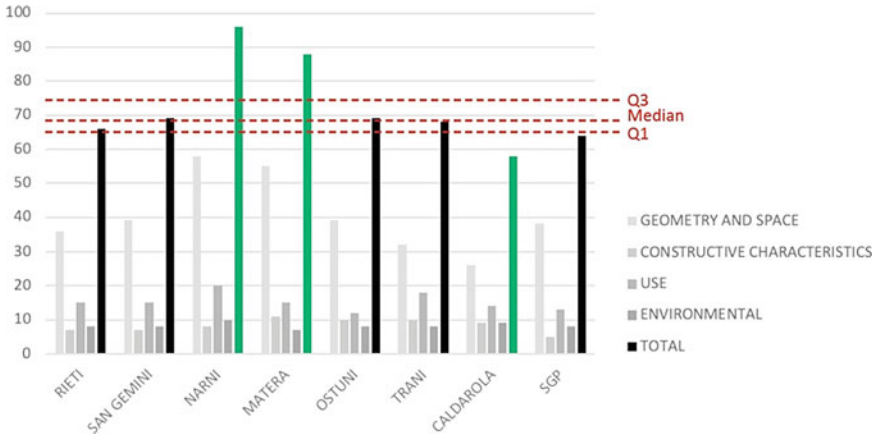



**Fig. 4** Results of the recurrence analysis of the collected data: Narni and Matera are cases of higher complexity, exceeding the Q1 threshold; Caldarola is the case of lower complexity since the total score is under the Q3 threshold

related to the use of space, confirmed by the results of the partial values in Fig. 3 about the daily crowding and the uses. The most relevant case studies have been identified according to the 25% percentile data, so values lower than the first quartile ($x < Q1 = 65.5$) and values higher than the third quartile ($x > Q3 = 74$) can be considered interesting because they represent extreme complexity within the sample. These 3 cases are marked in green in Fig. 3: Narni (96) and Matera (88) report the highest values exceeding Q1 threshold, while Caldarola the lowest (58), under Q3 threshold.

## 4 Insight and Future Works

The application of the form allows describing BE scenarios and its reliability in a multi-risk perspective. Firstly, the form innovatively collects OSs risk factors distinguishing its content (the outdoor space) and its frontier (surrounding buildings), thus allowing practitioners to evidence if OSs risk-affecting complexities rely more on the first or second set of factors. Moreover, the expeditious nature of the survey form is given by its checklist structure, with mainly Boolean evaluations or estimations of the number of the elements. Input data can be retrieved through existing databases (e.g. constructive features, use and function, context factors) already available at the local and municipal level (e.g.: through geo-referenced data) or easily consulted remotely (e.g.: through Geographic Information Systems-GIS). Therefore, the form allows a quick application by local administrations and non-expert technicians employed for developing multi-risk analysis and promoting mitigation strategies. Indeed, the approach presented could support the elaboration of specific actions for each case study based on simulation-oriented tools, starting from the selected characteristics, proposing and evaluating tailored risk-mitigation strategies. Despite the limited number of case study selected, they can be considered sufficient to consolidate the survey form structure for future application. Future developments in BE $S^2$ECURe project will use this preliminary study to expand the OSs sample in order to retrieve recurring complexity levels in historical OSs. According to the project goals [11], trends in the OSs features can be managed to define typological conditions of the BE, thus representing them through digital tools (GIS/BIM) and supporting practitioners in classifying the BE risks in homogeneous categories.

## 5 Conclusions

The Built Environment (BE) characterization requires knowledge of risk factors that may affect its performance during the emergency in order to assess its resilience to disasters. Due to the complexity BE-users interactions and the multiple hazards affecting the BE, a multi-risk approach should be pursued. This work proposes a methodology for characterizing the main risk factors of Open Spaces (OS) in the Built Environment (BE), as meso-scale elements that play a key role before and during emergency phases and influence the users' exposure and behaviour. A quick survey form for Areal Spaces (ASs) and Linear Spaces (LSs) is offered, intending to provide a proper repository for Sudden (SUODs) and SLow (SLODs) Onset Disasters risk factors, in terms of morphological, geometrical, constructive, intended use and context features of the OSs. Results validate the reliability of the survey form as risk factors repository for 8 Areal OSs, which were selected to include a variety of real BE conditions within the Italian territory. The form can also be extended to the entire urban settlements risk assessment, especially in case of complex interconnection between OSs, and applied to non-historical OSs, given the related form modifications.

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## References

1. Quagliarini, E., Lucesoli, M., Bernardini, G.: How to create seismic risk scenarios in historic built environment using rapid data collection and managing. J. Cult. Herit. **48**, 93–105 (2021)
2. Sharifi, A.: Urban form resilience: a meso-scale analysis. Cities **93**(May), 238–252 (2019)
3. Giuliani, F., De Falco, A., Cutini, V.: The role of urban configuration during disasters. A scenario-based methodology for the post-earthquake emergency management of Italian historic centres. Saf. Sci. **127**, 104700 (2020)
4. Feliciotti, A., Romice, O., Porta, S.: Design for change: five proxies for resilience in the urban form. Open House Int. **41**(4), 23–30 (2016)

5. Commissione tecnica per la microzonazione sismica: Manuale per l'analisi della condizione limite dell'emergenza (CLE) dell'insediamento urbano, Roma (2014)
6. Currà, E., Angelosanti, M., D'Amico, A.: integrated digital tools for earthquake risk reduction in historic urban landscape of Central Italy. In: 4th Digital Landscape International Symposium (2019)
7. Russo, M., et al.: Morphological systems of open spaces in built environment prone to Sudden-onset disasters. In: International Conference on Sustainability in Energy and Buildings SEB 2020, pp. 1–10 (2020)
8. Oliveri, M. (a cura di): Regione Umbria. Vulnerabilità urbana e prevenzione urbanistica degli effetti del sisma, il caso di Nocera Umbra. Urban. Quad. (2004)
9. Choi, Y., Yoon, H., Kim, D.: Where do people spend their leisure time on dusty days? Application of spatiotemporal behavioral responses to particulate matter pollution. Ann. Reg. Sci. **63**(2), 317–339 (2019)
10. Rus, K., Kilar, V., Koren, D.: Resilience assessment of complex urban systems to natural disasters: a new literature review. Int. J. Disaster Risk Reduct. **31**(January), 311–330 (2018)
11. Quagliarini, E., Currà, E., Fatiguso, F., Mochi, G., Salvalai, G.: Resilient and user-centered solutions for a safer built environment against sudden and slow onset disasters: The BE S2ECURe Project. In: Littlewood J.L.C., Howlett, R.J. (eds.) Sustainability in Energy and Buildings 2020. Smart Innovation, Systems and Technologies, vol. 203. Springer, Singapore (2021)
12. WHO: Definitions: emergencies (2014). [Online]. Available: https://www.who.int/hac/about/definitions/en/. Accessed: 29 Nov 2019
13. Enrico Mandolesi and Alessandra Ferrero, Piazze del Piceno. Gangemi Editore spa (2001)
14. Caniggia, G., Maffei, G.L.: Architectural Composition and Building Typology: Interpreting Basic Building. Alinea Editrice, Florence (2001)
15. Conzen, M.R.G.: L'analisi della forma urbana. Alnwick, Northumberland, vol. 13. Alnwick, Northumberland.: FrancoAngeli (2013)
16. Ronzani, G., Boschi, F.: Contributi di metodo per la lettura degli spazi urbani. CLUEB (2001)
17. Forbes, G.: Urban Roadway Classification. Urban Str. Symp, Dallas, Texas (1999)
18. Salvalai, G., Moretti, N., Blanco Cadena, J.D., Quagliarini, E.: SLow onset disaster events factors in Italian built environment archetypes. In: Smart Innovation, Systems and Technologies, vol. 203 (2021)
19. Anelli, A., Mori, F., Vona, M.: Fragility curves of the urban road network based on the debris distributions of interfering buildings. Appl. Sci. 10(1289) (2020)
20. León, J., Mokrani, C., Catalán, P., Cienfuegos, R., Femenías, C.: The role of built environment's physical urban form in supporting rapid tsunami evacuations: Using computer-based models and real-world data as examination tools. Front. Built Environ. 4 (2019)
21. Dan, H.C., He, L.H., Xu, B.: Experimental investigation on skid resistance of asphalt pavement under various slippery conditions. Int. J. Pavement Eng. **18**(6), 485–499 (2017)
22. Quagliarini, E., Bernardini, G., Santarelli, S., Lucesoli, M.: Evacuation paths in historic city centres: a holistic methodology for assessing their seismic risk. Int. J. Disaster Risk Reduct. **31**(July), 698–710 (2018)
23. Bosina, E., Weidmann, U.: Estimating pedestrian speed using aggregated literature data. Phys. A Stat. Mech. Its Appl. **468**, 1–29 (2017)
24. Zhu, X., Sun, B.: Study on earthquake risk reduction from the perspectives of the elderly. Saf. Sci. **91**, 326–334 (2017)
25. Woo, G.: Understanding the principles of terrorism risk modeling from Charlie Hebdo Attack in Paris. Def. Against Terror. Rev., 1–11 (2015)

# Impact of Climate and Economic Scenarios on the Global Costs of Nearly Zero Energy Buildings Renovations. A Stochastic LCC on a Reference Multi-story Building

**Elisa Di Giuseppe, Gianluca Maracchini, and Marco D'Orazio**

**Abstract** National long-term building renovation strategies should reduce the actual financial gap between nearly Zero Energy (nZE) and "minimum energy requirement" levels, to enlarge the impact of buildings' energy saving on climate neutrality. However, the design of specific policies to bridge this gap strongly depends on the long-term expected value and volatility of the macroeconomic environment during the building's lifetime. Standardized Life Cycle Costing methods disregard the long-term uncertainty affecting the macroeconomic variables and consequently misrepresent the associated risk on the economic convenience of building renovation. The present work applies a "stochastic" approach to LCC on alternative renovation options of a reference building located in different Italian climate areas towards the nZE target. The analysis focuses on the analysis of the impact of alternative macroeconomic scenarios on the investment gap between the "cost-optimal" and the nZE solutions. A widespread application of this methodology in the context of the European "Cost-Optimal" framework would allow establishing specific funding schemes and financing instruments to push a real "renovation wave" of EU buildings.

## 1 Introduction

The building sector in Europe (EU) is responsible for more than one-third of the emissions from energy [1] and 84% of building heating and cooling energy demand is still generated from fossil fuels [2]. This is essentially because EU building stock is very old hence almost 75% of it is energy inefficient according to current standards [3]. However, the annual energy renovation rate of EU buildings is low at some 1% and the annual rate of deep renovation (aiming to reduce energy consumption by at least 60%) is only 0.2% [4]. For this reason, the European Commission recently published its "Renovation wave" strategy, to double renovation rates in the next ten

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years, leading to higher energy and resource efficiency and reducing people's energy poverty, to reach climate-neutral Europe by 2050 [4].

Supporting the transformation of existing building stock towards the so-called "nearly Zero Energy" (nZE) standards is then a crucial requirement under the current legal EU framework [5]. Member States (MSs) shall furthermore "*develop policies and take measures such as the setting of targets in order to stimulate the transformation of buildings that are refurbished into nearly zero-energy buildings*" [6].

The EU directive 2010/31 on the Energy Performance of Buildings, the "EBPD recast", [6] established the principle of "cost-optimality" to guide MSs in setting buildings energy performance requirements in their national codes. The "Cost-Optimal" (CO) level of building energy performance is that which leads to the lowest global cost during a certain calculation period and can be considered as the minimum level of ambition for both building renovation and new buildings [5]. The CO calculation framework [7, 8] has been applied in 2013 by MSs to review their national building energy performance requirements and should be updated every five years to provide incentives to meet the energy performance thresholds for nZEBs.

Indeed, cost-benefits ratios are still more favorable for "light and medium" energy renovation than for deep nZE renovation [9]. National long-term renovation strategies in line with the EPBD should address this challenge to reduce the actual financial gap between nZEB and CO levels.

The design of specific policies to bridge this financial gap strongly depends on the long-term expected value and volatility of the macroeconomic environment during the building lifetime. However, standardized Life Cycle Costing (LCC) methods, as that used for the EU CO framework (the EN 15459-1:2017 [10]) disregard the long-term uncertainty and interdependence affecting the macroeconomic variables and consequently distort the impact of the associated risk on the economic convenience.

Some recent works provided contributions to make the stochastic nature of the macroeconomic variables explicit in LCC assessments [11–14]. Among these, Baldoni et al. [14] developed Vector AutoRegression models of four alternative macroeconomic scenarios based on real data, to perform LCC in different macroeconomic contexts and to evaluate how much these contexts influence the outcomes, especially the financial gap between a CO and a nZE solution. The present work contributes to this literature on stochastic LCC by presenting a new case study application, where the stochastic LCC is performed on alternative renovation options of a reference building located in different Italian climate areas towards the nZE target. The analysis focuses on the comparison among the macroeconomic scenarios and their impact on the investment gap between the CO and the nZE solutions.

## 2 Methodology

The assessment follows the typical CO calculation framework defined in the EPBD recast and subsequent regulations, with the following main steps: (i) identification of the Energy Efficiency Measures (EEMs) and their combination into several Renovation Solutions (RSs) for each climate area, with increasing energy performance levels towards the nZE target; (ii) evaluation of related investment and maintenance cost, and of service life of building components and equipment; (iii) calculation of the building primary energy consumption for each RS and in each climate area; (iv) assessment of the related Global Costs (GC) through the stochastic LCC, also considering future alternative macroeconomic scenarios.

## 2.1 The Building Case Study

The analyzed building is a small block of 3 floors and 6 apartments (Fig. 1). It is a real building in terms of geometric dimensions (a plan 16.36 m × 10.25 m), but which can be considered a typical archetype of buildings from the 1960s–1970s in Italy, which are about 6 million, out of a total of 30 million residential buildings. The typological and constructive features, drawn from the documents of the TABULA and EPISCOPE projects [15], are common even in later periods, making the building exemplary of a rather extensive part of the building stock. The building has a framed structure in reinforced concrete with 20 cm high brick-concrete floors (U-value = 2.19 W/m$^2$K). The external walls are made of double-facing hollow blocks with an air gap for a total thickness of 30 cm (U-value = 1.14 W/m$^2$K). Windows are made of wood and single glass (U-value = 4.90 W/m$^2$K). The heating and Domestic Hot Water (DHW) system for each flat consists of a conventional gas boiler (24 kW peak power) and radiators regulated by an ON/OFF thermostat. The building has a heated usable area of approximately 387 m$^2$, a heated gross volume (V) of approximately 1470 m$^3$, a dispersing surface (S) of approximately 920 m$^2$. The S/V ratio is equal to 0.626.

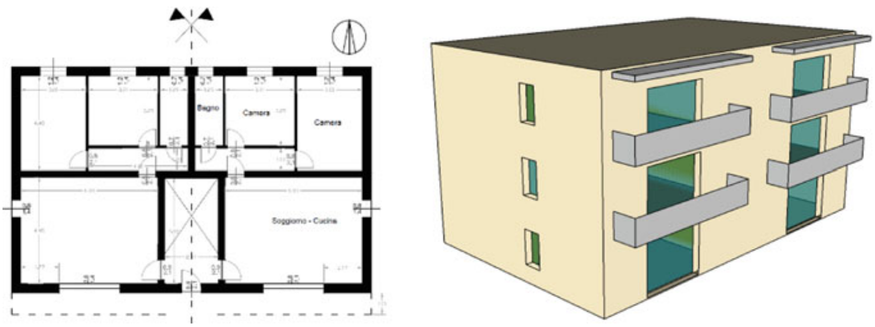


**Fig. 1** Representation of the plan type and Schematic three-dimensional model of the building

### 2.2 The Renovation Solutions and the Evaluation of the Energy Performance

The EEMs have been identified based on technical feasibility and existing literature, to reduce heating and DHW consumptions. In this study, other energy uses (conditioning, lighting) are neglected for the sake of brevity and of consistency with the actual CO calculation framework implemented in Italy.

For what concerns the building envelope, insulation systems based on Expanded Polystyrene (EPS) were used from the exterior, for the external walls, and from the interior, for the walls and floors between neighboring apartments or towards the stairwell. Thermal insulation was also planned for the building basement and roof, to be applied after removing pavement and roof tiles. Progressive performance levels have been identified for each EEM. In particular, for the opaque envelope, 5 levels were obtained with increasing insulation thickness. Levels 3 and 4 refer to the "minimum requirements" solutions (hereafter MR) according to the Italian legislation, to be considered, respectively, before and after 2021, while level 5 to the nZE building Italian definition [16].

Concerning the interventions on the windows, PVC frames were used for levels from 1 to 3, while aluminum frames for levels 4 and 5. Moreover, higher levels included the use of a low emissivity double-glass filled with argon gas and shading devices for windows facing the southern quadrant.

The EEMs on the building equipment for building heating and DHW generation included the use of a centralized system with a condensing gas boiler (until performance level 3) or an air-to-water heat pump (for levels 4 and 5) linked to an insulated storage tank for DHW, already set up for connection with solar panels. Moreover, a new distribution circuit with insulated pipes and properly regulation systems with increasing accuracy have been provided. Finally, as for the new electricity production equipment, it was decided to install a photovoltaic system (PV) with monocrystalline silicon cells in an increasing number in relation to the increasing level of performance.

The Italian climatic zones are classified from A to F, depending on the Heating Degree Days (HDD) (Table 1). The case study is analyzed in the five zones from B to F, given that the A area is limited to very few municipalities.

**Table 1** Features of the climate zones in Italy as established by the Italian Decree 412/1993

| Climate zone | HDD | Heating period | Maximum heating hours/day |
|---|---|---|---|
| A | <600 | 1st December–15th March | 6 |
| B | 600–900 | 1st December–31st March | 8 |
| C | 901–1400 | 15th November–31st March | 10 |
| D | 1401–2100 | 1st November–15th April | 12 |
| E | 2101–3000 | 15th October–15th April | 14 |
| F | >3000 | No limitations | No limitations |

Then, the EEMs were combined, giving rise to 5 Renovation Solution (RSs) for each climate zone, with progressively increasing energy performances, approaching nZEB with level 5. 25 building energy models were then obtained and simulated with the software "Namirial Termo v. 4.9", based on the Italian standard UNI/TS 11300 "(implementation of EN ISO 13790 [17] and ISO EN 52016 [18]).

The energy performance achieved by the building's alternative models was assessed in terms of primary energy and non-renewable primary energy requirements and the amount of consumed energy (according to the different considered energy sources, i.e. electricity (kWh) and natural gas ($m^3$)).

## 2.3 The Stochastic LCC Assessment

According to the CO framework, the GCs of the proposed RSs have been evaluated in a calculation period of 30 years, based on the procedure of EN 15459-1:2017. The following cost categories were included in the assessment: the initial investment and the annual maintenance costs of the EEMs; the replacement cost of EEMs at a specific year; the annual energy cost. The calculation was expressed in real terms and the discount factor (depending on the inflation rate and nominal interest rate) and the price development rates for human operations and energy were considered as yearly variable.

The stochastic LCC couples the Global Cost calculation to Monte-Carlo methods, i.e. values are selected from the Probability Density Functions (PDF) of input data and inserted into the GC equation for 5000 iterations, to get the PDF of the resulting outcomes. Moreover, the stochastic assessment is performed considering four alternative macro-economic scenarios, characterized by different distributions of the macro-economic variables entering the calculation (Table 2). The "regular growth" scenario represents the "baseline" and the actual economic condition in EU.

In addition to the macroeconomic variables, all the inputs' PDFs of Eq. (1) have been estimated according to the following assumptions. The mean values of the investment costs of the EEMs have been retrieved from the Italian regional price lists for building works. A uniform distribution (±10% around the mean) has been then applied considering the prices geographical variability and possible contingencies. For the service life, a uniform distribution is used with a variation of ±20% around the mean value to take into account the high uncertainty [61]. Uniform distributions of energy costs (gas and electricity) were obtained with the statistical analysis of the data retrieved from the national database [62], considering their variability, both regional and in relation to the consumption range. 100 GC distributions have been obtained from the stochastic LCC assessment of the 5 RSs in 5 climatic zones and under 4 macroeconomic scenarios.

**Table 2** Summary statistics (Mean and Standard Deviation, SD, of distributions, in %) of the macroeconomic scenarios, which are extensively described in [14]

| | Inflation rate | | Interest rate | | GDP | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Regular growth | 2.25 | 0.97 | 2.77 | 0.78 | 2.54 | 1.64 |
| | = | | = | | = | |
| Intense growth | 2.55 | 0.63 | 3.45 | 0.73 | 3.31 | 1.19 |
| | ↑ | | ↑ | | ↑ | |
| Stagflation | 8.41 | 3.35 | 4.81 | 0.32 | 0.34 | 3.21 |
| | ↑ | | ↑ | | ↓ | |
| Deflation | 0.46 | 1.11 | 1.50 | 0.63 | 1.34 | 1.62 |
| | ↓ | | ↓ | | ↓ | |

Gross Domestic Product (GDP) proxies the growth rate of prices for human operation. = identifies the "regular growth" scenario, the baseline case, ↑ means higher than the baseline, ↓ means lower than the baseline

## 3 Results

Figure 2a shows the initial investment costs for each RSs. The CI in all zones ranges from an average value of 397 €/m$^2$ for RS 1 to 865 €/m$^2$ for RS 5 (+117%). The investment gap between RS 3 (the MR of the Italian legislation) and RS 5 (the nZEB) is on average about 325 €/m$^2$ (60% difference).

The heating and DHW primary energy need of the various RSs differently ranges from a climatic zone to another one (Fig. 2b, c). Figure 2b shows that, in the warmest zone A + B, the primary energy consumption goes from a minimum of 25.44 kWh/m$^2$y for RS 5 (nZE solution) to a maximum of 45.79 kWh/m$^2$y in RS 1. In the coldest zone F, the range goes from a minimum of 70.95 kWh/m$^2$y to a maximum of 126.38 kWh/m$^2$y. Therefore, the energy-saving obtained in all zones progressing from RS 1 to the nZE standard is huge: the nZEBs can save around 44–48% of energy compared to RS1 and 27–40% compared to the "minimum requirements" renovations according to the Italian legislation (RSs 3). Focusing on the non-renewable primary energy (Fig. 2c), it can be noticed a largerz gap between the renovation scenarios 1 and 5 in all zones, due to the large component of energy from renewable sources, especially in scenarios 4 and 5.

However, the only energy saving perspective is not sufficient to establish the "optimal" solution from the point of view of affordability, i.e. the solution capable of minimizing the global costs over a sufficiently long time-horizon. Figure 3 then represents the GC obtained from the LCC assessments performed for all RSs in all the climatic zones (vertical axis) compared to their energy performance (non-renewable primary energy needs for winter heating and DHW in the horizontal axis). This graph reports the results obtained under the Regular Growth macroeconomic scenario, which can be considered the baseline scenario, where usual CO evaluations are performed. Results of the stochastic LCC return the PDF of the GC for each analyzed

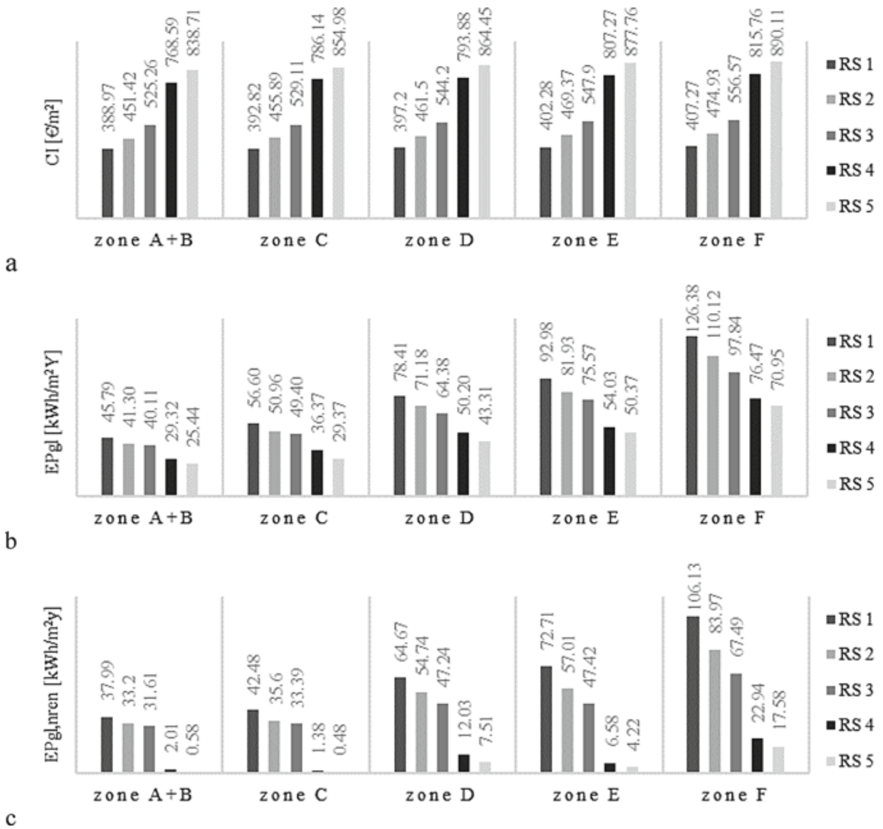


**Fig. 2** **a** Initial investment costs, **b** Primary energy consumption for heating and **c** Non-renewable primary energy consumption for heating and DHW of all the RSs

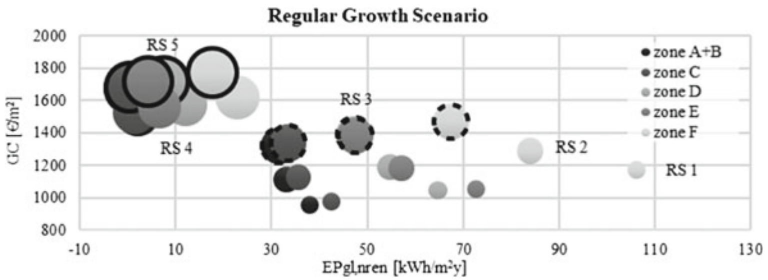


**Fig. 3** Stochastic Global Costs (y-axis) and energy performance (x-axis) of all RSs computed in all climatic zones under the macro-economic scenario "Regular Growth". The center of the "bubbles", identifies the mean GC, while the diameter the GC standard deviation

case. Therefore, any RS case is displayed in the form of a "bubble", whose center identifies the mean GC while the diameter the GC standard deviation. The different colors identify the climatic zones, while RSs ranging from 1 to 5 can be easily spotted looking at their decreasing energy consumption. For better understanding, bubbles referring to RSs 5 (nZEB) are surrounded by a solid line, while those of RSs 3 (MR) by a dashed line.

It can be noticed that the lowest mean GC is achieved by RS 1 in all climatic zones and ranges from about 950 €/m$^2$ (zone A + B) to 1170 €/m$^2$ (zone F). This means that, even if NZE solutions (RSs 5) can reduce energy until 48% compared to RSs 1, this saving is not sufficient to compensate, in a time horizon of 30 years, the investment costs, that are higher on average by 117% (as shown in Fig. 2a), and the higher related operating costs for maintenance and replacement of components. The GC of the MR solutions (RSs 3) ranges from about 1320 €/m$^2$ (zone A + B) to 1465 €/m$^2$ (zone F). Hence, the financial gap between the nZEBs and the actual standard construction for this case study is, on average, about 24%, with an average performance difference of about 34%. It is also noteworthy that the MR solutions (RSs 3), which have been defined based on the Cost-Optimal calculation framework introduced by the EU EPBD recast, do not correspond to the "cost-optimal" solutions, in this specific case study. Indeed, RSs 1 reach a lower GC, even with a worse energy performance.

The stochastic approach to LCC is made evident by the size of the bubbles (i.e. the standard deviation of the GC outcome), which, in certain cases, can make the result not unique. This is especially true for RS4 and RS 5, where the circumferences overlap in all climatic zones. The size of the bubbles considerably varies across the RSs, progressively growing towards the nZE scenarios. This finding is in disagreement with that of Baldoni et al. [14] and is due to the different methods of identification of inputs' PDFs. Indeed, it is observed that, while in Baldoni et al. a predetermined uncertainty (a uniform distribution within a variation range of ± 10%) was assigned to all stochastic inputs of the LCC analysis, in this study the uncertainties to the input data are assigned differently (as seen in Sect. 2.3). In particular, the energy tariffs have a lower uncertainty than in Baldoni et al. [14], as they were defined with an in-depth analysis of data for all climatic zones, and also based on the consumption thresholds reached in the various RSs. As a consequence, there is a greater variability of these tariffs in the less energy-intensive case studies. Finally, the higher uncertainty of GC in nZE solutions can also be due to the highest running costs for maintenance and replacement of components.

The analysis of LCC outcomes across the alternative macroeconomic scenarios is presented in Fig. 4 within a mean (x-axis)—coefficient of variation (y-axis) space. It emerges that the computed GCs are greatly influenced by the macroeconomic scenarios. For instance, concerning the RS 1, compared to the baseline, the mean GC increases by about 12% in the deflation scenario, while decreases by about 29% in the stagflation scenario. For RS 3, the mean GC increases by about 7% in the deflation scenario and decreases by about 27% in the stagflation scenario. Finally, it is worth noting that, for the nZEB (RS 5), the mean GC has only a slight increase in the deflation scenario (about 1.5%), while decreases by about 24% in the stagflation

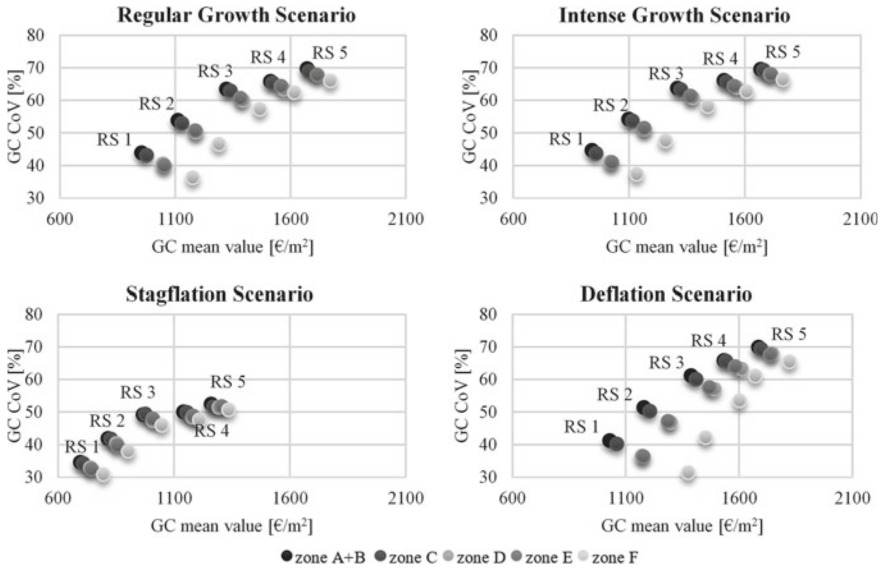


**Fig. 4** Stochastic LCC outcomes for all the macroeconomic scenarios presented within a mean—coefficient of variation (CoV) space

scenario. Moreover, in the deflation scenario, differences among the results obtained in the climatic zones are more noticeable. GCs in the coldest climatic zones are quite higher. Conversely, in the intense growth scenario, the GC outcomes are similar to those obtained in the regular growth scenario (differences lower than 3% in all zones and RSs). Apparently, the GC variation across scenarios is mostly due to the running costs for building heating, which are lower for the nZE solutions and in the warmest climatic zones.

Contrary to the findings of the case study analyzed by Baldoni et al. [14], in this analysis, the alternative economic scenarios do not entail a totally different ranking of the most cost-effective solutions, even if, as also stated by Baldoni et al. [14], in the stagflation scenario energy costs are less relevant and make RSs closer. This is because the analyzed renovation solutions for the building case study allow reaching an excellent thermal performance, although in the face of very high investments. In all macro-economic scenarios and climatic zones, the share of the investment cost is always higher than 50% of all global cost components. GCs are on average about 70% in RSs 1, 2 and 3, and always exceed 80% in RS 4 and 5. It can be also noticed from Fig. 4, how the GC variability (coefficient of variation) is influenced by the macroeconomic environment, especially in the stagflation scenario. However, also considering the uncertainty affecting the results, the ranking on the CO solutions appears clear and consistent among all scenarios. Finally, Fig. 4 also highlights that the difference between the RSs, especially in terms of financial gap between nZE and

MR solutions, depends on the underlying macroeconomic environment. Compared to the regular growth scenario, in all climatic zones, the financial gap slightly increases, from +24% to +25.4% and +29.2%, under intense growth and stagflation scenarios, respectively. Conversely, it decreases to +18.2% in the deflation scenario.

## 4 Conclusions

As demonstrated by the application presented in this paper, a "stochastic" approach to LCC, able to consider the volatility and variability of related inputs and especially the macroeconomic context of the analysis, is a useful tool to understand the variations of Global Costs results under different macroeconomic and climate scenarios. A widespread application of this methodology in the context of the EU CO framework would allow to better investigate at which conditions cost-benefits rations are more favorable for "light" buildings' energy renovation than for deep nZE ones. This is needed to develop proper funding schemes and financing instruments to reduce the actual economic gap among nZE and "minimum energy requirements" solutions.

## References

1. European Commission: Energy efficient buildings (2021). https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings. Accessed 31 March 2021
2. European Commission (EC): Heating and Cooling (2021). https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling. Accessed 3 March 2021
3. Filippidou, F., Jimenez Navarro, J.: Achieving the cost-effective energy transformation of Europe's buildings (2019). https://doi.org/10.2760/278207
4. European Commission: Annex to Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe—greening our buildings, creating jobs, improving lives (2020)
5. European Commission: Commission Recommendation (EU) 2016/1318 of 29 July 2016 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings (2016)
6. EU: Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Official Journal of the European Union (2010)
7. European Commission (EC): Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating (2012)
8. European Commission (EC): Guidelines accompanying Commission Delegated Regulation (EU), no. 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology (2012)
9. Esser, A., Dunne, A., Meeusen, T., Quaschning, S., Denis, W.: Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU Final report (2019)

10. CEN European Commitee for Standardization, EN 15459-1:2017. Energy performance of buildings - Economic evaluation procedure for energy systems in buildings - Part 1: Calculation procedures, Module M1-14 (2017)
11. Burhenne, S., Tsvetkova, O., Jacob, D., Henze, G.P., Wagner, A.: Uncertainty quantification for combined building performance and cost-benefit analyses. Build. Environ. **62**, 143–154 (2013). https://doi.org/10.1016/j.buildenv.2013.01.013
12. Baldoni, E., Coderoni, S., D'Orazio, M., Di Giuseppe, E., Esposti, R.: The role of economic and policy variables in energy-efficient retrofitting assessment. A stochastic life cycle costing methodology. Energy Policy **129**, 1207–1219 (2019). https://doi.org/10.1016/j.enpol.2019.03.018
13. Fregonara, E.: Economic–environmental sustainability in building projects: introducing risk and uncertainty in LCCE and LCCA. Sustainability. (2018). https://doi.org/10.3390/su10061901
14. Baldoni, E., Coderoni, S., D'Orazio, M., Di Giuseppe, E., Esposti, R.: From cost-optimal to nearly zero energy buildings' renovation: life cycle cost comparisons under alternative macroeconomic scenarios. J. Clean. Prod. **288**, 125606 (2021). https://doi.org/10.1016/j.jclepro.2020.125606
15. Episcope (2021). https://episcope.eu/welcome/. Accessed 26 April 2021
16. D.M. "Requisiti minimi," GU Serie Generale n.162 Del 15-7-2015 - Suppl. Ordinario n. 39. (2015)
17. CEN European Commitee for Standardization, EN ISO 13790: 2008 Energy performance of buildings - Calculation of energy use for space heating and cooling (2008)
18. CEN European Commitee for Standardization, EN ISO 52016-1:2017 - Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures (2017)

# Retrofit Strategies Optimization Based on Indoor Comfort Analysis Under Real Conditions: The Case Study of the Secondary School ITC Carrara

**Rosa Romano, Alessandra Donato, and Paola Gallo**

**Abstract** The building sector has a significant potential for energy saving. At present, about 35% of the EU buildings are over 50 years old, and almost 75% of the building stock is energy inefficient. Therefore, school buildings represent a significant part of the existing building stock and a noteworthy part of total energy use. Throughout Europe, most school buildings were built between the 1950s and the 1970s and needed to be renovated, including the energy upgrade towards nearly zero energy building targets (nZEB). School buildings' energy retrofit actions have to improve building design and the upgrade of energy systems and building components solutions and focus on the indoor environmental conditions for their occupants. Besides low energy consumption, efficient school buildings have many benefits from indoor comfort (thermal, visual, acoustic, and indoor air quality). Therefore, acting on the existing building stock implies understanding user needs to define adequate energy-saving strategies. This paper aims to present a method to define and assess retrofit strategies optimization of school buildings based on users' comfort analysis under real conditions. The research approach takes into account user preferences to evaluate energy-saving opportunities. The methodology consists of the thermal comfort assessment by combining physical environmental data monitoring through in-situ measurements and submitting subjective questionnaires to the occupants. Finally, the research work presents and evaluates the results of this experimentation applied on a school building (the secondary school Carrara) built in the 60 s and located in Lucca (Italy).

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## 1 Introduction

European Union (EU) has an important challenge in achieving climate neutrality by 2050, set out the basis for the long-term strategy on Climate Change in early 2020. As part of the European Green Deal, the Commission proposed to raise the 2030 "greenhouse gas emission" reduction target, including emissions and removals, to at least 55% compared to 1990 [1].

To ensure the achievement of these objectives, Member States have to look at the actions required across all sectors, including increasing energy production from renewables and improving building energy efficiency. Accordingly, renovation of existing buildings represents one of the key-action that can significantly improve energy savings and plays a crucial role in the clean energy transition.

The European Energy Efficiency Directive (27/2012/EU) provides that, from 1st January 2014, 3% of public buildings, particularly the school buildings, should be refurbished every year, with the objective of energy efficiency. The energy retrofit of public buildings, in fact, helps to reduce the management costs of local public authorities (municipalities, provinces/counties, and regions), reduces greenhouse gas emissions, and gets economic, social, and environmental benefits contributing to improving citizen's health [2].

In Italy, school buildings represent a significant part of the public non-residential building stock, with 52,000 units demonstrating poor operational performance. In addition, more than 67% of schools were built before 1974, before the introduction of the first Italian law concerning energy efficiency (national law no. 373/76), and about 8% were built in the last 20 years, with estimated primary energy consumption for heating and electricity of about 9.6 TWh per year and a total cost of 1.3 billion of euro [3].

Indeed, improving the energy efficiency of educational buildings provide social and economic benefits beyond the direct energy cost savings for several reasons: (1) Societal values are strongly affected by public models (renovation of educational buildings offer high visibility that can influence people's consciousness as well as to educate the next generation of citizens); (2) Success stories of the use of public funds that returns lower operating costs and healthier student learning environments represents exemplary realizations that can motivate other actors to multiply the intervention in the sector; (3) school sector offers national and international opportunities of information exchange to facilitate the transfer of best design and operational practices.

For this reason, acting on existing educational buildings is essential and, in the last years, several recent research projects co-founded by European Commission deal with energy-efficient of new schools and existing school buildings—like MED—TEENERGY (2007–2013), "School of the Future" (2011–2016), and "ZEMedS" (2013–2016), supporting new initiatives to increase the energy and the indoor environment performance of schools, also in Mediterranean climates. Furthermore, improving the indoor quality in school buildings, such as better lighting, thermal comfort, and air quality, could significantly benefit students' learning and performance [4, 5]. Indeed, some studies on educational buildings [6, 7] assess the IEQ to define retrofit actions combining experimental and subjective measurements thanks to questionnaires and monitoring campaigns.

Accordingly, this paper aims to present a method to define and assess retrofit strategies optimization of school buildings based on users' comfort analysis under real conditions. The research approach takes into account user preferences to evaluate energy-saving opportunities. The methodology consists of the thermal comfort assessment by combining physical environmental data monitoring through in-situ measurements and submitting subjective questionnaires to the occupants. In detail, the research work presents and evaluates the results of this experimentation applied on a school building (the secondary school Carrara) built in the 60 s and located in Lucca (Italy).

## 2 Tools and Methods

The research activities to define the renovation actions for the Carrara school were organized in the following phases: (1) occupancy survey on subjective comfort analysis; (2) in-situ measurement of environmental parameters; (3) comparison between subjective comfort analysis and field of measurements; (4) simulation of retrofitting options based on results. The investigation was carried out in 8 classrooms with the same size and different exposure. The analysis concerned indoor environment satisfaction and preference, focusing on thermal comfort, considering the effect on the students' performance in terms of attention, comprehension, and learning levels. The methodology adopted to assess the IEQ considers both results from in-situ measurements and subjective data collected by surveys and interviews with occupants to evaluate the IEQ comfort. The occupancy surveys were performed simultaneously during the regular lesson periods in all eight classes. For this reason, a questionnaire was implemented to investigate students' and teachers' well-being and performance, considering several aspects related to the indoor quality of the environment in which the school activities occur.

Since March 2017, in-situ measurements were carried out on three representative classrooms of the school building with different issues on thermal comfort. Thermo-hygrometric parameters—indoor air temperature and relative humidity—were collected until the end of the school year.

The elaboration of the questionnaire data highlighted some issues about occupants' dissatisfaction with IEQ comfort level and judgments related to the thermal environment perceptions, with specific reference to the conditions of classrooms object of the measurements campaign. The data from the occupancy survey and in-situ measurements were compiled and analysed first separately, and then the data were aggregated and compared to establish the relation between survey results and physical measurements. Therefore, technological problems were identified and analysed, and renovation solutions to improve the IEQ were proposed through simulation comfort models.

### 2.1 The Case Study

The ITC Carrara is a high school building built in the 60 s, and consists of four different units labeled A, B, C, and D weakly joined to a one-floor structure. The 3-story buildings are rectangular and have a total heated surface area of 7.717.78 $m^2$, with the main façades oriented towards the south and north. Building energy audit, thermography, on-site measurement of environmental parameters, and thermal bridge analysis showed an obsolete and poorly maintained building envelope. The poor thermo-hygrometric performances of the facades and roof led to high heat losses in winter months (with consequent high-energy consumption for heating) and overheating in summer (with a consequent discomfort condition), particularly in classrooms with south exposition. There was no air conditioning, so the windows needed to be opened in summer to ensure sufficient air exchange and avoid excessive overheating, with an increase of noise levels due to the traffic of the nearby streets. Finally, the lack of adequate solar shading in some cases led to glare phenomena on the students' desks [8].

In 2015 Lucca Public Administration started the energy and seismic renovation of unit A, a 3-story pavilion with a one-floor basement and a surface of about 536.27 $m^2$/level. Before the renovation, the heating energy consumption of pavilion A was 145.14 kWh/$m^2$ year. The lighting system consisted of fluorescent lamps with an electricity consumption of 1.626,80 kWh/year. The energy retrofitting was focused on the building envelope renovation to reduce energy consumptions and improve indoor comfort, and it consists of: (1) External insulation of the wall to decrease the energy losses without increasing the own weight of the building (U: 0.16 W/$m^2$ K); (2) Reduction of the transparent surfaces and windows replacement with an aluminum frame with thermal break and Low-e double glass (U: 1.20 W/$m^2$ K); (3) Roof Insulation (U: 0.16 W/$m^2$ K). Furthermore, additional retrofit interventions concerned: hydronic radiant ceiling systems installation for the heating system; replacement of existing with LED lamp and BMS control system. As a result, the building's global energy for heating and cooling decrease by 40% (from 145.14 to 62.43 kWh/$m^2$ for year).

### 2.2 Occupancy Surveys on Subjective Comfort Analysis

In 2017, a comfort analysis was conducted on subjective data collected by survey and interviews with occupants aimed at finding out the judgment about the IEQ comfort perception concerning the thermal comfort in terms of acceptability and preference of colder or warmer environments after the energy renovation of the 2015.

For this reason, a questionnaire (anonymous and reported information about the age of the single user and the position occupied in the classroom) was implemented to investigate the wellbeing and performance of students and teachers, considering several aspects related to the indoor quality of the environment in which the school activities take place. The questionnaire campaign referred to about 170 students attending eight different classes of the schools, different for position and the exposure of the windows. It was structured on a total of 32 questions concerning the categories listed below: (1) General characteristics of the school environment; (2) Thermal Comfort; (3) Visual Comfort; (4) Acoustic Comfort; (5) Security; (6) Psycho-physical wellbeing. A 4-point scale was adopted to rate each category below based on qualitative values: Insufficient/Poor/Sufficient/Good.

Furthermore, students have been questioned on how much their comfort perception could be affected by non-physical parameters relate (i) their visual and acoustic perception of the working area, (ii) subjective perception of safety and security of school environment (iii) how personal health conditions are affected by the environment.

The questionnaire also provided a section for General Data and a Suggestions section, and its structure allowed to separately evaluate users' opinions on comfort perceptions in north-facing classrooms and south-facing classrooms.

### *2.3 In-Situ Measurements of Environmental Parameters*

In situ measurements are widely used to help assess building envelope performance and evaluate 'before and after' occupancy conditions in environmental retrofit projects.

Since March 2017, these measurements were carried out during the regular lesson time in three representative classrooms (Fig. 1) to collect quantitative thermo-hygrometric parameters (indoor air temperature and relative humidity). Tinytag Ultra 2—TGU-4500 dataloggers (−25 to + 85 °C/0 to 95% RH), with an accuracy of ±0.5 °C and 3% of the measured value, were used.

Table 1 summarizes the main features of the selected classrooms. The thermal parameters were recorded each hour from the 27th of March to 21st of July. During the field campaign, the occupants' actions in the classrooms were not investigated: the students could act by opening the windows for natural ventilation of the classroom, but they cannot adjust the solar gains and natural daylight because there are no lighting control systems and shading devices for windows.

For several reasons, it was not possible to carry out field measurements during the winter period, and considering that, for Italian law, Lucca is classified as climatic zone D, with 1.715 degree days, the heating system was on until the 15th of April, the investigations on monitored parameters focused on overheating problems during

**Fig. 1** View of the classrooms selected for both subjective surveys and monitoring campaign of thermal parameters

**Table 1** Main features of the classrooms selected for monitoring campaign

| Classroom | Level | Students | Age | Floor area ($m^2$) | H (m) | Windows to floor ratio | Windows exposure |
|---|---|---|---|---|---|---|---|
| 1A | Ground floor | 23 | 15/16 | 44.50 | 3.90 | 0.13 | North |
| 7A | First floor | 21 | 14/15 | 50.00 | 3.15 | 0.15 | West |
| 10A | First floor | 22 | 14/15 | 47.65 | 3.15 | 0.18 | South |

the hot season. The results from field measurements of the three classrooms will be described in the following section.

## 3 Results and Discussion

The results have been evaluated by post-processing operation and were used to quantify the users' wellbeing under real conditions for each performance category.

In general, most of the users declared an overall positive opinion on the general conditions of the school environment after the renovation.

The analysis revealed that 68% of people consider the school environment's general comfort level in terms of spatial functionality, services, cleaning and maintenance, safety, etc. Regarding the judgment for IEQ, the answers have been plotted grouped in three comfort categories (acoustic, thermal, visual) based on the subjective votes previously defined. For each group, the percentage of frequency distribution has been defined based on the subjective judgment expressed for the indoor quality environment (Fig. 2). Results show that 50% of the people considered "insufficient" thermal and visual comfort.

There are some differences in thermal comfort perception between students attending classrooms with different exposure (Fig. 3). In the classrooms with north exposure, more than 45% of the total felt very cold in the winter period and would prefer a warmer environment; with an increase in the number of dissatisfied in the

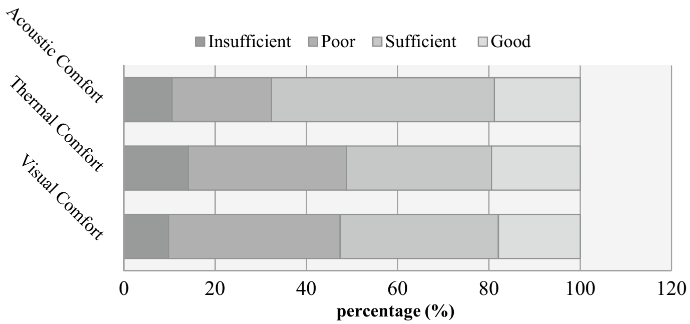
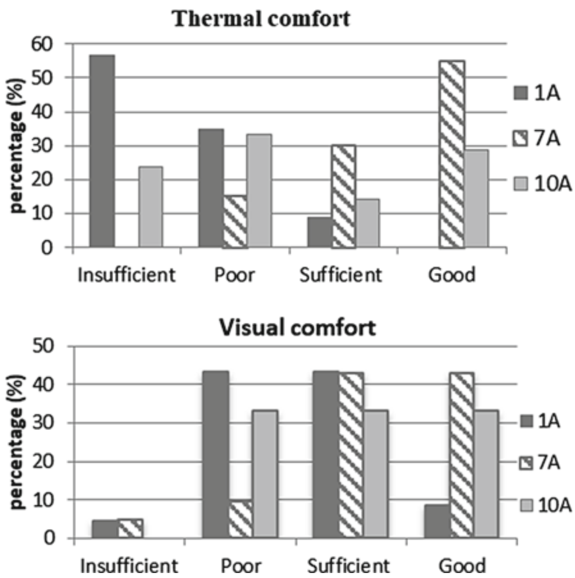



**Fig. 2** Total subjective judgement expressed for the indoor quality environment

**Fig. 3** Subjective judgement expressed for indoor comfort (thermal and visual) of selected classrooms (1A: North exposure, 7A: West exposure, 10A: South exposure)



classroom 1A on the ground floor, where almost the whole of students (22 out of 23) claimed that the classroom is very cold in the winter season. Beyond the north exposure, this problem is a consequence of the lack of thermal isolation of the ground floor. In the classrooms with south exposure, 37% of the total felt very hot in the summer season. In particular, in classroom 17 A, the percentage raised to 90%.

Moreover, significant differences concern the visual comfort in consequence of the different orientations of the classrooms. More in detail, 58% of the pupils expressed a lack of natural daylight in workspaces, and 22% complained of discomfort conditions related to glare phenomena due to the lack of shading devices. In this case, the results also depended on the student's seated position in the classroom (Close to windows, Central position, Close to the door). These issues were more evident in that classroom with south exposure. In addition, the artificial lighting control devices appeared to be inadequate.

According to the occupants' perception analyzed in this section, the prevalent judgment revealed a general thermal dissatisfaction related to feelings of warmth and visual discomfort related to glare phenomena. The field of action suggested by occupants for optimizing comfort, acceptability, and tolerability of the school environment concerns windows (38%) and lighting (22%).

### *3.1 Comparison Between Subjective Comfort Analysis and Field of Measurements*

Concerning thermal issues, subjective data from surveys from selected classrooms were compared with monitoring campaign results to verify the coherence between the occupants' perception of the indoor environmental quality and the physical parameters measured during the monitoring campaign.

A first analysis focused on a typical mid-season week (from 26th March to the 1st of April 2017) when the heating system was turned on with moderate outdoor temperature values. The aim was to investigate the thermal conditions of the classroom (1A) located on the ground floor with north exposure. About this classroom, students interviewed reported problems of thermal discomfort during the winter season attributable to a feeling of cold. The total dispersion surface towards the external environment of this classroom includes a glazing facade facing north composed of three windows openable, an insulated opaque wall exposed to the West, and the surface of the ground floor without thermal insulation. The following graph (Fig. 4) shows that despite the heating system was on during the week and the outdoor temperature under 16 °C during the day and around 10 °C at night, the indoor mean temperature of classroom 1A exposed to the north was relatively low than that of the other classrooms.

The air temperature T (1A) is over 18 °C most of the daytime and close to 20 °C, but it does not benefit from solar thermal gains, so the mean air temperature is lower than 3 °C compared to the other classrooms. When there are no school activities

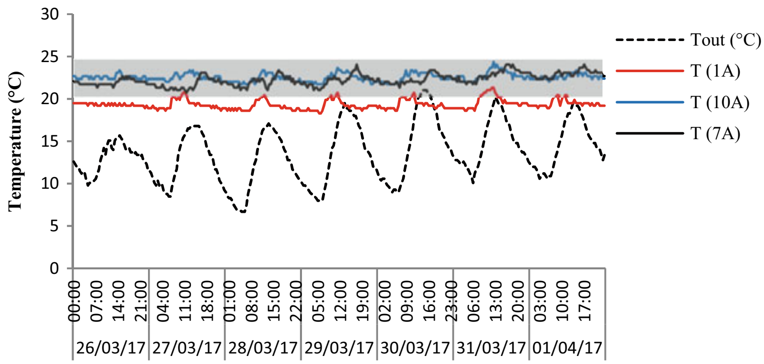



**Fig. 4** Indoor air temperature profile in a typical week of mid-season (from 26th March to the 1st April 2017)

during the weekend, the indoor temperature never drops below 18 °C, also during the nighttime when the outdoor temperature is under 8 °C.

Although, the data show a good thermal performance of the building envelope, students and professors reported discomfort during the site inspection related to the winter season (in the classrooms 1A and 10A), probably due to the interior relative humidity that moves from 50 to 60% during the morning when the exterior relative humidity ranges from 35 to 50%.

A second analysis was conducted in a typical spring week from 22nd May to 28th May 2017 about the two classrooms located on the first floor (7A and 10A) to investigate discomfort due to overheating problems, widely reported by students and professors in the questionnaire surveys. Despite the exterior temperature was under 26 °C in the morning and around 16 °C at night, the indoor temperature of classroom 7A was relatively high, close to 28–29 °C at midday, and dropped to 25 °C during the night, while the indoor relative humidity moves from 40 to 50% (Fig. 5). The highest

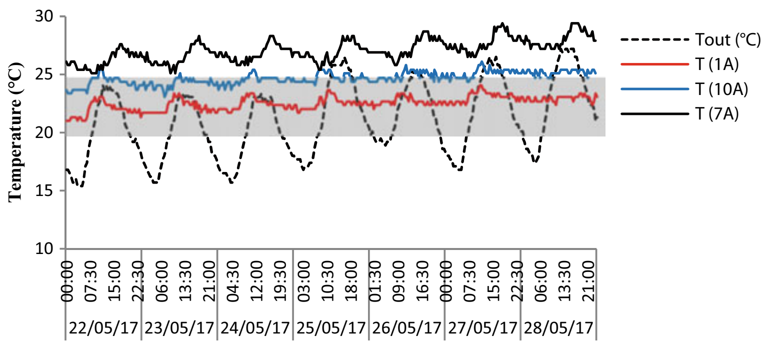



**Fig. 5** Indoor air temperature profiles in a typical spring week (from 22th May to 28th May)

**Table 2** Data values for monitored indoor air temperature and relative humidity in a typical hot day

| | Outdoor | | 1A (North exposure) | | 10A (South exposure) | | 7A (West exposure) | |
|---|---|---|---|---|---|---|---|---|
| 31st May | $UR_{out}$ (%) | $T_{out}$ (°C ) | UR (%) | T (°C) | UR (%) | T (°C) | UR (%) | T (°C) |
| 0:00 a.m. | 68.1 | 18.9 | 53.0 | 24.1 | 52.8 | 25.8 | 43.8 | 28,3 |
| 3:00 a.m. | 71.1 | 17.4 | 53.0 | 23.7 | 53.3 | 26.1 | 44.3 | 27.9 |
| 6:00 a.m. | 65.9 | 18,6 | 52.6 | 23.7 | 53.3 | 25.8 | 43.8 | 28,3 |
| *9:00 a.m.* | *54.1* | *22.4* | *53.0* | *24.1* | *49.7* | *26.9* | *42.1* | *27.6* |
| *12:00 p.m.* | *43.4* | *25.8* | *48,0* | *24.4* | *49.7* | *26.1* | *41.3* | *27.6* |
| *3:00 p.m.* | *39.4* | *25.8* | *51.7* | *24.1* | *50.2* | *26.1* | *40.5* | *29.1* |
| 6:00 p.m. | 46.6 | 24.7 | 50.7 | 23.7 | 50.6 | 26.1 | 40.0 | 29.4 |
| 9:00 p.m. | 72.9 | 21.4 | 52.1 | 24.1 | 51.5 | 26.5 | 41.7 | 29.1 |
| 11:00 p.m. | 68,1 | 19.5 | 52.6 | 24.1 | 51.9 | 26.1 | 42.1 | 28.7 |
| Mean | 58.8 | 21.6 | 51.9 | 24.0 | 51.4 | 26.2 | 42.2 | 28.4 |
| MAX | 72.9 | 25.8 | 53.0 | 24.4 | 53.3 | 26.9 | 44.3 | 29.4 |
| **Min** | 39.4 | 17.4 | 48.0 | 23.7 | 49.7 | 25.8 | 40.0 | 27.6 |

temperature values occur in the afternoon due to the solar gains through windows with west exposure and without any shading device.

Table 2 reported thermo-hygrometric parameters collected during a typical hot day of the monitoring campaign. The parameters involved are (i) outdoor Tout (°C) and $UR_{out}$ (%), (ii) T (°C), and UR (%) of each classroom. Regarding the period in which the school activities occur (from 9 a.m. to 3 p.m.), the indoor temperature values in classroom 7A are higher than the outdoor temperature of 3–4 °C with a mean value of 28.4 °C. In-situ measurements confirm the judgments expressed by people in occupancy surveys on feelings of warmth during the hot season. Despite the temperature range stated by theoretical comfort models, in the absence of a cooling system and natural ventilated classrooms, the thermal comfort levels acceptable by students corresponds to temperatures between 20 and 22.5 °C.

## 4 Conclusions

The investigations performed on the Carrara school highlighted that acceptable indoor comfort levels during the winter period are mainly due to the good performance of building envelope insulation. However, in the spring and autumn months, the student judgment about the thermal environment is insufficient, with overheating inside south-facing classrooms due to the lack of an adequate shading system and a mechanical ventilation system.

Furthermore, the indoor environmental quality results show a significant correlation was found between subjective judgments and objective measurements on thermal comfort. Therefore, if the retrofit of existing buildings stock has a great potential to improve global energy efficiency, energy performance must be directly linked to indoor environmental quality. Besides, the occupants' behavior should also be considered to integrate all technologies finalized to increase the indoor quality of educational environments, including thermal, visual, lighting, and acoustic comfort, proposing methods based on a tailored approach.

Finally, in the renovation of school buildings located in the Mediterranean area, the focus should be on indoor comfort levels during the summer season, adopting strategies that improve air exchange and guarantee lower indoor temperatures within the school environment to reduce the students' discomfort that prefer lower indoor temperatures (20–22.5 °C) than stated by theoretical comfort models.

## References

1. European Green Deal COM/2019/640 final
2. Dall'O', G., Sarto, L.: Potential and limits to improve energy efficiency in space heating in existing school buildings in northern Italy. Energy Build. **67**, 298–308 (2013)
3. RIUSO03, Ristrutturazione edilizia riqualificazione energetica rigenerazione urbana, CRESME (2014). https://architettitrieste.files.wordpress.com/2014/02/rapporto_riuso03.pdf. Last accessed 25 June 2021
4. Turunen, M., Toyinbo, O., Putus, T., Nevalainen, A., Shaughnessy, R., Haverinen-Shaughnessy, U.: Indoor environmental quality in school buildings, and the health and wellbeing of students. Int. J. Hygiene Environ. Health **217**(7), 733–739 (2014)
5. Dascalaki, E.G., Sermpetzoglou, V.G.: Energy performance and indoor environmental quality in Hellenic schools. Energy Build. **43**(2–3), 718–727 (2011)
6. Corgnati, S.P., Ansaldi, R., Filippi, M.: Thermal comfort in Italian classrooms under free running conditions during mid seasons: assessment through objective and subjective approaches. Build. Environ. **44**(4), 785–792 (2009)
7. Ming, H.: Assessment of effective energy retrofit strategies and related impact on indoor environmental quality: a case study of an elementary school in the state of Maryland. Journal Green Build. **12**(2), 38–55 (2017)
8. Rossi, M., Romano, R., Capasso M.: Comfortable and energy efficient educational spaces Strategies, methods and building components for energy retrofit in different climate zones. In: PLEA 2020—Planning Post Carbon Cities. Conference on Passive and Low Energy Architecture, Coruña, vol. 1, pp. 358–363 (2020)

# Design Patterns for Low-Carbon Buildings: A Proposal

**Simon Tucker and Clarice Bleil de Souza**

**Abstract** Design patterns as introduced by Christopher Alexander and colleagues are proposed in this paper as a means of guiding building designers through the often complex processes of low-carbon building design. The patterns are intended to be integrated into the Building Information Modelling (BIM) environments that are increasingly used in architectural and building engineering design practice, where patterns provide relevant information at appropriate times, carrying out environmental analyses as required, both as selected by the building designer and automatically. The paper provides examples of patterns from some of the various domains and disciplines that encompass low-carbon design of the built environment, as a means of exploring whether patterns could facilitate communication between those domains and disciplines. The focus is on low-carbon building design and building simulation, but patterns used in computer science and interface and interaction design are also discussed as these fit well with the object-oriented environment of contemporary software design and BIM systems.

## 1 Introduction

There is an ongoing need for reducing carbon and greenhouse gas emissions resulting from the construction, refurbishment and operation of buildings. The processes and interactions of the built environment industries and professions are complex, as are the physical processes resulting in emissions. Legislation sets targets that all actors should follow, and various researchers, organisations and professional bodies publish

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guidelines and other information on how carbon reductions may be met, some of which may influence the formulation of future legislation and planning laws.

Building designers (architects, engineers, consultants etc.) use their experience and expertise and seek advice and information when needed, to design for lower emissions either to satisfy or surpass regulations. Advice and information are available in a number of forms including checklists and instructions [1], guides to assessment of emissions levels [2], precedents and references [3, 4], calculation and assessment methodologies [5, 6], rules of thumb for designing low energy buildings, guidebooks, key performance indicators, sophisticated prediction and measurement methods, specialist consultancies etc.

This paper discusses the potential use of design patterns in the complex landscape of low-carbon design. Design patterns potentially provide the designer with reliable and high-quality solutions to commonly encountered problems in the design environment of the domain s/he is working in. A design pattern describes a common problem and its solution in context, describes the forces that have been resolved by the solution [7, 8] and suggests link to other patterns. Examples from practice that support and justify the solution given are usually provided, and the pattern is delivered in a format appropriate to the design domain. In architectural design this is typically a blend of text and illustrations [7]. Patterns are generally seen as an effective knowledge transfer method between the expert and the design domains and have not previously been proposed for use in low-carbon building design although have been proposed for use with Building Performance Simulation (BPS) [9, 10]. Unlike the existing forms of advice and information mentioned above, design patterns record tacit, contextualized knowledge for transferring between experts and general building designers, facilitating dialogue and decision-making using natural language rather than specific technical representation systems, and are a comprehensive alternative to existing methods.

If the creation of a low-carbon built environment and its parts are taken as an ongoing series of interconnected problems for which designers attempt to find solutions, then design patterns might help to solve these problems. The paper illustrates in outline how patterns might be used across the various domains, by a building designer working in a digital environment. Examples focus on low-carbon building design, and building performance simulation, but also touch on design management, and software development. For the purposes of this paper the term ‘low-carbon’ is taken to encompass related terms such as ‘zero-carbon’ and ‘net zero-carbon’.

## 2 Design Patterns

### *2.1 Origin of Design Patterns*

The ideas behind design patterns were developed by Alexander et al. [7, 8] as a way of capturing in a transmissible form the best qualities of the built environment, with the intention that others could use to them in their own design processes and thereby incorporate to their work the qualities inherent in and represented by these patterns. A large number of patterns (253) at the scale of towns and cities, buildings, and construction details, were derived from observation of the physical, social and economic elements and interconnections of built environments that appealed to Alexander and colleagues, and which they claimed were 'timeless' in their validity as 'solutions' to the complex problems of creating high quality spaces and places for human life to unfold.

Combinations of appropriate patterns are supposed to be selected for each project and used together, such that the outcome contains the qualities desired, and provide dynamic and coherent solutions to the problems that originally existed and which the project aimed to address. Design patterns in architecture have had supporters and detractors [11–14]. However, it is not the intention of this paper to discuss in any depth the qualities of Alexander's patterns but rather to describe how their subsequent use in domains other than architecture might suggest their future use in addressing problems of designing low-carbon environments.

## 2.2 Design Pattern Domains

Patterns have been proposed and used in a number of domains including architectural design, computer science and IT, educational pedagogy and others. In computer science design patterns have had great success and much work has been published in this field for over 30 years [15], ranging from object-oriented programming (e.g. [16–18]) to machine learning [19], and design patterns published for a number of computer languages. Other fields related to computing in which patterns have been produced are Human–Computer Interaction, Graphical User Interface design and Interaction Design (e.g. [20]). Borchers [21] argued that patterns can express expertise in the different domains of a multi-disciplinary project and therefore act as a 'lingua franca' to the members of the team. This idea is applied here to the field of low-carbon design.

The use of design patterns could promote communication and information sharing in design teams and facilitate the design and construction of low/zero-carbon buildings. To explore this idea, outline design patterns for the building design and software development domains shown in Fig. 1 are proposed here. The former is the environment in which the activity of building design takes place and is assumed to consist of design management, low-carbon building design, and building performance analysis. The software development environment is where the software systems that deliver design patterns into the digital environment of building designers are created. The focus of this paper is on the building design environment, but the software development environment is included to emphasise that its creation is part of a multidisciplinary project that could use design patterns throughout.

The arrows in Fig. 1 indicate the two-way interaction between pattern domains. For example 'low-carbon building patterns' which describe solutions to making and operating low-carbon buildings lead to the use of specific 'building performance

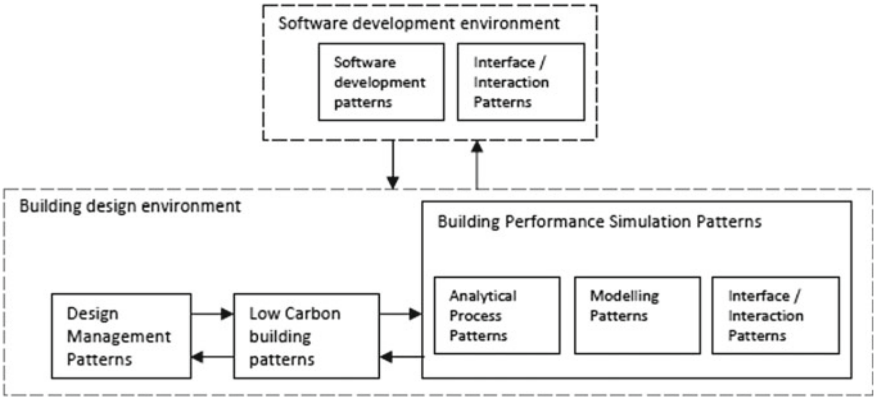


**Fig. 1** Building design and software development patterns

simulation patterns' which describe solutions to obtaining numerical data that will inform design decisions (e.g. does design option A produce lower emissions than option B?). When this data has been obtained it will often be the case that another design approach will be considered, hence the arrow back to 'low-carbon design patterns'. Figure 1 also indicates the nested structures possible with patterns. Within 'building performance simulation patterns' are more detailed patterns which describe successful and repeatable analytical procedures, modelling practices, and graphical interface and interaction solutions that enable designers to explore outputs and results.

# 3 Building Design and Software Development Patterns

## *3.1 Low-Carbon Design Patterns*

Expertise concerning low-energy / low-carbon building design can be expressed in design patterns. These patterns could include problem–solution pairing related to carbon emissions in use, embodied carbon, lifecycle carbon etc., providing that definitive knowledge and expertise is available. Such knowledge is available to various degrees of certainty as an outcome of ongoing research and practice-based activities from industry, academia and other organisations. For example, UKGBC [1] outlines the following net zero-carbon strategy which is set out as a series of stages, which if followed will provide 'solutions' to the problem of creating zero-carbon buildings.

Each stage of Table 1 is supported with associated advice and instructions and could be seen as the solution to a smaller 'sub problem' of the larger problem of creating low-carbon buildings. The construction and use of design patterns is illustrated below focusing on stage 3 of Table 1 for reasons of space. This stage is well understood and applies equally to 'low-energy buildings' in general. Knowledge

**Table 1** A zero-carbon strategy (summarised from [1])

| | |
|---|---|
| 1 | Establish net zero-carbon scope |
| 2 | Reduce construction impacts |
| 3 | Reduce operational energy use |
| 4 | Increase renewable energy supply |
| 5 | Offset any remaining carbon |

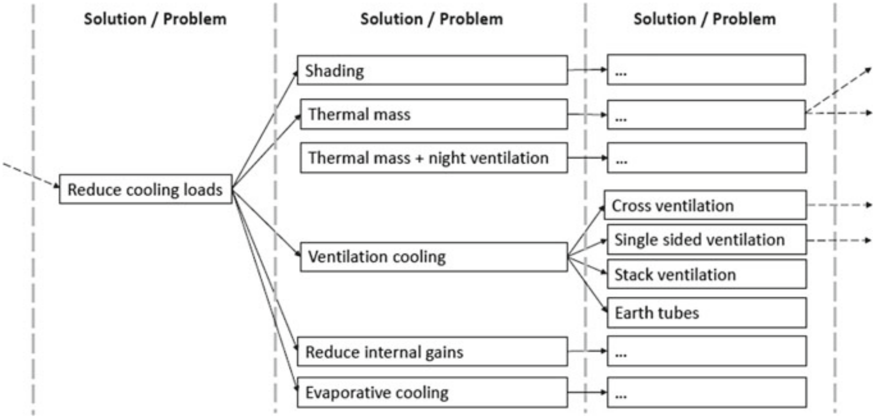


**Fig. 2** Some examples of low energy design problems and potential solutions

of how low-energy buildings work is available in design guides, case studies of best practice etc. (e.g. [3–6]), and if reduced to essentials involves the problems of decreasing heating and cooling loads and using climatic energy flows where appropriate to achieve thermal comfort for the occupants. There are established and well understood ways of solving these problems for different building types and climatic zones, and some of these are shown in Fig. 2.

The elements of Fig. 2 are labelled as ‘Solution/Problem’ because a solution can often be seen also as a further problem (e.g. ‘Ventilation cooling is a solution to ‘Reduce cooling loads’ but can become the problem of ‘Implement Ventilation cooling’). Problem–solution pairs are generated by taking a problem and coupling it to a potential solution. Figure 2 shows a small part of the low-carbon design abstract problem–solution space. Note that ‘Reduce cooling loads’ can itself be seen as a potential solution to the problem of ‘Overheating’, and ‘Cross-ventilation’ can be seen as a problem, for example in ‘how can cross ventilation be successfully implemented?’ or ‘will cross ventilation work for the current building proposal?’. In the context of design, at every level of decomposition of a problem the solution will probably at least partly be to ‘provide information’, and at some point this information will likely be the results of testing a solution. Problem–solution pairs are successively generated in this way until the problem–solution pair does not require further decomposition, because the final problem is to test the solution, at which point another sort of pattern (see Sect. 3.2) is used. Any problem–solution pair can

**Table 2** Generic template for a low-carbon design pattern (modified from [9])

| | |
|---|---|
| Pattern name | Name should clearly reflect the abstract problem–solution pair and can refer to building typology, specific design actions, design goals to be addressed, climate etc. |
| Introduction | Situates the pattern in context to larger patterns, connecting it to a network of different but related design decisions |
| Problem | A brief outline of the problem addressed by the pattern, including the aims of the design decision(s) to be undertaken |
| Context and examples | Situates the use of the pattern in relation to wider aspects of low-carbon design and design practice, explaining the context of the decision(s) to be undertaken by designers and providing examples and information (e.g., on theory or practice) to justify the advice given by the pattern |
| Solution | A description of the technique or features of the building that will potentially resolve the problem |
| Further patterns | Information on which smaller patterns to move on to, in light of the aims of the designer and the results given by the current pattern |

potentially be made into a design pattern with supporting advice and information, to be tested and further refined or discarded considering its relevance and effectiveness in addressing the problem.

The pattern is recorded in an appropriate format. All existing pattern systems have their own consistent format, which describes problem and solution, has a descriptive name, and contains examples and discussion on how the pattern can be used in the wider design context. Table 2 shows a generic pattern template, and a developed example of a Building Performance Simulation pattern is presented in Sect. 3.2.

## *3.2 Building Performance Simulation Patterns*

To model building performance and test alternative low energy solutions Building Performance Simulation (BPS) is used. In the BPS domain there are also problem–solution pairs, where a typical problem concerns how to model a scenario in order to obtain the required information, for example concerning heat loads. Previous work by the authors [9, 10] has shown how complex simulation scenarios can be broken into steps that can be followed by a simulation user to obtain simulation results that will help in design decision-making. These steps are in the form of design patterns, each of which includes problem, solution, advice, links to similar examples etc. When implemented in a BIM environment they also contain premade building models, analytical procedures, defined inputs and outputs, and methods of interacting with these outputs.

A design pattern to test for 'Ventilation cooling' (cross and single sided) is shown in Table 3. BPS patterns include sections (marked *) that specify technical aspects

**Table 3** Specification for a ‘ventilation cooling’ pattern

| Pattern name | Ventilation cooling (cross/single sided) |
|---|---|
| Introduction | Previous patterns have shown that cooling is required, which could be achieved using active systems, passive systems or a combination of both. This pattern tests whether ventilation cooling from windows and vents will be sufficient and provides information on building modifications to make to improve the effectiveness of ventilation cooling. Both cross and single sided ventilation are covered |
| Problem | *To determine the building performance when ventilation cooling is used*. The building designer needs to know whether ventilation cooling will be sufficient in the current building and needs information on how to modify the building should the current performance need improving |
| Context and examples | The effectiveness of ventilation for cooling (both cross and single sided) depends on factors including wind speed and direction, opening size and location, position of internal walls, doors and vents. Links to examples of successful ventilation cooling solutions are provided here. Links to theory (building physics) and simulation methods are provided here |
| Solution | A network airflow model is used. The user is prompted to specify opening sizes and schedules (selected if required from drop down list) |
| Modelling details* | Building model including all partitions, internal zones and ventilation openings. Annual weather file including hourly wind speed and direction |
| Analytical processes* | Network model of airflow is used (or equivalent). Parametric variation of windows & vents between 0% open and 100% open (steps of 25%) |
| Interface/interaction* | Output; Hourly temperature and air flow rate (line chart); Hours over upper comfort temperature (table); Plan indicating airflow rates between zones, highlighting lowest airflow positions |
| Interpretation and quality assurance | Advice on airflow rate interpretation |
| Further patterns | Reducing cooling loads, Shading, Thermal mass, Thermal mass + night ventilation, Reducing internal gains, Ventilation cooling (earth tubes), Ventilation cooling (stack) |

of the simulation procedures to be used, and are supposed to be to be linked with further patterns.

**Table 4** Examples of analysis problem–solution pairs

| Problem | Solution |
|---|---|
| Determining the effect on performance of a modification(s) | Compare the results of the modified model(s) with the base model |
| Determining whether a building proposal meets a performance target | Compare the result with the target |
| Determining the sensitivity of parameters X…n in relation to a target(s)? | Sensitivity test (i.e. parametric variation of the relevant parameters) |
| Determining optimum values of user defined parameters X … n for best performance | Optimisation routine |

### *3.3 Analytical Process Patterns*

Analytical process patterns are used within building performance simulation patterns. The advantage of incorporating the analytical process within a pattern rather than simply calling it an algorithm, is that (as in all design pattern construction) this demands that the range of actual problems and contexts that the abstract problem–solution pattern is intended to solve must be thought about carefully. Pattern development in this case acts as a tool to more thoroughly explore the space of problem–solution pairs, a process that leads to development of further patterns, modification of existing patterns and deletion of patterns when a better one is found. Examples are shown in Table 4.

### *3.4 Modelling Patterns*

Modelling patterns describe commonly used modeling techniques and practices needed to simulate the type of performance being examined and the building and construction elements and attributes to be modelled that are coherent with the analytical process set up to undertake the investigation. Libraries of modeling patterns can be created related to for example 'base-case' or 'free-running' models.

### *3.5 Interface/Interaction Patterns*

Tidwell [20] authored interface design patterns including patterns on user behaviour, structuring of information, navigation, layout, actions and commands, interaction with users, information graphics, style and aesthetics and others. These patterns aim at increasing 'useability' of complex digital environments and have proven to be very popular. Such patterns can be used to instruct and facilitate navigation of BPS results in an interactive way, so that designers can query simulation outputs at different level of temporal and spatial detail. They could also be used in the development of the software development environment to facilitate the connection between BIM and BPS.

### *3.6 Design Management Patterns*

It is likely that some ways of managing a low-carbon project will be more appropriate than others. For instance, Integrated Design Processes (IDP) and Integrated Project Delivery (IPD) focus on enabling close collaboration among the different specialists involved in a design team, so that integrated solutions addressing social, economic, ecological and sustainable goals are achieved. Interoperable data exchange protocols are recommended by the literature together with documentation on the level of information, detail, tolerances, and purpose of model etc., to feature in contracts [22]. However, the collection and transformation of this information in the form of project management patterns are the subject of future work.

### *3.7 Software Development Patterns and Building Information Management*

Design patterns are closely linked to object-oriented programming which has made much use of them (e.g. [16–18]). Design patterns can be coded as objects and/or classes of object, and those described above could be integrated into an object-oriented software environment. A well-known example of patterns in computer science are the object-oriented software development patterns of Gamma et al. [16]. These include creational patterns used to create classes and objects, structural patterns that describe how objects and classes are related to larger structures, and behavioral patterns that describe how classes and objects behave with respect to each other. Examples of their use in a BPS context are shown in Table 5.

**Table 5** Object-oriented pattern type [16] and use in BPS context

| Pattern type | Example in BPS context |
|---|---|
| Creational patterns | Automatic generation of a pattern instance based on the outputs of another pattern (e.g. a pattern who’s output identifies cooling loads generates an instance of a shading pattern) |
| Structural patterns | Specifies how a BPS pattern is related to a low-carbon design pattern |
| Behavioral patterns | Specifies how a ‘sensitivity test’ pattern is applied to building parameter objects |

Software development activity should consider the potential links with BIM systems. BIM is an object-based manufacturing-centered approach to coordinating design information amongst the design team and contractors [23], and some work has been done on using patterns to facilitate BIM information sharing [24]. Since design patterns are objects that hold information for the purposes of transferring knowledge 'on demand' to building designers, they could be integrated into the BIM environment to connect federate models with simulation routines. More specifically, 'design pattern' objects that embody knowledge on low-carbon design, building performance simulation etc. could be added to the main BIM objects of 'construction entities', 'built spaces', and 'construction elements'. For example, the ventilation cooling pattern (Table 3) and all other patterns would be made available through the BIM system, and if used in a project would be attached to the building model just as construction elements of the building are attached. This would facilitate the integration of BPS to BIM systems, as it would enable information about the building, BPS assumptions and results to be recorded in a single environment, facilitating data transfer, coordination and auditing as well as project query and specification at different levels of detail. Current experiments of integrating BIM with BPS (e.g. Autocad Revit Insight [25]) do not provide such an environment.

## 4 Discussion

Whereas it can be argued that the topics of low-carbon design and building performance modelling and simulations can be and are learnt in theory (see [26] for new development in the latter), most knowledge transfer and application are heavily based on 'learning by doing' supported by standard design guides, checklists and similar in different knowledge domains (architecture, civil and mechanical engineering). Since in low-carbon design the assessment of how well a technology, technique or building works is vital, low-carbon design patterns linked to BPS patterns offer a promising future, not only to connect both the theory and the 'doing' but to connect different disciplinary domains in a single environment. This approach is coherent, transparent, and easy to upgrade and modify, in synchrony with ongoing development in contemporary object-oriented computer systems. The use of patterns in linking various domains needs further research and development, but the example given here of linking low-carbon patterns to BPS patterns is promising. A limitation of the paper is that the computational methods of implementing a patterns-based system linked to BIM have not yet been addressed and require further work.

## 5 Conclusions

This paper has outlined how design patterns could be used as a 'lingua franca' [21] in the complex processes of producing a low-carbon built environment. Although the idea behind design patterns is over 40 years old, their close links with object-oriented programming and the increasingly ubiquitous use of digital design environments, coupled with the need for accurate building performance modelling, suggest that patterns could become a relevant methodology in low-carbon design. Almost all critics and researchers of design patterns agree that well written patterns possess a powerful educational value. Understanding how to meet the challenges of creating a low-carbon built environment could be made easier through use of a consistent and transparent systematic approach inspired by Alexander's proposal.

## References

1. UK Green Building Council: Net Zero Carbon Buildings: A Framework Definition (2019)
2. Royal Institution of Chartered Surveyors: Whole Life Carbon Assessment for The Built Environment, 1st edn (2017)
3. CarbonBuzz Homepage: https://www.carbonbuzz.org/index.jsp. Last accessed 18 June 2021
4. 2030 Palette Homepage, http://www.2030palette.org/. Last accessed 18 June 2021
5. BREEAM (Building Research Establishment Environmental Assessment Method) Homepage, https://www.breeam.com/. Last accessed 18 June 2021
6. LEED (Leadership in Energy and Environmental Design) Homepage, http://www.usgbc.org. Last accessed 18 June 2021
7. Alexander, C., Ishikawa, S., Silverstein, M.: A Pattern Language: Towns, building and construction. Oxford University Press, New York (1977)
8. Alexander, C.: The Timeless Way of Building. Oxford University Press, New York (1979)
9. Tucker, S., Bleil de Souza, C.: Thermal simulation outputs: exploring the concept of patterns in design decision-making. J. Build. Performance Simul. **9**(1), 30–49 (2016)
10. Bleil de Souza, C., Tucker, S.: Thermal simulation software outputs: a framework to produce meaningful information for design decision-making. J. Build. Performance Simul. **8**(2), 57–78 (2015)
11. Bhatt, R.: Christopher Alexander's pattern language: an alternative exploration of space-making practices. J. Archit. **15**(6), 711–729 (2010)
12. Dawes, M., Ostwald, M.: Christopher Alexander's *A Pattern Language*: analysing, mapping and classifying the critical response. City, Territory and Architecture **4**, 17 (2017)
13. Dovey, K.: The pattern language and its enemies. Des. Stud. **II**(1), 3–9 (1990)
14. Protzen, J.P.: The poverty of pattern language. Des. Methods Theories **12**(3/4), 194 (1978)
15. Coplien, J.O., Schmidt, D.C.: Pattern Languages of Program Design (PLoP), 1st edn. Addison Wesley, Reading, MA (1995)
16. Gamma, E., Helm, R., Johnson, R., Vlissides, J.: Design Patterns: Elements of Reusable Object-Oriented Software. Addison Wesley, Reading, MA (1995)
17. Buschmann, F., Meunier, R., Rohnert, H., Sommerlad, P., Stal, M.: Pattern-Oriented Software Architecture Volume 1: A System of Patterns. Wiley, New York (1996)
18. Fowler, M.: Analysis Patterns: Reusable Object Models, 1st edn. Addison Wesley Professional (1996)
19. Lakshmanan, V.: Machine Learning Design Patterns: Solutions to Common Challenges in Data Preparation, Model Building, and MLOps. O'Reilly, Farnham (2020)
20. Tidwell, J.: Designing Interfaces, 3rd edn. O'Reilly, Farnham (2020)
21. Borchers, J.O.: A Pattern Approach to Interaction Design. AI & Soc. **15**(4), 359–376 (2001)
22. American Institute of Architects: Integrated Project Delivery: A Guide, The American Intitute of Architects **1**(1), 10 (2007)
23. EN ISO 12006-2: Building construction—Organization of information about construction works Part 2 : Framework for classification. BSI Standards Publication (2020)

24. Isikdag, U.: Design patterns for BIM-based service-oriented architectures. Autom. Constr. **25**, 59–71 (2012)
25. Autocad Revit Insight. Homepage, https://www.autodesk.co.uk/products/insight/overview. Last accessed 18 June 2021
26. Beausoleil-Morrison, I.: Fundamentals of Building Performance Simulation. Routledge, New York (2020)

# Transport Systems for Smarter Cities, a Practical Case Applied to Traffic Management in the City of Montreal

**Abdellah Chehri, Teena Sharma, Benoit Debaque, Nicolas Duclos, and Paul Fortier**

**Abstract** The concept of a 'smart city' emerged from studies in urbanism, combined with information and communications technologies (ICTs). Several cities worldwide are trying to build intelligence into existing systems to increase the efficiency of transport management. Transport management systems and software tools have effectively curtail traffic woes around some megacities of the world. Today, geospatial data and mapping are among the technologies that cities use the most. This article focuses on the transport aspect of smart cities to respond to smart cities' issues. To understand a little better the applications of a smart city on transport, we present a case study about the city of Montreal in Quebec, Canada.

## 1 Introduction

The concept of smart cities was born to respond to the problem of climate change. Indeed, a smart city is above all about being responsible whether at the level of its inhabitants, the administration or the infrastructure put in place. This requires

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a cleaner renewal of construction materials and the implementation of new technologies to improve the criteria in terms of environment, safety, or comfort of citizens.

Our century has seen the emergence of several technologies that are currently used in the life of every day. It concerns intelligent transport systems. These systems' transports bring together the multitude of applications used to share information and communication. These systems will be verified and presented in the future with the development smart cities and dramatically increase the quality of life for city dwellers.

Due to the fact that that studies of the development and operation of smart cities are still in their infancy, there are many gaps in the literature. In order to focus on the impact of communications in smart cities, it is relevant to deal with the subject by following the following problem: How do the systems of will communications change vehicles and transport?

Nowadays, the environmental aspect has been slightly forgotten in the definition of smart cities to make room for the technical side. This technological side is all more present with advances in information and communications technologies (ICTs). Indeed, it is these ICTs that are at the origin of most of the new services. As an example of ICT, we can spot surveillance cameras, red lights intelligent devices, city radars, or various sensors to retrieve information such as pollution level or radiation rate.

To understand the concept of smart cities from the point of view technological, it is possible to compare them to a brain where each sensor present would be associable with a neuron, managing its application, and where the communication systems would play the role of synapses allowing the interaction between all these sensors. This, therefore, offers immense possibilities such as spotting the source of a fire faster, even before help arrives, thanks to a series of thermal sensors installed in an entire district.

Smart cities can be defined by an autonomous ecosystem restricted by a population and a responsible administration, allowing technological means to respond to issues in terms of the environment, safety, and comfort of citizens [1]. Therefore, the communications systems will play a crucial role in these broad areas. It is, therefore, necessary to focus on them to be able to analyze their roles as clearly as possible [2, 3].

In order to better conduct the study, this article is divided into two parts. The first part will concern smart cities by analyzing a concrete example which is the city of Montreal. As well as intelligent transport systems and the impact of communications technologies that will be more and more present in our lives. The second part will focus on the future of these technologies and the advances that could revolutionize the world of transport.

The rest of the paper is organized as follows; the smart city technological ecosystems are described in Sect. 2. We focus our analysis on the city of Montreal. The place of the intelligent transportation system is given in Sect. 3. Section 4 puts the light on the future of the transportation system in the smart city. The conclusion is given in Sect. 5.

## 2 Smart City Technological Ecosystems, Case Study: Montreal

In order to understand how to become a smart city, let's take a look at the strategy in place of the town of Montreal. Montreal being an agglomeration regrouping more than 2 million inhabitants, is faced with severe problems in terms of pollution, heavy traffic, or security. It is for these reasons that the choice to become a city smart was decided. To become a smart city, a 4-axis strategy has been stated.

First, you have to collect data, for this several means can be put in place, such as distributing surveys to citizens to recover the issues important for the city or installing sensors or surveillance cameras to identify risk areas or areas for improvement.

Once all this data was recovered, the next step was based on communication. Indeed, an intelligent city wants to be responsible on the part of the administration towards citizens. For this, a website and mobile applications have been set up to disseminate real-time information to citizens, such as traffic jams or traffic incidents that could impact passers-by. In addition to this information aspect, infrastructures were built to deploy wired and public Wi-Fi networks. Finally, learning centers on new technologies were also set up to develop local ideas.

It is from step 3 that the city really started to become intelligent with the coordination strategy. This stage targeted public services, therefore transport, road traffic, safety, water, and energy.

Finally, the last step was to collaborate with local businesses to help them develop new technologies. This strategy made Montreal an intelligent city, but what were the concrete changes?

In fact, in order to follow this strategy, several ideas and infrastructures have been implemented. First of all, implementing a universal transport card working with a subscription, the Opus card. This card made it possible to streamline transport traffic public. Indeed, users no longer need to take out change or their credit card. This significantly reduces the wait. In addition, in order to set up this card he has, it was also necessary to implement compatible terminals in all stations in Montreal.

A second application designed by the city was the priority measures for buses. These measures have greatly improved the bus service offered by the city of Montreal by offering less traffic jams, time savings for users of 10%, and less greenhouse gas emissions. The infrastructures developed for this application are the following:

- Priority candle-type lights: these lights give priority to the bus during intersections allowing them to follow their circuit more quickly and not to get stuck in traffic.
- Priority lights in real-time: These lights are equipped with presence sensors connected to software in which artificial intelligence has been programmed to identify the shape of the buses. When a bus arrives, the lights will turn green to give it access to the road, thus reducing waiting time.
- Reserved lanes: Reserved lanes for buses have been designed on the main roads. These tracks required several months of work and allowed the buses to be slowed down by traffic jams created by motorist traffic.


**Fig. 1** Dynamic panel (http://ville.montreal.qc.ca)

- Queue avoidance lanes: As with reserved lanes, these lanes are designed aim to spare the road traffic to the bus.

The third infrastructure concerns dynamic panels allowing to provide real-time information on car parks and their capacities. For this Presence sensors have been installed in the parking spaces to retrieve the number of free places. These sensors send their information to a control center through communications systems then the information is classified by the report to the car parks concerned. Following this classification, the panels are updated to display the number of places remaining. This application has dramatically helped to fluidify the traffic because motorists no longer need to look in several parking lots before find a place. In addition, this has resulted in a saving of time and comfort for users of the road. And finally, it has reduced greenhouse gas emissions in the city (see Fig. 1).

The fourth infrastructure concerns a regulatory aspect. Indeed, during the definition of smart cities, the concept of responsibility was introduced. This concept also passes by respect for the law and security. For this, photo radars were set up. These radars make it possible to identify motorists who do not respect the limits of speed and therefore adversely affect the safety of other citizens. In addition to these cameras, radars on certain traffic lights have also been implemented to identify the drivers who wouldn't stop.

## 3 The Place of Intelligent Transport Systems

A surveillance camera system has also been put in place. This system has two separate roles, the first and to guarantee security to citizens. The second is traffic management. In this case, we are no longer talking about surveillance cameras but rather traffic cameras.

The images from the cameras will be retrieved then sent by communications in a control center. Following this, the images will be processed in real-time to determine congested roads and offer motorists routes better suited to their travels.

As we can see in Fig. 2, here is the state of the traffic collected by the cameras, as well as the number of cameras (blue) for Sunday, November 17, 2019.

Another application that has made Montreal a smart city is the implementation of virtual template systems. These systems respond to a problem very precisely. Indeed, before these systems, it frequently happened that the trucks collided and get stuck under the bridges present in the cities. To counter this problem, several lasers were installed; these lasers are intended to retrieve the height information of the trucks so that it is then compared to the height of the bridges. When the truck is too big, a dynamic panel will warn the driver that he will not pass (Fig. 3).

Another application allowing Montreal to be considered an intelligent city concern the management of traffic lights. Almost half of the light traffic in Montreal is said to be "intelligent". They are actually connected through fiber optics or wireless communications systems to a gigantic network controlled by a team of professionals. This

**Fig. 2** State of the traffic collected by the cameras

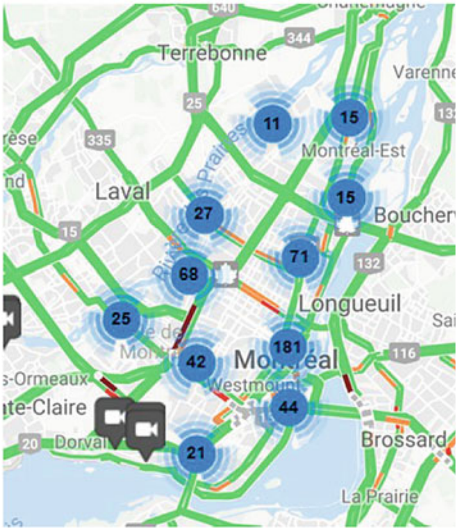



**Fig. 3** Virtual template systems (truck anti-collision system)

feature allows operators to act on the light in real-time according to the events that occur. For example, suppose an accident occurs at an intersection. In that case, the operators can decide to block traffic in this part of the city to allow help to arrive more quickly on the scene and not be hampered by traffic during the operation.

Therefore, thanks to all these additions, the city of Montreal has been able to become a city intelligent, thus increasing the safety and comfort of its citizens and reducing its environmental impact thanks to better management of road traffic.

### *3.1 Electronic Payments*

Here, the goal is to respond to the problem of deadlines. Indeed, several means are currently in place to meet the need for payments. When a motorist arrives at a toll booth and has to pay with coins, this generates time. Therefore, on a busy motorway, this can create traffic jams that can subsequently cause accidents or increase the gas concentration by tight. For this reason, ITS intervene in this field using an electronic toll system, which allows the driver to pay in advance with a subscription and not have to stop.

A second application for electronic payment is the Opus card. This card has been in place in Montreal to allow public transport users to avoid taking out their credit cards or change. It makes it possible to respond to similar problems when going through a toll and streamline traffic in public transportation.

### *3.2 Emergency Management*

Here the goal of ITS is to detect incidents to prevent emergency services. This application is therefore made in two parts. The first concerns the detection of incidents.

In order to detect incidents, thermal cameras have been installed on the bridges. These cameras allow vehicles to be detected by identifying their signatures (characteristic shapes of cars); a part of machine learning also makes it possible to identify the type of vehicle (car, truck, trailer, etc.). When the vehicle is stopped for a while, the system will notify the agents who monitor the bridge so that these agents can then prevent the adapted relief.

This device is not the only one enabling incident to be detected. Indeed, the software is adapted to existing video infrastructures and allows the detection of stationary vehicles, accidents, or audible alarms. These systems are devices of automatic incident detection (AID).

The second part of ITS emergency management concerns the services motorist assistance. These services can be in many forms, such as emergency calls or sends from the vehicle's position. To operate these systems, sensors are present inside the car. In the event of shocks, the sensors will analyze the damage suffered and decide to warn an operator or directly to the emergency services.

### 3.3 Traffic Management

Traffic management is made up of several distinct points. First of all, there is the collects information. As explained when defining ITS, big data plays a crucial role in intelligent transport. These data may relate to the speed of vehicles via sensors or video surveillance images for spot congested areas. Once all this data is recovered, it will be analyzed by algorithms to determine regions of traffic jams. Following this identification, the information will be returned to motorists via radios or even GPS applications.

Here the goal is to meet several criteria, firstly the fact of detecting upstream traffic jams save motorists time and fuel. Then, it also helps to regulate the roads and, therefore, reduce the number of accidents, and finally, this helps reduce the concentration of greenhouse gases around large cities. This aspect of traffic management clearly shows the importance of ITS and its applications daily.

### 3.4 Advanced Vehicle Safety Systems

In this part, as the name suggests, it is the security aspect that the STI favors. This concerns the implementation of driving assistance such as power steering or braking assistance, which are systems that are starting to date.

The automobile is getting smarter and more so with the arrival of autonomous vehicles and the insertion of artificial intelligence that makes vehicles capable of detecting pedestrians or even avoiding collisions. The ITS play a major role in these areas by allowing data to be collected and communicated between the control and operational parts of a vehicle [4].

### 3.5 Data Management

This part flows from all the others. The collected data needs to be stored to be processed or kept in memory to have elements of comparison in recurring problems. This is particularly the case of large cities that collect a colossal amount of data thanks to the STI. To store all these data from the extensive “database,” centers are constructed.

## 3.6 Construction Aid

The field of construction, particularly roads, may be subject to issues that cannot be resolved in some countries. This is the case in Canada; when winter is approaching, the snow is ultimately preventing professionals from doing their job. Here, the role of ITS is to collect meteorological data in a database to predict the climatic conditions that could occur during the project. This aspect is not comparable with weather predictions given by scientists who only act from one week to another because it considers the experience of previous years to determine the start date of the project and the end date.

## 3.7 Transport of Goods

Freight transportation is an area we all face when we order a product on the internet or go shopping in a store. Indeed, this field represents a vital part of our current society. It is, therefore, expected that ITS had developed there.

Freight carriers first gave way to ITS by integrating systems of location and GPS to manage the fleets and have help on the routes to respect. These ITS save time and reduce the distances to be covered in grouping several routes, which means fuel savings and a reduction in emissions $CO_2$. Nowadays, even simple packages are equipped with tracking systems to follow the product from the warehouse to the customer and avoid theft or loss of a relay.

## 3.8 Regulations

Whether on the road, in trains, or cities, regulations and laws are omnipresent. ITS, therefore, make it possible to enforce these laws and identify users who violate them. Several solutions have been implemented for this.

First of all, automatic speed cameras. These radars are used to locate vehicles that do not respect the speed regulations on the roads. These radars are also becoming intelligent with the addition of artificial intelligence because they can now spot if the driver is on the phone and the speed of the vehicle. The ITS present in public transport, which manifests itself through surveillance cameras. These cameras can retrieve images, which agents view to determine if people may be in danger and thus prevent a rescue team.

## 4 The Future of Intelligent Transport Systems

According to all major and minor discoveries that occur every day, the world of technology is constantly in motion. All these changes also impact the field of intelligent transport systems. Indeed, the significant developments that impact and will affect these systems in the future are, in the first place, autonomous vehicles. Autonomous vehicles are a perfect example to illustrate intelligent transport systems and the impact of communications. For these vehicles to drive independently, they need to be in total harmony with their environment. This harmony is therefore achieved through ITS [5].

Secondly, it is the development of 5G, which significantly improves the responsiveness and ITS applications, which will be addressed. As we could see, the main communications systems used by ITS are mobile networks, so, logically, a communication system was offering data transfer capabilities as well immense that 5G is part of the future of ITS.

Finally, the third part differs from communication systems but is also part of the intelligent transport systems is artificial intelligence. Several applications using artificial intelligence have already been deployed (radar, traffic lights in Montreal).

### *4.1 Autonomous Vehicles*

Autonomous vehicles have been a hot topic for some years now. Autonomous vehicles with features like automatic parking are already available. Future technologies are expected to continue to build on each other, creating an increased level of automation so that some are predicting commercial volume availability of these vehicles between 2020 and 2025.

The technology behind the operation of autonomous vehicles is complex and has many facets. Simply put, fully autonomous vehicles process map data and sensor information to determine their exact location, then apply that data (with predictive software) to determine where they are moving.

Five significant challenges will need to be overcome before fully autonomous vehicles hit the road: consumer concerns, market demand, technology, regulation, and law.

Perception is the first pillar of autonomous driving. There is a lot of Deep Learning involved. Algorithms such as YOLO (You Only Look Once) or SSD (Single Shot Detector) have been very well explained and are very popular in this field. Object detection networks take images as input, and most commonly outputs bounding boxes together with class labels for all objects of interest, as shown in Fig. 4. Object detection using bounding boxes is closely related to semantic image segmentation, which aims to assign each pixel in an image to a semantic class label [6–8].


**Fig. 4** Visualization of ground truth bounding boxes for object detection using YOLOv5

Whether from a technological point of view with the multitude of sensors and communications that make up these systems. What is on is that they will revolutionize transport systems.

## 4.2 The 5G Network and Its Implication in Smart City

Autonomous vehicles, traffic mapping, connected trash cans … The foundations of the smart city will rest mainly on 5G networks, able to provide the connectivity necessary for some of its uses.

Thanks to the very high connectivity of 5G, it becomes possible to absorb the massification of connected objects. The 5G is ten times faster than the previous generation, with a latency of the order of a millisecond. This is decisive for the growth of the connected car, the deployment of which will transform the city of tomorrow. Furthermore, with such a high data rate, a large data of the smart city can be fully exploited.

Another advantage of connected street furniture: good management, less energy, and more economical. Thus, the intelligent building management system distinguishes Montreal: by interconnecting its heating, electricity, and cooling management devices, it can adjust its energy consumption as closely as possible to real needs and thus achieve cost savings.

Associated with artificial intelligence, 5G paves the way for concrete and innovative uses, such as predictive analysis of mobility flows and their management in real-time. This is why 5G will enable the full potential of smart city technologies to be realized.

## 5 Conclusion

This paper describes the concepts of smart cities and intelligent transport systems through definitions, the case study on the city of Montreal, which focused on the transport aspect, as an example of the application of ITS and finally different types of communications systems that are used by transportation systems intelligent.

We defined the impact of three technological advances that will revolutionize intelligent transport systems such as autonomous vehicles, 5G mobile networks, and artificial intelligence.

Regarding the problem set out in the introduction, we were able to realize the impact of communications systems on ITS and, therefore, on transport and how communications systems improve and improve future transport.

The ITS and smart cities offer immense possibilities on transport, whether in terms of greenhouse gas reduction with traffic management, road safety, and the various sensors and infrastructures present on the roads. The system offers the comfort of road users with the decrease in time spent in traffic jams and networks mobile devices, allowing many applications.

More fluid, more sustainable, and better managed, the smart city will fully benefit from 5G. Thanks to this new generation of mobile networks, connected city technologies will take on a new dimension, thus creating an ecosystem conducive to innovative services. The 5G changes the rules of the game and offers companies significant opportunities within the smart city.

## References

1. Limon-Ruiz, M., Larios-Rosillo, V.M., Maciel, R., Beltran, R., Orizaga-Trejo, J.A., Ceballos, G.R.: User-oriented representation of Smart Cities indicators to support citizens governments decision-making processes. In: 2019 IEEE International Smart Cities Conference (ISC2), pp. 396–401 (2019). https://doi.org/10.1109/ISC246665.2019.9071742
2. Agbali, M., Trillo, C., Fernando, T., Oyedele, L., Ibrahim, I.A., Olatunji, V.O.: Towards a refined conceptual framework model for a smart and sustainable city assessment. In: 2019 IEEE International Smart Cities Conference (ISC2), pp. 658–664 (2019). https://doi.org/10.1109/ISC246665.2019.9071697
3. Nam, T., Pardo, T.A.: Conceptualizing smart city with dimensions of technology people and institutions. In: Proceedings of the 12th Annual International Digital Government Research Conference: Digital Government Innovation in Challenging Times (2011)
4. Chehri, A., Quadar, N., Saadane, R.: Communication and localization techniques in VANET network for intelligent traffic system in smart cities: a review. In: Qu, X., Zhen, L., Howlett, R., Jain, L. (eds.) Smart Transportation Systems. Smart Innovation, Systems and Technologies, vol 185. Springer, Singapore (2020). https://doi.org/10.1007/978-981-15-5270-0_15
5. Chehri, A., Mouftah, H.T.: Autonomous vehicles in the sustainable cities, the beginning of a green adventure. Sustain. Cities Soc. **51**, 101751 (2019)
6. Ahmed, I., Jeon, G., Chehri, A., Hassan, M.M.: Adapting Gaussian YOLOv3 with transfer learning for overhead view human detection in smart cities and societies. Sustain. Cities Soc. **70** (2021)

7. Chehri, H., Chehri, A., Saadane, R.: Traffic signs detection and recognition system in snowy environment using deep learning. In: Ben Ahmed, M., Rakıp Karaș, İ., Santos, D., Sergeyeva, O., Boudhir, A.A. (eds.) Innovations in Smart Cities Applications Volume 4. SCA 2020. Lecture Notes in Networks and Systems, vol. 183. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-66840-2_38
8. El Ouahmani, T., Chehri, A., Hakem, N.: Bio-inspired routing protocol in VANET networks—a case study. In: Elsevier's Procedia Computer Science 23rd International Conference on Knowledge-Based and Intelligent Information & Engineering Systems, 4–6 Sept 2019

# Vortex Optimization of a Low-Head Gravity Hydroelectric Power Plant

**Manuel Ayala-Chauvin, Henrry Rojas-Asuero, Genís Riba-Sanmartí, and Jaime Ramón-Campoverde**

**Abstract** Gravitational Water Vortex Power Plant (GWVPP) is a Small-Scale Hydropower System which converts energy in a moving fluid to rotational energy. The main advantage of this technology is the low head hydraulic requirements. The aim of this work is to optimize the hydraulic geometry of the vortex, to achieve this, two prototypes (A and B) were designed and built to validate the proposed design process. The prototype A has a flat-bottom chamber and prototype B has a conical chamber outlet; both induce spiraling fluid streamlines. Prototypes were studied numerically and experimentally. The numerical study was developed in ANSYS CFX R19.0 software and the experimental phase was carried out in the fluid's laboratory of the Technical University of Loja in Ecuador. The results show that the conical chamber improves strong free-surface vortex formation and increases water velocity in the center of the vortex flow. Finally, the proposed design method was validated and allows to reproduce the hydraulic structures of the gravity water vortex power plant.

## 1 Introduction

Electric energy is fundamental for activities that improve living standards. However, traditionally, this activity significantly impacts on the environment for many reasons, such as the atmospheric pollution caused by fossil fuels that dominate electricity

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production worldwide [1]. This inspires organizations worldwide to pay more attention to sustainable energy generation approaches, where Renewable Energy (RE) sources are the future of energy systems [2]. Solar Energy, Wind Energy, and Small-Scale Hydropower (SSH) are interesting fields due to their large potential [3–5].

Mini-hydro provides renewable energy production, reduces environmental and landscape impact. In addition, it provides numerous social and economic benefits [6]. In this sense, the viability of these systems is being evaluated globally to make them sustainable in contexts that lack energy access [7].

SSH turbines are used for electricity generation by river flow [5], considered one of the most efficient and profitable technologies for rural electrification programs [8]. SSH has few negative impacts on the riverine, and it is appropriate in remote areas in which the expansion of the electricity distribution network is not possible, or it is not reliable. Small hydroelectric generation allows distributed energy generation from renewable sources, boosting the energy autonomy of communities at the local level [9, 10]. According to the European Commission, SSH capacity production should be less than 10 MW [11]. However, there is no internationally agreed-upon definition for SSH capacity. There are several types of SSH turbines, but there is an innovative and striking technology called Gravitational Water Vortex Power Plant (GWVPP) [12].

GWVPP could be considered a juvenile water turbine, with only a few commercial units deployed internationally. The main advantage of GWVPP is the ultra-low hydraulic head requirement. It does not create interference in the water-life ecosystems. It can operate in sites with head lower than two meters [12–14]. It exploits the rotation energy available in a strong free-surface vortex flow [15]. The water is channeled and conveyed to a vortex chamber. The vortex chamber has a tangential inlet and a central outlet. The combination of localized low pressure at the orifice and the concept of induced circulation at the tangential inlet influences free-surface vortex flow [16, 17].

Experimental studies by Mulligan and Hull [18] determined that the optimum vortex force occurs within the range of orifice diameter to chamber diameter (d/D) ratios of 0.14–0.18. However, geometry at the vortex exit was not experimented with in this research.

In this regard, Rojas-Asuero et al. [19] compared different vortex shapes and determined that an increase in velocity is generated with a conical outlet. In addition, he determined that linking the open channel with the vortex chamber reduces energy loss at the chamber inlet. Furthermore, according to [12], conical chamber structures at the outlet are more efficient than cylindrical ones with otherwise similar inlet and outlet conditions.

The design of these structures using fluid dynamics software has been a great contribution. These analyses with computational fluid dynamics allow determining the main geometric parameters that affect the efficiency of GWVPP systems. These results, when validated against experimental results, are used to optimize the simulations and produce better designs [20].

In this way, advances were made that allowed studying the geometric effects of a free-surface vortex and determining the depth-discharge relationship [15]. In addition, the parameters affecting the formation of an air-cored vortex and its strength were investigated using the computational fluid dynamics approach [16]. However, the technology has not yet advanced beyond the prototyping stage [17].

Experimental and theoretical studies on GWVPP have been widely developed in the current literature to improve the efficiency and design of these systems [14, 15]. This numerical and experimental combination has led to increased performance of GWVPP systems [23].

The simulation allows to systematically compare flow velocities with the geometry of the device, and thus validate the model with experimental observations [24]. Additionally, the characteristic curves can be predicted as a function of inlet flow and turbine rotation.

In this work we aim to optimize the output of a vortex for which two prototypes were designed and built to validate the geometry of the proposed design. The numerical study was developed in ANSYS CFX R19.0 software, and the experimental setup was built in the Hydraulic Laboratory of the Technical University of Loja in Ecuador.

## 2 Method

The prototype A has a flat-bottom chamber (Fig. 1b) that induces spiraling fluid streamlines. The chamber perimeter takes a logarithmic spiral form (Fig. 1a). The inlet open-channel is located in the upper part of the chamber. The bottom part of the chamber has a hole at the center. The prototype B has a conical chamber outlet (Fig. 1c). Furthermore, the rest of the parameters are equal to the prototype A. Free-surface vortex formation was considered with a subcritical approach flow.

Figure 1 shows the components and notations of the GWVPP hydraulic structure which will be used in this section.

The analytical method was used to determine the open-channel and vortex chamber geometries. The flow rate ($Q$) was first defined; it can be obtained from hydrological studies and power generation analysis for the implementation site. Also, the discharge number ($Nq$) and approach flow factor ($\alpha$) were set. These quantities and their suggested range (Table 1) were obtained from [15].

The discharge number, $Nq$, is equivalent to the outlet Froude number. $Nq$ relates the flow rate ($Q$) and orifice diameter ($d$) at the chamber.

$Nq$ is given by Eq. (1):

$$Nq = \frac{Q}{\sqrt{g}d^{\frac{5}{2}}} \tag{1}$$

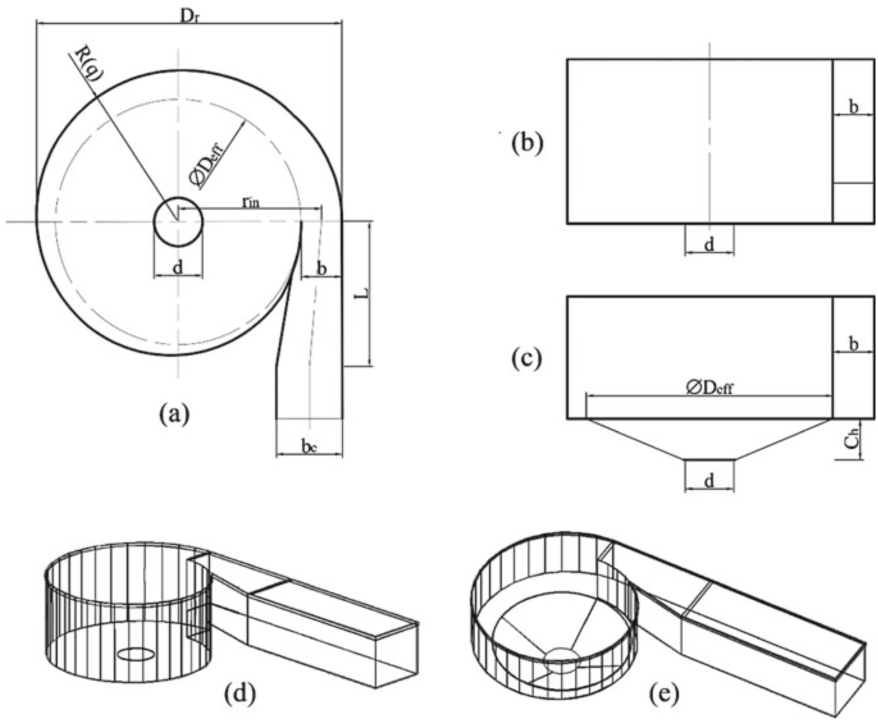


**Fig. 1** Components and dimensions of vortex chamber. Top view of vortex chamber (**a**), flat-bottom chamber (**b**) conical chamber outlet (**c**), 3D flat-bottom chamber prototype A (**d**) and 3D conical chamber outlet prototype B (**e**)

**Table 1** Input data for the design process

| Quantity | Dimension | Suggested range | Input data |
|---|---|---|---|
| Flow rate (Q) | $m^3/s$ | – | 0.005 |
| Discharge number (Nq) | Dimensionless quantity | Nq < 0.7 | 0.36 |
| Approach flow factor (α) | Dimensionless quantity | 1 < α < 5 | 2.75 |

Approach flow factor ($\alpha$) Eq. (2) is calculated based on approach flow parameters, inlet radius ($r_{in}$), and inlet width ($b$):

$$\alpha = \frac{r_{in}}{b} \tag{2}$$

According to [15] with $\alpha$ and the relation vortex flow, depth/orifice diameter ($h/d$) is possible to estimate $Nq$'s values.

For both prototypes, $Q$ was selected due to pump availability in the laboratory. $Nq$ and $\alpha$ values were assumed as numbers between the suggested ranges. Suggested ranges are benchmarks that allow creating strong free-surface vortex flow relatively steady following vortex flow zones in the chart.

From discharge number ($Nq$) Eq. (1) the orifice diameter ($d$) was determined

$$d = \left(\frac{Q}{Nq\sqrt{g}}\right)^{\frac{2}{5}} \tag{3}$$

As was previously shown, Mulligan and Hull [18] propose a relationship between the orifice diameter ($d$) and chamber diameter ($D$) to optimize vortex strength. So, a $D$ value was obtained from d value. $D$ is a reference for the calculation of the real external diameter ($D_r$)

$$\frac{d}{D} = 0.16 \tag{4}$$

Inlet width ($b$) can be determined from $\alpha$ Eq. (2). With a geometrical analysis, it was possible to express $r_{in}$ in the next form

$$r_{in} = \frac{D}{2} - \frac{b}{2} \tag{5}$$

Substituting both of the Eqs. (2) and (5) the following expression was achieved

$$b = \frac{D}{2\alpha + 1} \tag{6}$$

Effective scroll diameter ($\emptyset D_{eff}$) was also defined from geometrical analysis

$$\emptyset D_{eff} = 2\left(\frac{D}{2} - b\right) \tag{7}$$

Therefore, using Eqs. (5) and (7)

$$r_{in} = \frac{\emptyset D_{eff} + b}{2} \tag{8}$$

For the prototypes, the chamber wall had 2 mm thickness which was depreciated for the analysis. Many studies suggest spiral shape in vortex chambers the best option [22, 25, 26]. $D$ was considered as the first reference, but it was necessary to determine the actual external diameter ($D_r$) to adapt it to a logarithmic spiral.

$$D_r = \left(r_{in} + \frac{b}{2}\right)\left[1 + \left(\frac{r_{in} - \frac{b}{2}}{r_{in} + \frac{b}{2}}\right)^{0.5}\right] \tag{9}$$

To determine the vortex flow depth ($h$) another expression of [15] was used.

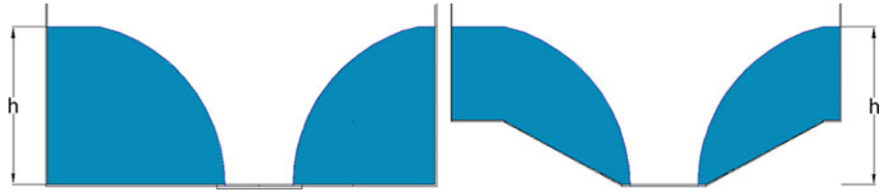


**Fig. 2** Vortex flow depth in chamber section

$$Q = \frac{k_\alpha}{\left(\frac{5\alpha d}{h}\right)^{n_\alpha}} \sqrt{g} d^{5/2} \tag{10}$$

Therefore, $h$ can be expressed (See Fig. 2).

$$h = \frac{5\alpha d}{\left(\frac{k_\alpha d^{2.5}\sqrt{g}}{Q}\right)^{\frac{1}{n\alpha}}} \tag{11}$$

All the parameters of the equation except for $k_\alpha$, $n_\alpha$ (auxiliary hydraulic parameters) were determined. They were defined with the next expressions [15, 26]

$$k_\alpha = -0.12\alpha^3 + 0.79\alpha^2 + 0.62\alpha + 0.36 \tag{12}$$

$$n_\alpha = -0.05\alpha^2 + 0.39\alpha + 0.55 \tag{13}$$

$h$ is the optimum vortex flow depth. This value must be guaranteed in the system performance. It is necessary to use $Nq$ and the relation $h/d$. To complete the chamber design process, the logarithmic spiral shape was defined Eq. (14).

$$r(\theta) = ac^\theta \tag{14}$$

$a$ and $c$ are geometrical constants based on $r_{in}$ and $b$.

$$a = \left(r_{in} + \frac{b}{2}\right) \tag{15}$$

$$c = \left(\frac{r_{in} - \frac{b}{2}}{r_{in} + \frac{b}{2}}\right)^{\frac{1}{2\pi}} \tag{16}$$

From Eqs. (14) and (15)

$$r(\theta) = \left(r_{in} + \frac{b}{2}\right)c^\theta \tag{17}$$

where $r(\theta)$ is the radius of the spiral at an angle $\theta$ between 0 and 360°. $\theta$ is the angle in radians and $c$ is a geometric constant of the logarithmic spiral related to the inlet radius and the inlet width. Coordinates $x$ and $y$ are described for the next expressions

$$x = r(\theta)\cos(\theta) \tag{18}$$

$$y = r(\theta)\mathrm{sen}(\theta) \tag{19}$$

For open-channel characteristics, the rectangular section is the best alternative to get a better adaptability with the chamber inlet. For every flow-rate in open-channels, there are specific most efficient cross-sections. Then, based on the Chezy and Manning equation (See Fig. 3a):

$$b_c = \left(\frac{2^{\frac{7}{3}}Qn}{S^{\frac{1}{2}}}\right)^{\frac{3}{8}} \tag{20}$$

$b_c$ is the open-channel bottom width, n is the Manning's roughness coefficient, and $S$ is the longitudinal open-channel slope. $S$ can be defined from topographical information of the implementation site. However, the designer must guaranty subcritical velocities to adopt this methodology. The most efficient cross-section in rectangular geometry occurs when the depth of flow in the channel ($y_c$) is equal to $b_c/2$.

Figure 3a shows top view of open-channel. To avoid overflow in the channel a security height was added, so channel depth $h_c$ (Fig. 3b) was calculated as follow

$$h_c = 1.2y_c \tag{21}$$

Evaluating different flow conditions, for the prototypes $h_c = 1.5y_c$. Due to the difference between $b_c$ and $b$ (Fig. 1a) it was necessary to establish a hydraulic transition length ($L$) as [19] suggest. Thus, the following expression determines $L$ to reduce hydraulic losses.

$$L = \frac{b_c - b}{\tan(12.5°)} \tag{22}$$

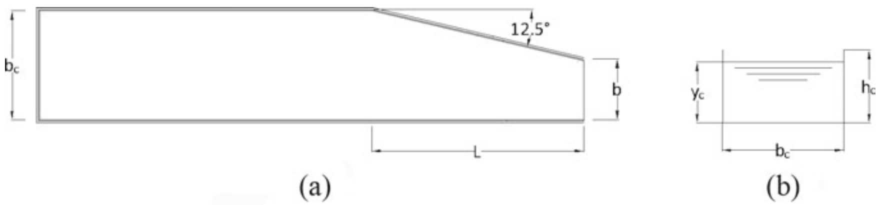


**Fig. 3** **a** Top view of open-channel and hydraulic transition and **b** open channel cross-section

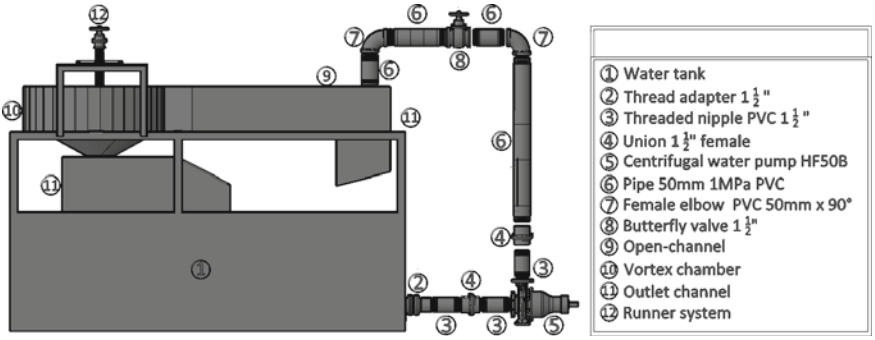


**Fig. 4** Experimental Setup for laboratory work

According to [8, 19, 27] suggest better vortex performance occurs when the cone-diameter increases. To ensure a correct conical outlet geometry $\O D_{eff}$ was used as cone base diameter ($C_d$). Cone height ($C_h$) was determined from the next expression (See Fig. 1c).

$$C_h = h - y_c \tag{23}$$

## 2.1 *Experimental Setup*

Experiments were conducted at the Hydraulic Laboratory of the Technical University of Loja. The physical model and its complementary components are depicted in Fig. 4. It was made of galvanized steel sheets. The flow was supplied from a recirculating pump system. The flow rate of the pump is adjustable from a valve connected to the pipe.

Table 2 shows the calculation summary with the condition given by the input data Table 1. The first appreciation, of comparison between prototypes, is that A was easier to construct but the flat-bottom chamber represents a mechanical stress concentration. Prototype A would not facilitate the sediments out, but B would, reduce the chamber's maintenance. Figure 1d, e shows 3D models of prototypes A and B.

# 3 Results

Figure 5 shows vortex formation time for different flow rates in prototypes A and B. The former takes more time to create the vortex in evaluated flow rate. When $Q$ is minimum (1.20 l/s) difference in vortex formation is around 31%. On average, the

**Table 2** Dimensions of vortex chambers and open-channel

| Denomination | Symbol | Value (m) |
|---|---|---|
| Orifice diameter | $d$ | 0.11 |
| Inlet width | $b$ | 0.10 |
| Effective scroll diameter | $\emptyset D_{eff}$ | 0.43 |
| Inlet radius | $r_{in}$ | 0.27 |
| real external diameter | $D_r$ | 0.58 |
| Cone height | $c_h$ | 0.09 |
| Cone base diameter | $c_d$ | 0.43 |
| Vortex flow depth | $h$ | 0.17 |
| Open channel bottom width | $b_c$ | 0.18 |
| Depth of flow in the channel | $y_c$ | 0.09 |
| Channel depth | $h_c$ | 0.14 |
| Hydraulic transition length | L | 0.35 |

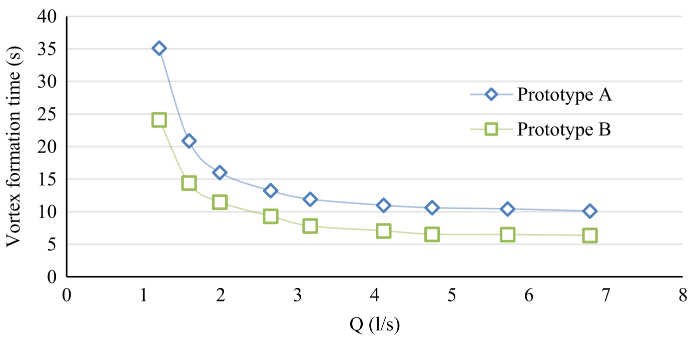


**Fig. 5** Vortex formation time comparison between prototype A and prototype B

difference in vortex formation time between prototype A and B is around 33%. This indicates that the conical chamber outlet improves vortex formation.

For both prototypes A and B, there was an increase of streamlines velocity of more than 600%; the water flow entered the canal with an average velocity of 0.17 m/s and got velocities of 1.3 m/s (the darkest tone of the outlet hole). This verified the tank efficiency in the generation system since increasing the flow speed at the point of mechanical extraction. Comparing both prototypes, as shown numerically, the formation of the vortex was more stable in prototype B due to the discharge cone.

In the numerical simulation, channel's streamlines behavior and how the vortex formation is generated were evaluated. The CFD modelling software used in this study was ANSYS CFX R19.0 The numerical model of the free surface in this software is based on the Eurelian fluid's approach. In this approach two fluids, air and water, occupy the same domain. The domain temperature is isothermal. The temperature of the domain was set to 25 °C. 1 atm was set as the reference pressure.

The buoyancy reference density was set to the density of air at 25 °C. BSL EARSM Turbulence Model was used to analyze the flow patterns. The governing equations for the unsteady, vicious, turbulent flow are the Navier–Stokes equations (Fig. 6).

The first increase in velocity was about 2.5 times the original velocity and was generated due to the progressive narrowing of the channel (hydraulic transition). At this point, there was a formation of slight turbulence that did not affect the formation of the vortex according to the simulation results. It was verified in the built prototype (See Fig. 7) that, although the velocity inlet increased the laminar-turbulent transition of the flow, it did not affect the vortex's formation.

Prototype B demonstrated better behavior than A; some photographic are presented in Fig. 7, vortex formation can be appreciated. In the laboratory work, when $Q$ increased, the vortex still worked and stayed stable, even when $Q$ was 70% greater than the design value.

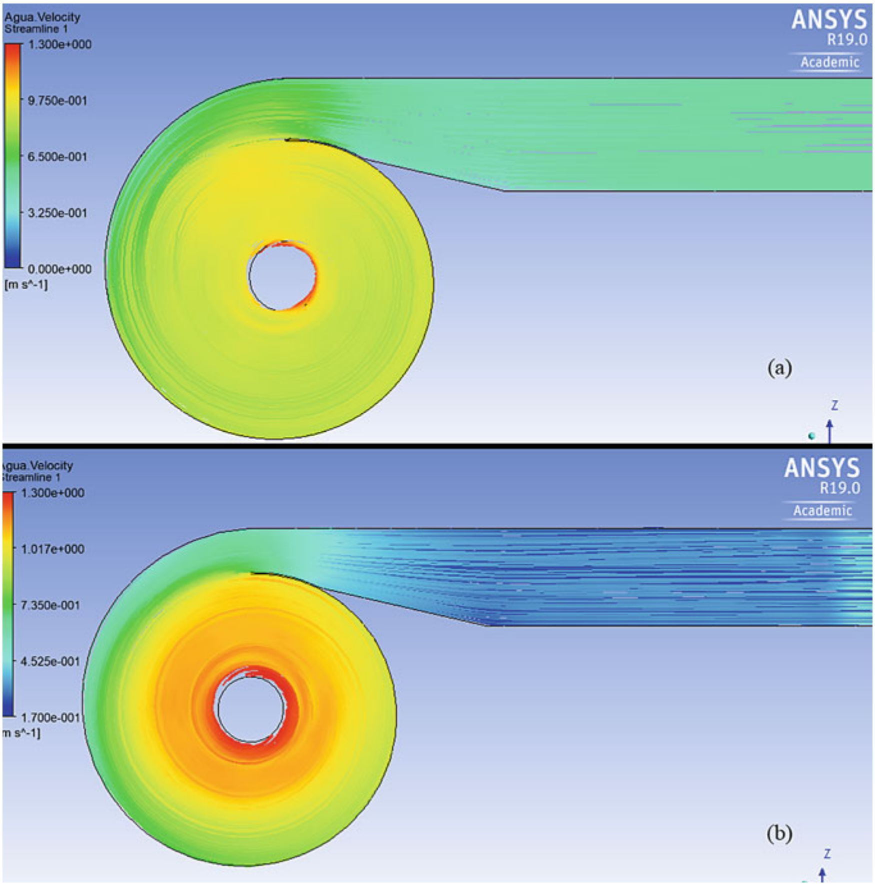


**Fig. 6** Streamlines at 35 s. **a** prototype A and **b** prototype B

**Fig. 7** Prototypes A and B

## 4 Discussion

Low head generation systems are a suitable solution for rural electrification [28]. In addition, they allow boosting the concept of distributed generation by boosting the energy sustainability of the territories. The gravity water vortex power plant (GWVPP) is a technique for harnessing low head hydro power, so it is necessary to decrease hydraulic losses as much as possible to improve efficiency. In this study, it is claimed that conical geometry compared to cylindrical geometry is more efficient and can reach 65% efficiency. These systems are ideal for countries such as Ecuador that have hydraulic resources for power generation, providing a solution to isolated communities.

## 5 Conclusion

Gravitational Water Vortex Power Plant can be defined as one of the cleanest Small-Scale Hydropower systems, for its implementation does not require several land extensions for the reservoir, and does not create a water ecosystem fragmentation. It has significant advantages in comparison with the traditional hydroelectric systems.

Two variants of the Gravitational Water Vortex Hydraulic Power Plant were considered in this study, A and B, with a flat and conical chamber outlet respectively. Both variants were studied numerically and prototyped in the lab.

Prototype A is easier to build, but is under higher mechanical stress and tends to accumulate sediments, while B evacuates water and sediments better, leading to lower maintenance needs overall.

The hydraulic performance of variant B is generally better, with faster vortex creation times and higher angular velocities. It was also determined for both prototypes that the angular velocity of the vortex is higher when the runner is close to the discharge.

The conical chamber outlet of variant B improves strong free-surface vortex formation and increases water velocity at the center of the vortex flow.

One of the main conclusions of this study is that the performance of ultra-low head water vortex plants is very sensitive to the geometry of the chamber, and that the benefits of the conical configuration greatly outweigh the constructive drawbacks.

Since the investment required to install one of these plants may be significant for the type of community that may benefit of this plant, it is very important to obtain a good ROI (Return On Investment) to optimize the geometry in a case-to-case basis.

The next steps of this research are to keep optimizing the design of the conical chamber, and also to install a test plant on a real working environment.

After the design is validated, micro-hydraulic power plants will be installed on several locations in Ecuador and other Andean countries. These facilities will empower local communities, increase their resilience and dynamize the local economy.

## References

1. British-Petroleum: BP Statistical Review of World Energy 2019 (2019). https://doi.org/10.1001/jama.1973.03220300055017.
2. Hatata, A.Y., El-Saadawi, M.M., Saad, S.: A feasibility study of small hydro power for selected locations in Egypt. Energy Strateg. Rev. **24**, 300–313 (2019). https://doi.org/10.1016/j.esr.2019.04.013
3. Nawri, N., Petersen, G.N., Bjornsson, H., Hahmann, A.N., Jónasson, K., Hasager, C.B., Clausen, N.-E.: The wind energy potential of Iceland. Renew. Energy. **69**, 290–299 (2014). https://doi.org/10.1016/j.renene.2014.03.040
4. Kabir, E., Kumar, P., Kumar, S., Adelodun, A.A., Kim, K.-H.: Solar energy: potential and future prospects. Renew. Sustain. Energy Rev. **82**, 894–900 (2018). https://doi.org/10.1016/j.rser.2017.09.094
5. Tian, Y., Zhang, F., Yuan, Z., Che, Z., Zafetti, N.: Assessment power generation potential of small hydropower plants using GIS software. Energy Rep. **6**, 1393–1404 (2020). https://doi.org/10.1016/j.egyr.2020.05.023
6. Rotilio, M., Marchionni, C., De Berardinis, P.: The Small-Scale Hydropower Plants in Sites of Environmental Value: An Italian Case Study (2017). https://doi.org/10.3390/su9122211
7. Chala, G.T., Ma'Arof, M.I.N., Sharma, R.: Trends in an increased dependence towards hydropower energy utilization—a short review. Cogent Eng. **6**, 1631541 (2019). https://doi.org/10.1080/23311916.2019.1631541
8. Balkhair, K.S., Rahman, K.U.: Sustainable and economical small-scale and low-head hydropower generation: a promising alternative potential solution for energy generation at local and regional scale. Appl. Energy **188**, 378–391 (2017). https://doi.org/10.1016/j.apenergy.2016.12.012
9. Gagliano, A., Tina, G.M., Nocera, F., Patania, F.: Technical and economic perspective for repowering of micro hydro power plants: a case study of an early XX century power plant. Energy Procedia. **62**, 512–521 (2014). https://doi.org/10.1016/j.egypro.2014.12.413
10. Quaranta, E., Bonjean, M., Cuvato, D., Nicolet, C., Dreyer, M., Gaspoz, A., Rey-Mermet, S., Boulicaut, B., Pratalata, L., Pinelli, M., Tomaselli, G., Pinamonti, P., Pichler, R., Turin, P., Turrin, D., Foust, J., Trumbo, B., Ahmann, M., Modersitzki, M., Kist, S., Mosca, C., Malerba, C., Francesconi, A., Casoli, I., Ferrari, R., Stefani, V., Scibetta, M., Meucci, L., Gostner, W., Bergamin, R., Pretto, F.D., Turcato, D., Kocher, V., Lefaucheux, P., Elmaataoui, A., Mariucci, M., Sarma, P., Slachmuylders, G., Clementi, R., Pasut, F., Bragato, N.: Hydropower case study collection: innovative low head and ecologically improved turbines, hydropower in existing

infrastructures, hydropeaking reduction. Digitalization and Governing Systems (2020). https://doi.org/10.3390/su12218873
11. Pérez-Sánchez, M., Sánchez-Romero, F.J., Ramos, H.M., López-Jiménez, P.A.: Energy Recovery in Existing Water Networks: Towards Greater Sustainability (2017). https://doi.org/10.3390/w9020097
12. Dhakal, S., Timilsina, A.B., Dhakal, R., Fuyal, D., Bajracharya, T.R., Pandit, H.P., Amatya, N., Nakarmi, A.M.: Comparison of cylindrical and conical basins with optimum position of runner: gravitational water vortex power plant. Renew. Sustain. Energy Rev. **48**, 662–669 (2015). https://doi.org/10.1016/j.rser.2015.04.030
13. Alzamora Guzmán, V.J., Glasscock, J.A., Whitehouse, F.: Design and construction of an off-grid gravitational vortex hydropower plant: a case study in rural Peru. Sustain. Energy Technol. Assessments. **35**, 131–138 (2019). https://doi.org/10.1016/j.seta.2019.06.004
14. Ayala-Chauvin, M., Benavides, H., Riba, G., Blanco, E.: Underwater power generator based on gravity vortex siphon boost energy transition. J. Sustain. Dev. Energy, Water Environ. Syst. (2020). https://doi.org/10.13044/j.sdewes.d8.0374
15. Mulligan, S., Casserly, J., Sherlock, R.: Effects of geometry on strong free-surface vortices in subcritical approach flows. J. Hydraul. Eng. **142**, 1–12 (2016). https://doi.org/10.1061/(ASCE)HY.1943-7900.0001194
16. Chattha, J.A., Cheema, T.A., Khan, N.H.: Numerical investigation of basin geometries for vortex generation in a gravitational water vortex power plant. In: 2017 8th Int. Renew. Energy Congr. IREC 2017 (2017). https://doi.org/10.1109/IREC.2017.7926028
17. Rahman, M.M., Tan, J.H., Fadzlita, M.T., Wan Khairul Muzammil, A.R.: A review on the development of gravitational water vortex power plant as alternative renewable energy resources. IOP Conf. Ser. Mater. Sci. Eng. **217** (2017). https://doi.org/10.1088/1757-899X/217/1/012007
18. Mulligan, S., Hull, P.: Design and optimisation of a water vortex hydropower plant. Sligeach Dep. Civ. Eng. Constr. **6**, 62330 (2010)
19. Rojas-Asuero, H., Benavides-Muñoz, H.: Diseño de una central minihidráulica basada en un vórtice gravitacional (2014)
20. Shabara, H.M., Yaakob, O.B., Ahmed, Y.M., Elbatran, A.H.: CFD simulation of water gravitation vortex pool flow for mini hydropower plants. J. Teknol. **74**, 77–81 (2015). https://doi.org/10.11113/jt.v74.4645
21. Timilsina, A.B., Mulligan, S., Bajracharya, T.R.: Water vortex hydropower technology: a state-of-the-art review of developmental trends. Clean Technol. Environ. Policy **20**, 1737–1760 (2018). https://doi.org/10.1007/s10098-018-1589-0
22. Domfeh, M.K., Gyamfi, S., Amo-Boateng, M., Andoh, R., Ofosu, E.A., Tabor, G.: Free surface vortices at hydropower intakes: a state-of-the-art review. Sci. African. **8**, e00355 (2020). https://doi.org/10.1016/j.sciaf.2020.e00355
23. Ruiz Sánchez, A., Guevara Muñoz, A.J.: Numerical and experimental evaluation of concave and convex designs for gravitational water vortex turbine. J. Adv. Res. Fluid Mech. Therm. Sci. **64**, 160–172 (2019). 2289-7879
24. Powalla, D., Hoerner, S., Cleynen, O., Müller, N., Stamm, J., Thévenin, D.: A Computational Fluid Dynamics Model for a Water Vortex Power Plant as Platform for Etho- and Ecohydraulic Research (2021). https://doi.org/10.3390/en14030639
25. Mulligan, S., Creedon, L., Casserly, J., Sherlock, R.: An improved model for the tangential velocity distribution in strong free-surface vortices: an experimental and theoretical study. J. Hydraul. Res. **57**, 547–560 (2019). https://doi.org/10.1080/00221686.2018.1499050
26. Warjito, Budiarso, Christopher, C.R., Adanta, D.: The effect of basin geometry on gravitational vortex hydropower. IOP Conf. Ser. Mater. Sci. Eng. **788** (2020). https://doi.org/10.1088/1757-899X/788/1/012081.
27. Patiño-Armijos, E., Benavides-Muñoz, H.: Estudio del comportamiento hidráulico de un flujo a través de un sistema de vórtice gravitacional utilizando técnicas de Dinámica de fluidos computacional (CFD) (2014)
28. Uamusse, M.M., Tussupova, K., Persson, K.M., Berndtsson, R.: Mini-Grid Hydropower for Rural Electrification in Mozambique: Meeting Local Needs with Supply in a Nexus Approach (2019). https://doi.org/10.3390/w11020305

# A Simple Trombe Wall Enhanced with a Phase Change Material: Building Performance Study

**Jakub Čurpek and Miroslav Čekon**

**Abstract** Viable utilizing of solar energy by a building envelope can be achieved by different structural principles and material layer positions inside the construction. An application of passive responsive materials actuated by various boundary stimuli reveals considerable potential of heat transfer management through the façade system. This paper is focused on the thermal performance of the simple Trombe wall concept enhanced with a phase change material (PCM). The main concern is based on initial performance prediction using calibrated building energy simulation to identify the energy effective parameters for this system. Adjustment of different thermo-physical properties of integrated materials revealed substantial effect on overall thermal efficiency in terms of cooling loads and pointed out the effect of phase change temperature of PCMs.

## 1 Introduction

The principles of passive solar walls represent one of the optional ways in a building energy saving campaign. The great potential among these walls represents Trombe wall system with its considerable solar/thermal performance for covering building energy loads. Generally, the main characteristic of Trombe wall as a massive wall structure is closely related to its thermal energy storage properties, which can reduce building energy consumption. A traditional concept of the wall structure consists of external glass, air cavity and main massive wall with high sensible heat accumulation. Actual research studies indicated that this kind of passive solar utilization in buildings has a various shortcoming except aesthetic value (excessive heat losses during cloudy cold days, internal heat transfers occur uncertainly, overheating may outweigh the winter benefits in some climate zones, etc.) [1].

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One of the options, how to improve the energy performance of the wall system is substituting massive heavy wall structure to lightweight latent heat storage material instead of the sensible storage material conventionally employed. This principle determinates more heat energy storage in a smaller volume. Phase change material (PCM) represents promising passive solar technology and more implementable material in lightweight building envelope structures. Moreover, this smart material has a different behaviour under dynamic solar radiation exposure. PCM can store latent heat energy from incoming solar radiation in certain narrow temperature range—temperature stabilization. Its daily work principle is based on storage heat energy during daytime and release it during night-time. The accurate determination of its material typology and position within building envelope should be specially considered for different climate zones. The PCM based Trombe wall could decrease and equalize indoor air temperature fluctuations and inside heat energy demands. The working principle of this physical method is based on three steps: thermal energy absorbing, storing and releasing. The latent heat storage capacity of PCM is in dependency with the rate of narrow temperature change required according to applied boundary conditions and the material volume. However, the main disadvantages of PCM-Trombe wall are that one PCM has only one phase change temperature which could be active only in one season through whole year. Accordingly, Zhu et al. [2] proposed and numerically investigated the Trombe wall with double layers of shape stabilized PCMs panel. The simulation outputs indicated the optimum values of phase change temperature of external and internal PCM wallboard are 30 °C and 18 °C, respectively. Oluah et al. [3] investigated the selection of PCM for optimum Trombe wall performance, where the weights of the four criteria were considered (heat of fusion, thermal conductivity, density and cost). The results revealed that the thermal conductivity had the highest rank of 72.12%, and the eutectic combination of capric acid and palmitic acid had the best rank of 95.1% for Trombe wall application. Sergei et al. [4] revised the current potential of the Trombe wall for cold climate zones. Accordingly, the most appropriate design solutions were established with the consideration of PCM layer. Omara and Abuelnuor [5] presented comprehensive review about different design aspects of integrating PCMs in Trombe walls. It was highlighted that this wall structure shows higher saving in total energy consumption compared with a conventional Trombe wall. The weakest thermal element in the Trombe wall system is the front external glazing due to increased heat losses through it mainly in colder climates. Accordingly, transparent insulation systems have been adopted with low thermal conductivity. Manz [6] investigated the passive solar wall composed of a translucent PCM storage device covered by transparent insulation material (TIM) with capillary structure made of PMMA. However, there is a lack information in these structural systems in terms of their real energy potential with combination of different values of absorptivity of solar absorber (Fig. 1).

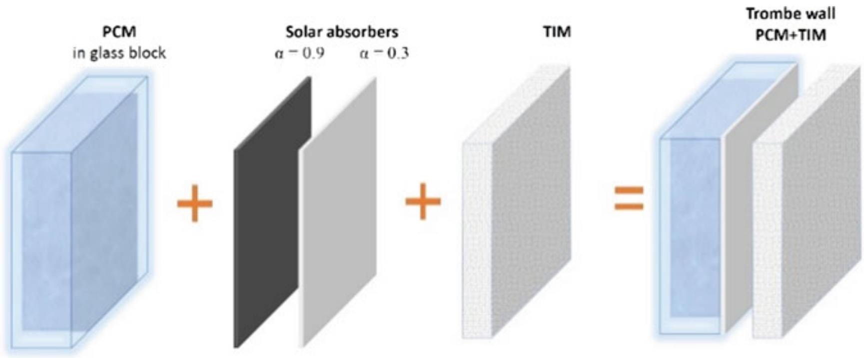


**Fig. 1** Material combination of thermo-physical advances in Trombe wall

## 2 Methodological Approach

Presented simulation study is focused on the thermal performance investigation of novel structure of PCM Trombe wall coupled with Transparent Insulation Material (TIM) during the summer season in climate zone of Bratislava, Slovakia. A solar façade prototype based on TIM glazing system coupled with a black painted absorber was developed and validated in previous studies [7, 8]. It shows that the TIM integration is potentially limited by overheating phenomena. Accordingly, it reveals a maximum cooling energy load obtained via dynamic outdoor tests and validated with building performance simulations. As the overheating factor of TIM incorporation represents one of the critical aspects, a proper design of TES has its legitimate place. Therefore, the objective of this analysis is to identify the energy effective parameters for building integrated PCMs in the Trombe wall (TW-PCM + TIM). In this study, this was primarily focused on the effect between latent heat storage (LHS) and sensible heat storage (SHS) based on ordinary concrete with the aim to simulate potential reduction of a maximum cooling energy load achieved during summer period.

### *2.1 Simple Trombe PCM Wall*

A simple Trombe wall (TW) enhanced with PCM (TW-PCM) was designed to analyze the effect of TES within heat accumulation layer behind the TIM system. The used basic materials and geometrical parameters are shown in Fig. 2.

Total size of the evaluated models is $1.19 \times 1.19$ m with $1.15 \times 1.05$ m size of the transparent insulation material (TIM). Firstly, reference base and PCM-based case models are simulated and compared with experimentally measured prototype of a transparent insulation façade (TIF) (see [7]). TIF utilizes a gypsum board (GB) as the base layer for integration of solar absorber. In a real façade this could also fulfil the

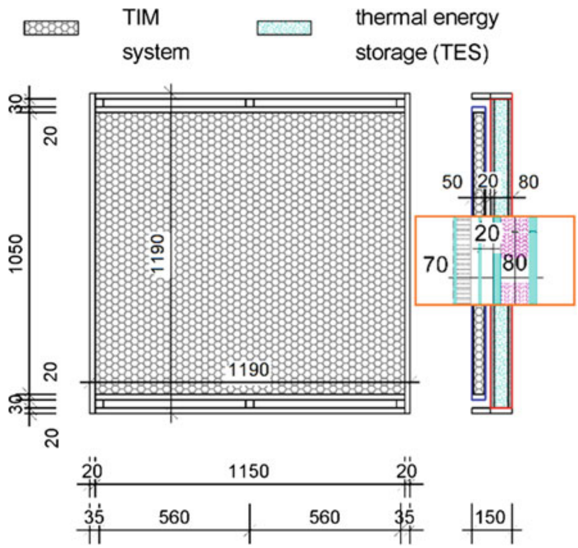


**Fig. 2** A fragment of designed Trombe-wall concept; material and geometrical (mm) parameters

role of a thermal storage, however due to its thickness in a very limited form. Accordingly, for the purpose of the empirical validation study this layer was simplified to a 25 mm GB panel. This was intended to enable it to provide a performance prediction model of the TIM system coupled with the two different solar absorbers (see [8]). For this study, a reference model represents a base case simulation and incorporates an ordinary concrete wall of 80 mm thickness (BS0). Secondly, the performance of this base case is compared with four proposed scenarios comprising of different PCM type embedded in-between two simple glass panes (BS1–BS4), see Table 1. All models (experimental and simulation) utilize commercially available TIM Kapilux TWD [9], which comprises of transparent honeycomb plastics enclosed with glazing and the structure is filled with krypton gas. There is an air cavity between the TIM and TES (22 mm). The TWD has thermal transmittance $U_{TWD}$ 0.7 W m$^{-2}$ K$^{-1}$, which corresponds to $R_{TWD}$ 1.26 m$^2$ K W$^{-1}$. Normal incidence and diffuse total solar energy transmittance or solar heat gain coefficients $g_{t,\perp}$ and $g_{t,h}$ are 58% and 46% respectively. Light transmissions $\tau_{t,\perp}$ and $\tau_{t,h}$ are 70% and 51% respectively.

**Table 1** Evaluated models and their key character

| Model | Description | TES type, thickness |
|---|---|---|
| *EXP* | Experimental based on [7, 8] | Gypsum board, 25 mm |
| *BS0* | Reference concrete based SHS | Ordinary concrete 80, mm |
| *BS1* | PCM based LHS in-between 2 glass panes of 7 mm | Paraffin RT27, 60 mm |
| *BS2* | PCM based LHS in-between 2 glass panes of 7 mm | Paraffin RT35, 60 mm |
| *BS3* | PCM based LHS in-between 2 glass panes of 7 mm | Paraffin RT35HC, 60 mm |
| *BS4* | PCM based LHS in-between 2 glass panes of 7 mm | Paraffin RT42, 60 mm |

**Table 2** Thermo-optical input material parameters of transparent materials

| Material | D [mm] | λ [W/(m K)] | τ [–] | α [–] | ε [–] |
|---|---|---|---|---|---|
| Outermost glass pane | 5 | 1.0 | 0.73 | – | 0.84 |
| TIM Kapipane | 26 | 0.069 | 0.74 | – | 0.9 |
| Krypton | 14 | 0.009 | - | – | – |
| Innermost glass pane | 5 | 1.0 | 0.73 | – | 0.1 |
| Air cavity | 22 | – | – | – | – |
| Solar absorber | – | – | – | 0.9/0.3 | 0.9 |

**Table 3** Thermo-physical input material parameters of TES material

| Material | Density [kg/m$^3$] | Specific heat [J/kg K] | Thickness [mm] | Thermal conductivity [W/(m K)] |
|---|---|---|---|---|
| Concrete | 2000 | 1000 | 80 | 1.2 |
| PCMs | 800 | 2000 | 60 | 0.2 |

Thirdly, the studied models differ in the variation of solar absorbance values (α): high (0.9) and low (0.3) absorptivity of solar absorber is contrasted, transmittance (τ), emissivity (ε) and thermal conductivity (λ) in Table 2. The base structure for the reference model is made of 80 mm concrete wall that serves as a SHS and subsequent PCM-based concepts (Table 3). In this way, the effect of different solar absorber parameters prior to the TES are evaluated.

## 2.2 Research Methods and Simulation Capabilities

To comprehensively investigate the latent TES of a simple Trombe wall concept and predict the thermal performance of the building when the PCM is incorporated, a simulation model has been employed based on experimentally validated building energy performance prediction model in previous study [7]. This was primarily intended on the application of this model to investigate the latent TES of the proposed TW-PCM. The main goal is to include TES function for it to provide performance data on a climate adaptive response under critical summer period. For this purpose, natural ventilation conditions are activated. A proper computational model of a façade structure that contains TIM associated with the thermo-optical properties was characterized. All these parameters are inserted as input into the BES program DesignBuilder that works under the EnergyPlus computational engine. The main goal of the simulation is to analyse the effect of latent thermal energy storage and standard heat accumulation layer based on ordinary concrete with two different solar absorbers on temperature response and cooling energy load through their components. This is conducted by using building performance simulation and subsequently comparative analysis of the results obtained with different scenarios analysed. As demonstrated in Fig. 2, this model allows the option of a ventilation function of the façade air cavity. Therefore, two test scenarios were simulated in tandem as well, first in the nonventilated and second in the naturally ventilated façade air cavity mode. Thus, the simulations covered several possible scenarios on the energy effective parameters.

The simulation model works with the one-dimensional method of both thermal heat transfers and solar spectrum transmittance through the façade element. Due to the PCM application, Conduction Finite Difference (CondFD) solution algorithm was selected which works with fully-implicit finite difference scheme based on the heat capacity method with an auxiliary function (temperature-enthalpy curve is determined by dataset of 16 nodes for latent heat evolution). The system was modelled as multi-zone model (three zone) which comprising the following independent zones: the box, the air cavity within the façade component, and the adjacent compensation room zone. The outside boundary conditions were used the real climatic data measured by the weather station and implemented by using the open-source program Elements for creating and editing custom weather files for BES purpose.

## 3 Simulation Results

The calibration of simulation model was performed according to real climate conditions (incidence vertical solar radiation and outdoor air temperature). The data presented in the graphs below show the results of the two test cases (unvented and vented test case) that demonstrate the difference in the energy efficiency of the simulation compared to the reference model. Depending on the activation of natural ventilation, a more effective reduction in the maximum cooling energy load can be achieved by a combination of both the activation of natural ventilation and the use of the TES. In addition, the decreasing of the surface thermo-optical property (absorbance) of solar absorber determinates the reduction in peak values. The main observation is focused on peak levels of each curve in diagrams and their mutual time delays according to thermal storage capacity of materials. The sum of the cooling loads through the investigated period has been performed and the optimal energy potential of the applied material was stated.

The non-ventilated case is specified with closed air cavity inside the façade element structure, where the natural heat convection transfer is suppresed which determinates increased values of cooling loads. According to simulation results (Fig. 3), PCM type RT 35 (*BS2*) maximally decreased the peak values during both daily and nocturnal period and equalized the curve function through period. However, type RT35 HC(*BS3*) (HC type possess a higher latent heat capacity of 25–30% compared to classic RT materials and phase change occurs in a narrower temperature range) can decrease the peak value at midday (Day 1) about 20 W in comparison with RT 35 (*BS2*).

This decreasing is due to increased latent heat capacity of material, where RT 35 HC (*BS3*) can continuosly absorb thermal energy in longer time. On the contrary, the total sumarization revealed that PCM RT 27 (*BS1*) with a value of cooling load 4976

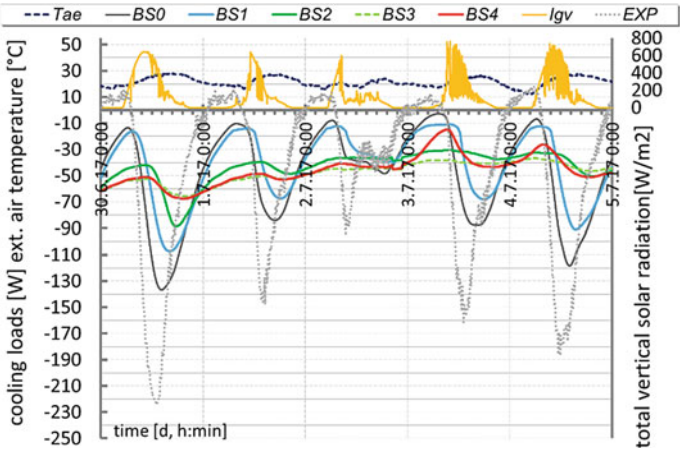


**Fig. 3** The data obtained computationally for heat flow response corresponding to the cooling energy load for unvented test case (*Note EXP* results obtained experimentally for validation)

Wh represents the best heat storage type in this configuration (Table 4). In addition, one specific effect is observed. Though the PCM can significantly reduce heat flow and corresponding temperature fluctuation (see Fig. 3), while the resulting heat load covered may be the same for both LHS and SHS (see Table 4). This is evidently shown for *BS0* (concrete) and *BS3* (RT35HC), respectively.

The ventilated case provides the natural heat convection transfer decreases values of cooling loads. Comparative analysis by simulation results (Fig. 4) revealed that PCM type RT 35 (*BS2*) maximally equalized the curve function through overall period, and can provide almost stable values of cooling load. However, the overall sumarization of used materials revealed that PCM RT 42 (*BS4*) with total value of cooling load 2201 Wh is the optimal heat storage type in this configuration (Table 5).

It is shown, that the PCM with higher melt temperature can start absorbing thermal energy at higher exposure of solar radiation and outside temperature. Accordingly, in case of ventilated regime, the PCM RT 42 (*BS4*) has almost the same curve function as concrete case during the last two days (Day 4 and 5). This PCM is not able to

**Table 4** Daily cooling load (in Watthours) simulated per each day and its total sum (unvented)

| | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Sum |
|---|---|---|---|---|---|---|
| Concrete (*BS0*) | 1683 | 1039 | 745 | 1007 | 1376 | 5850 |
| RT27 (*BS1*) | 1428 | 921 | 666 | 811 | 1150 | 4976 |
| RT35 (*BS2*) | 1422 | 1097 | 908 | 802 | 949 | 5178 |
| RT35HC (*BS3*) | 1409 | 1283 | 1086 | 954 | 994 | 5726 |
| RT42 (*BS4*) | 1418 | 1264 | 1045 | 791 | 980 | 5498 |

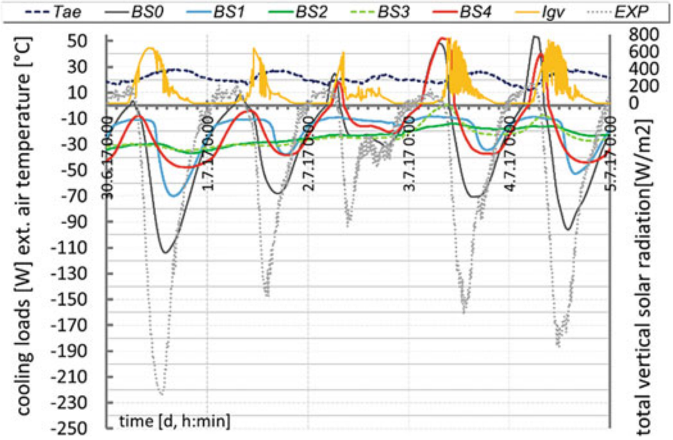


**Fig. 4** The data obtained computationally for heat flow response corresponding to the cooling energy load for vented test case (*Note EXP* results obtained for unvented test case)

**Table 5** Daily cooling load (in Watthours) simulated per each day and its total sum (vented)

| | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Sum |
|---|---|---|---|---|---|---|
| Concrete (*BS0*) | 1233 | 681 | 354 | 485 | 781 | 3537 |
| RT27 (*BS1*) | 802 | 451 | 283 | 384 | 582 | 2502 |
| RT35 (*BS2*) | 783 | 703 | 552 | 402 | 459 | 2899 |
| RT35HC (*BS3*) | 771 | 728 | 599 | 335 | 475 | 2908 |
| RT42 (*BS4*) | 798 | 593 | 260 | 111 | 439 | 2201 |

start absorbing latent heat energy, therefore it works evidently with sensible part of enthalpy.

The effect of two different solar absorbance parameters is presented in Figs. 5 and 6. Primarily, the case with a standard black-painted absorber (0.9) was used as a reference, while the test scenario with a light-shaded absorber (0.3) was used for comparative purposes in order to analyze the color properties and energy performance of the studied absorbers applied in a Trombe-wall. For unvented test scenario, it is shown, that light-based absorber lead to a nearly 10 to 20 W lower simulated heat flow in peaks under diurnal conditions. In addition, the overall sumarization of results revealed that lower value of a solar absorber (0.3) reduces the total value of cooling load from 21 to 29% (Table 6).

For vented test scenario (Fig. 6), it is shown, that light-based absorber lead to the same effect as it was shown in unvented case. However, there are slightly smaller differences compared to unvented case. The overall sumarization of results revealed that lower value of a solar absorber (0.3) reduces the total value of cooling load from 33 to 50% (Table 7). Further potential reducing of cooling needs can be achieved by proper adjustment of the night ventilation strategies (see e.g. [10]).

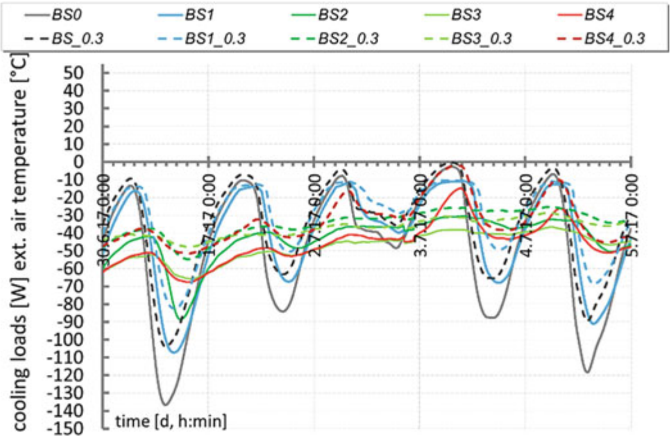


**Fig. 5** The data obtained computationally for heat flow response corresponding to the cooling energy load and effect on different solar absorber parameters (0.9 and 0.3) for unvented test case

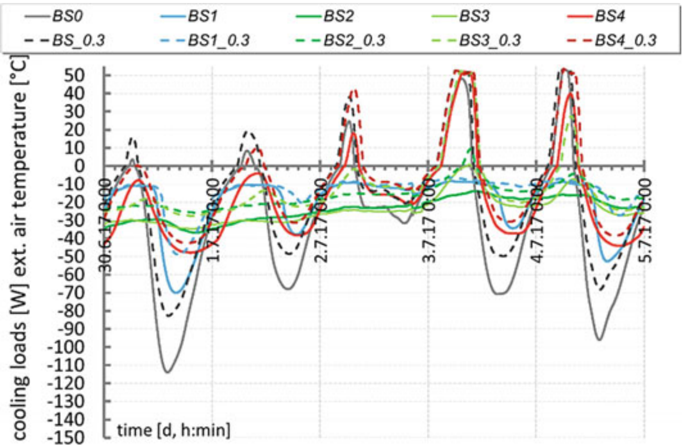


**Fig. 6** The data obtained computationally for heat flow response corresponding to the cooling energy load and effect on different solar absorber parameters (0.9 and 0.3) for vented test case

**Table 6** Total cooling load in comparison with two different absorber values (unvented)

| Cooling load in Wh | Concrete | RT27 | RT35 | RT35HC | RT42 |
|---|---|---|---|---|---|
| Absorber 0.9 | 5850 | 4976 | 5178 | 5726 | 5498 |
| Absorber 0.3 | 4327 | 3675 | 4093 | 4417 | 3907 |
| Percent difference (%) | 26 | 26% | 21 | 23 | 29 |

**Table 7** Total cooling load simulated and comparison of two different absorber values (vented)

| Cooling load in Wh | Concrete | RT27 | RT35 | RT35HC | RT42 |
|---|---|---|---|---|---|
| Absorber 0.9 | 3537 | 2502 | 2899 | 2908 | 2201 |
| Absorber 0.3 | 2038 | 1680 | 1951 | 1462 | 1001 |
| Percent difference (%) | 42 | 33 | 33 | 49 | 50 |

The results provide several points for summary. It is shown that the simulated a simple Trombe-wall concepts based on the four different PCM types exhibits lower minimum heat flow, and reduced heat flow amplitude along with more stable thermal response, as compared with the reference one without the PCM. And the results from numerical modeling identify that the optimal type of the PCM should be around a melting point of 35 °C. Depending on ventilation regime, the absorptivity of the solar absorber inside the air façade cavity can decrease the cooling energy load and heat flow response of the lighter absorber type by 21% to 50% respectively.

## 4 Conclusion

Presented paper compares several variants of a newly introduced TW-PCM + TIM concept with one reference case model based on SHS utilizing ordinary concrete. Thermal energy storage aspects and thermo-responsive reactions were evaluated. Various PCMs were investigated with different temperature ranges of latent heat capacity. The fluctuations of cooling load can be decreased by thermal buffer structure (PCM), but it is necessary to take into consideration that absorbed heat energy can increase the cooling load in nocturnal period of day by continuous realizing of latent heat energy. The overall summarization of both ventilation regimes pointed out that PCM significantly decreased the cooling load by 874 Wh for nonventilated case (RT 27) and by 1336 Wh for ventilated case (RT 42) in comparison with concrete wall. Based on the simulated thermal performance it is possible to conclude that the TW-PCM has the potential to replace conventional TES based on ordinary concrete wall. Though the developed TW-PCM + TIM concept does not meet even contemporary heat loss requirements (like $U$-value), however, this is offset by utilization of significant solar heat gains and their effective heat storage potential. Further step of the simulation campaign will be focused on the visible spectrum transfer into the interior and its effect on natural daylighting.

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## References


1. Omrany, H., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Raahemigar, K., Tookey, J.: Application of passive wall system for improving the energy efficiency in building: a comprehensive review. Renew. Sustain. Energy Rev. **62**, 1252–1269 (2016)
2. Zhu, N., Li, S., Hu, P., Lei, F., Deng, R.: Numerical investigation on performance of phase change material Trombe wall in building. Energy **187**, 116057 (2019)
3. Oluah, C., Akinlabi, E.T., Njoku, H.O.: Selection of phase change material for improved performance of Trombe wall system using the entropy weight and TOPSIS methodology. Energy Build. **217**, 109967 (2020)
4. Sergei, K., Shen, C., Jiang, Y.: A review of the current work potential of a trombe wall. Renew. Sustain. Energy Rev. **130**, 109947 (2020)
5. Omara, A.A.M., Abuelnuor, A.A.A.: Trombe walls with phase change materials: a review. Energy Storage, e123 (2020)
6. Manz, H.: Donnenstrahlungsbeladene Latentwärmespeicher in Gebäuoefassaden. PhD. Thesis, ETH Zurich, Switzerland (1996)
7. Čekon, M., Čurpek, J.: A transparent insulation façade enhanced with a selective absorber: a cooling energy load and validated building energy performance prediction model. Energy Build. **183**, 266–282 (2019)
8. Čekon, M., Čurpek, J., Slávik, R., Šikula, O.: Coupled transparent insulation system with low emissivity solar absorber: an experimentally validated building energy simulation study. Sci. Technol. Built Environ. **26**(4), 511–523 (2020)
9. OKALUX Homepage https://www.okalux.de/fileadmin/user_upload/aktuell/Downloads/Infotexte/Infotext_KAPILUX_TWD.pdf. Last accessed 16 March 2021
10. Simões, N., Manaia, M., Simões, I.: Energy performance of solar and Trombe walls in mediterranean climates. Energy, 121197 (2021)

# Merging Heat Stress Hazard and Crowding Features to Frame Risk Scenarios Within the Urban Built Environment

**Juan Diego Blanco Cadena, Graziano Salvalai, Gabriele Bernardini, and Enrico Quagliarini**

**Abstract** Risk assessment for SLow Onset Disasters (SLODs) in the built environment combine the hazard features, and its effects on the built environment itself, with users' exposure and vulnerability, including behavioral issues. Although different methods exist for identifying the main SLODs drivers and their trend over time and space, limited information is found to set up significant risk scenarios by effectively merging hazard and crowding' features. Hence, this research is aimed at testing a methodology to create relevant risk scenarios for a single SLOD type, in the urban built environment. The work focuses on heat stress because of its growing incidence trend in urban areas. The methodology is applied to a neighborhood portion in Milan, Italy, which is a significant urban scenario for the considered SLOD. Through the application of quick and remote data collection methodologies, preliminary risk levels are traced over the daytime merging hazard and exposure, thus enabling a quick methodology application by practitioners. Results organize extreme and recurring risk scenarios considering relevant users' types and behavioral patterns in respect to both the neighborhood space use and the heat stress arousal. Such scenarios can contribute to the definition of input conditions for simulation-based risk assessment.

## 1 Introduction

Climate change evidence has been found since the 1950s, mainly attributed to anthropogenic activities [1]. This phenomenon has affected the level of wellbeing and safety for the users of the Built Environment (BE). In fact, most of SLow-Onset Disasters

[1] https://www.preventionweb.net/news/view/53004 (last access: 22/04/2021).

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(SLODs) are recognized effects of climate change. Although SLODs are characterized by a slow unfolding,[1] their destruction capacity and impact on society are large, especially on urban BEs, characterized by physical vulnerabilities, large population density and current space intended uses [2].

In such contexts, heat waves events are a recurrent and a critical evidence (human health wise) of increasing temperature SLODs within the BE. Especially, given their gradually rising frequency and intensity [3–5], and their correlation with hospital admissions for heat strokes [6]. Temperatures, and complementary environmental conditions, can produce severe perceived temperature in people, especially those who are prevalently outdoor, and those less capable of tolerating heat (i.e. elders and children) [6–8]. To recognize and quantify the degree of such hazard, heat stress perception categories have been allocated to outdoor thermal comfort metrics.

Increasing temperatures SLOD, is characterized by people repeatedly and/or continuously exposed to unfavorable thermal conditions that progressively deteriorate health. These conditions mainly arise on summer, although mid-seasons also witness such distressing events. Moreover, BE characteristics can boost the hazard intensity, according to the BE physical vulnerability. Such vulnerability is associated with the phenomenon of the Urban Heat Island (UHI). Higher urban air temperatures are the resulting positive thermal balance of urban BE associated to their inherent anthropogenic heat release and their tendency towards: (1) excess storage of solar radiation, (2) lack of green spaces and heat sinks, (3) non-circulation of air in urban canyons and (4) low emitted infrared radiation to the atmosphere [2].

In addition, the increasing temperature SLOD risk should be determined by the combined effect of hazard and physical vulnerability factors, together with the number (exposure) and type of users (social vulnerability) hosted in urban BE. The latter can vary depending on [8–13]: (1) the users' behavioral dynamics (e.g. movement and presence patterns over time and space), mainly referred to the number of people who present and exposed to the hazard; (2) the users' features and preference determining individual vulnerability (e.g. age, health and body characteristics), linked to the groups of people who are more fragile to the studied hazard.

## 2 Literature Review

The environmental conditions and perceived heat stress, can vary across the urban BE (e.g. micro-climates). Such distribution, can be modelled throughout the use of computer-aided simulation tools [14], but the human dimension is normally excluded when analyzing this type of hazards [15]. Thus, input data of temporal and zonal occupation should be provided, as a result of the interaction between the BE and its users, to perform granular simulation-based methodologies for risk-assessment [16]and risk-mitigation (mainly, BE modifications that relieve UHI [17]).

To simulate human behavior when exposed to certain environmental conditions, models have been created using such as urban stressors [9]. Yet, their application remains extremely complex, specially when determining an specific starting input scenario configuration and the computational time [18, 19]. Overlooking the issue of efficient hardware [20], the configuration of relevant scenarios remains an open problem. Remote sensing strategies and online tools surge as good alternatives to obtain environmental conditions, BE elements dimension, use and users' habits (according to the space function), that allows creation of time-dependent weather, crowding levels and behavioral patterns. Nevertheless, methodologies are needed to detect extreme and recurring risk conditions in the BE that can increase the applicability and ease of risk assessment strategies, focusing on critical and/or most probable distressing conditions to which BE users could be potentially exposed.

In this perspective, this work is aimed at developing and testing a methodological procedure to narrow down relevant scenarios of recurrent and intense heat stress risk of a delineated area to enable and ease further BE risk assessment through simulation-based approaches. The methodology is set for a urban BE portion (i.e. a part of a neighborhood) evaluating the frequency of heat stress hazard for BE users (considering both the environmental features and the BE physical vulnerability), and their exposure. Data on hazard and exposure are collected through remote analysis techniques, and they are organized over a daily trend. Then, the most severe and recurrent scenario conditions are identified according to a comparison-based approach.

## 3 Methodology

The proposed methodology defines single-hazard SLOD plus exposure conditions needed as input scenarios for human behavior modelling in a representative BE. The methodology is organized in 2 main steps. First, hazard (Sect. 3.2) and exposure data (Sect. 3.3) are collected according to a time-dependent approach. Then, data are compared to retrieve extreme (i.e. most severe) and recurring (i.e. frequency) combined conditions (Sect. 3.4), by additionally assigning main users' behavioral patterns according to the specific site characteristics.

### *3.1 The Case Study Built Environment*

The case study is located in northern Italy. A region that has been labelled on the EM-DAT [4] as a "extreme temperature affected country" and the European Environment Agency (EEA)[2] has reported a 0.3–0.35 °C average annual temperature increase trend for the same area. From which, Milan (Italy) is a representative location to study heat-stress risk within densely populated cities [21]. Moreover, the district of Città Studi was identified as a region with likely high exposure (high population density) and

[2] https://www.eea.europa.eu/data-and-maps/figures/trends-in-annual-temperature-across-1 (last access: 04/11/2020).

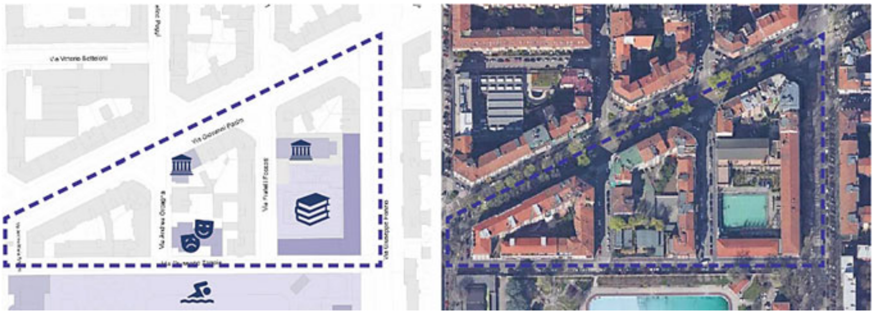

**Fig. 1** Case study area from municipality's GIS tools (https://geoportale.comune.milano.it/sit/, last access: 04/11/2020; left side) and Google Maps view (right side)

physically vulnerable based on their Land Use Land Cover. It has a low greenery area coverage (15.4%), fairly high built surface area (29.4%) and volume coverage.

This city portion hosts an average concentration of susceptible population (adults > 65 and toddlers < 5 years-old represent 22.3%). Which can be attributed to the hosted home cares (2) and educational institutes (20). Finally, this area has reliable open weather data sources for studying its fluctuations (Milano—via Juvara). However, only a narrower representative portion of the identified district (20,108 m$^2$) was studied (see Fig. 1), because: (1) this portion hosts a significant number of residents; (2) it has different urban BE units (e.g. piazza, piazzale and urban canyon) with busy roads [3]; (4) it holds potential crowding points (e.g. schools, nearby university, theatre, religious building), a nearby water body and embed greenery.

## 3.2 *Collecting and Processing Hazard Data*

Hazard detection necessitates a well-equipped sensor network and a reference standard for comparing the estimates of heat stress. Data was processed as follows:

1. Identify available weather stations' location and datatypes collected for selecting the most appropriate data sources to estimate hourly outdoor heat stress.
2. Collect sufficient data (e.g. 5 year records) to be processed. For each hour, compute heat stress and establish if moderate heat stress level hazard is existent (TRUE = 1) or not (FALSE = 0), based on a reference standard.
3. Organize hourly Boolean data and average them by time (e.g. 08:00).
4. Plot average values to delineate the daily profile of the mean frequency heat stress hazard arousal for each hour of the day.

### 3.3 Collecting and Processing Exposure Data

Given the heat stress nature, most exposed users are those who repeatedly attend the BE, such as residents, frequent visitors, and/or workers. Buildings intended use was retrieved through available GIS tools (i.e. online open ArcGIS API) and combining Google Maps and Google Street View (goo.gl/maps/LtPrx2ABaFwmK2GX9, last access: 22/04/2021). The building covered area and number of floors was extracted with GIS tools, and/or determined with "Map Area Calculator" tools (calcmaps.com, last access: 26/04/2021) and Google Street View visualization where data was missing. Adopting a conservative approach, the gross building total area was calculated by multiplying covered area and number of floors, and grouped by building type.

Then, the building users' by type was calculated by multiplying its gross area by an established occupancy load density (persons/m$^2$). For every case, the load factors were allocated from values suggested for an ordinary European context [22, 23] as follows: (1) for residential building, 28.3 m$^2$/person; (2) for commercial buildings, 17 m$^2$/person; (3) for restaurants and bars, 6.1 m$^2$/person; (4) for educational, religious and homecare buildings, 5.4 m$^2$/person; (5) for the theatre, 2 m$^2$/person. Point 1 was associated to *residents* in terms of users' category, while points 2–5 were related to the *visitors*' category. Furthermore, *pedestrians* were assumed to occupy sidewalks and open spaces at a 10 m$^2$/person.

To introduce social vulnerability, residents were divided in four BE user types given their age: toddlers (0–4 years); young people, i.e. students (5–24 years); adults (25–65 years); elderly (over 65 years). The residents percentage for each users' type is derived from census databases (https://www.comune.milano.it/aree-tematiche/dati-statistici, last access: 26/04/2021). School and homecare occupants were divided into students or elders and workers (0.8–0.2 and 0.4–0.6 respectively). Visitors were only considered as adults. The following assumptions were provided for the occupation dynamics over daytime, by identifying the different main users' types and their statistically constructed occupancy profiles [22]: (1) toddlers and elderly were always considered present over time; (2) young people were considered at home from 0:00 to 7:00 and from 14:00 to 24:00, following school activities; (3) adults were considered at home from 0:00 to 7:00 and from 19:00 to 24:00, according to standard working time in Italy. The visitors' presence (only adults) was set depending on the specific opening time of the building, retrieved from Google Maps statistics. Finally, pedestrians were considered constant from 7:00 to 1:00, from superimposing commercials buildings opening time.

### 3.4 Retrieving Extreme and Recurring Conditions

Hazard and users' exposure data are organized over time, considering a standard working day because of its frequency over the year. Relevant scenarios are then evaluated by pointing out the daytime in which hazard and exposure high values coincide. Then, recurring environmental conditions are estimated by calculating the modal values, to outline the most severe risk and probable-hazard scenario to test BE and user's interaction under increasing temperatures SLOD risk.

# 4 Results

## 4.1 Frequent Intense Heat Stress Hazard Encountered

Weather data was extracted from 2015 to 2019 from the regional environmental monitoring agency ARPA Lombardy.[3] In specific, from a station <1 km distant from the center of the case study.

However, Mean Radiant Temperature could not be computed with available data. Thus, heat stress was allocated using RiskT [24] (employing only air temperature, solar radiation, wind speed and relative humidity), assuming that BE users will not be exposed to direct solar radiation neither high air velocity. RiskT weighting factors were set as:

- $t_{db\text{-}air} = 0.4$ for temperatures above 26 °C, or $t_{\text{db-air}} = -0.4$ if below 18 °C;
- $I_{tot} = 0.3$ for irradiation over 300 W/m$^2$;
- $RH = 0.15$ for values below 30% or above 70%; and
- $V_a = 0.15$ for values below 2 m/s.

RiskT was screened for 44,124 h to determine the existence of heat stress if RiskT > 0.5. During this period, $t_{db\text{-}air}$ peaks were registered above 38 °C, while $I_{tot}$ reached 952 W/m$^2$ as a maximum registered value. Also, more than 5000 h were reported having a hazardous heat stress condition (i.e. 5364), which represents approximately 12% of the collected data.

Then, the discrete 0 (FALSE) and 1 (TRUE) values of presence of hazardous heat stress were grouped and averaged by each of the 24 h/day to establish the mean frequency in which they arise. These showed hazard frequency arousal peaks between 10:00 and 18:00, with the maximum between 15:00 and 16:00 h (see Fig. 3).

## 4.2 People Exposure Trends

Table 1 resumes the results concerning the users' exposure by quantifying the maximum number of exposed people for each building intended use and the related building features. Excluding the time-related trends in the use of the BE, residential buildings represent ~25% of the potentially exposed population. Considering

[3] https://www.arpalombardia.it/ (last access: 04/11/2020).

**Table 1** BE users' maximum occupancy for each building type, including their gross area

| Building intended use | Gross area [m$^2$] | Maximum users' number [persons] |
|---|---|---|
| Homecare center | 1860 | 345 |
| School | 8120 | 1504 |
| Theatre | 1124 | 562 |
| Church | 603 | 112 |
| Residential | 29,513 | 1043 |
| Commerce (stores + bars) | 1871 + 680 | 111 + 112 |
| Pedestrian area | 3828 | 383 |

residents only, 22.3% (233) of them would fall within the toddlers and elders category, while 60.3% (182) would be adults, this being considered workers, and 17.4% (628) would be young people, considered students. Schools involve the ~36% of the exposed users, but their occupation is focused on morning hours. Finally, commercial activities, the church and the homecare center are less relevant in terms of crowding, but they are critical attractors for the BE users' movement in outdoor areas [16].

Starting from the occupancy per building type, Fig. 2 summarizes the BE occupation number over time depending on the users' categories, for a typical working day, because of its statistical frequency over the year. Results show how the impact of *visitors*' number (i.e. students) leads to the peak values in users' exposure during the morning time.

Before coupling hazard and exposure, the complexity of the problem was reduced by grouping BE users only on main demographic groups. Figure 3 presents a direct comparison between the frequency probability of hazards and a nominal occupancy profile differentiated by working-age (workers), studying-age (students), and elders and toddlers (Elders and toddlers). The hazard-related frequency in Fig. 3 is expressed in terms of RiskT, while the exposure-related values have been normalized by the

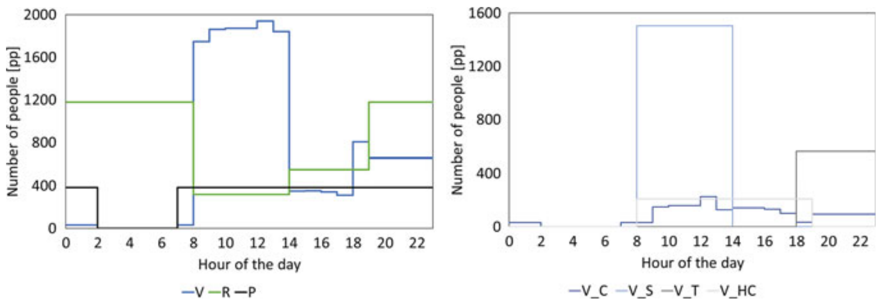


**Fig. 2** Daily occupation trend by aggregated BE user categories, on the left, considering visitors (V), residents (R) and pedestrians (P); and, diversified visitors [commercial buildings (V_C), schools (V_S), theaters (V_T) and Homecare (V_HC)] on the right

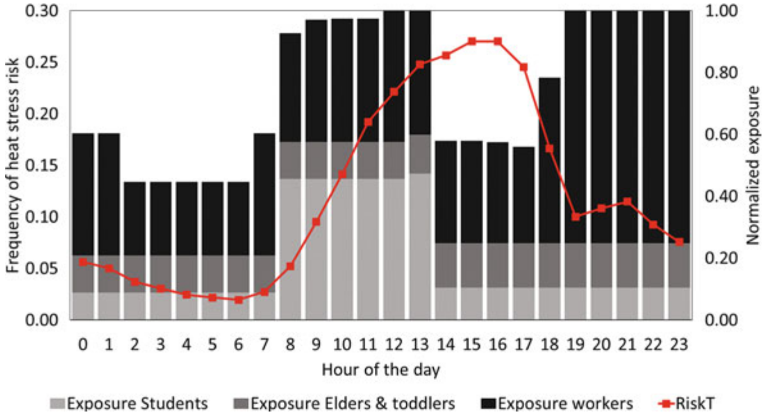


**Fig. 3** Daily hazard and exposure trend of the case study BE, by demographic group type

maximum number of people present. As reported in Fig. 2, Fig. 3 highlights a high exposure during the morning time because of the concentration of students' present.

## 4.3 Significant Scenarios for Simulating Users' Behavior

Scenarios were selected aiming for both frequent and severe conditions, using RiskT arousal probability and level of exposure. Thus, assessing Fig. 3, the following were recognized as useful input for future work on granular analysis of SLOD risk ($\overline{\text{RiskT}}$ > 0.20): in the late morning (12:00 and 13:00), when studying and working-age visitors are more exposed; and, in the mid afternoon (15:00 and 16:00) when the presence of working-age visitors prevail. Hence, for those hours, the mode of the rounded integer values of the environmental parameters were found for the 5-year period (Table 2).

These scenarios have similar conditions, air temperatures approximately at 28 or 30 °C, relative humidity between 35 and 40%, wind velocity at 10 m from the ground around 2 m/s, and un-obstructed solar irradiation between 574 and 760 W/m$^2$

**Table 2** Scenario configuration for simulation approaches under high heat stress conditions

| Hour | $\overline{\text{RiskT}}$ | E_W [pp] | E_S [pp] | E_E&T [pp] | $t_{db\text{-}air}$ [°C] | RH [%] | $V_a$ [m/s] | $I_{tot}$ [W/m$^2$] |
|---|---|---|---|---|---|---|---|---|
| 12 | 0.22 | 1119 | 1203 | 318 | 28 | 38 | 2 | 745 |
| 13 | 0.25 | 1021 | 1203 | 318 | 28 | 40 | 2 | 760 |
| 15 | 0.27 | 735 | 233 | 318 | 30 | 36 | 2 | 628 |
| 16 | 0.27 | 724 | 233 | 318 | 30 | 34 | 2 | 574 |

Exposure divided in working age (E_W), studying-age (E_S) and elders and toddlers (E_E&T)

(approximately, twice the 300 $W/m^2$ threshold limit for heat risk). Although the environmental conditions are similar, the time of the day plays an important role, as the position of the sun would redefine the direct solar radiation distribution and intensity.

Therefore, an extreme and recurrent risk scenario would be the one at 13:00, because of the combine peak between exposure and hazard frequency of arousal (i.e. see RiskT). Meanwhile, the conditions retrieved between 15:00 and 16:00 can be considered as the most recurring risk scenario because of the significant number of exposed people and the peak of RiskT > 0.5 frequency of arousal (see Fig. 3).

## 5 Discussion

To consider users' behavior outdoor on permanence, displacement speed and paths traversed (which determine the real affections, and are driven by heat stress) requires input scenarios to ease its realization. Therefore, a methodology that systematically obtains such settings, as those presented for hours 12:00, 13:00, 15:00 and 16:00, could be of great interest. Also, the presented methodology has great value as it does not require complex computation techniques, neither lengthy machine time, it uses freely available data sources, and can be easily managed by non-expert practitioners.

Having the scenario baseline, it is possible to obtain granular distribution of heat stress within the BE; to later introduce user behavior models to adapt their walking speed to minimize stimulation, or to find refuge [9, 16]. Such models, could adopt as well, agent based modeling approaches that combine the different group of users' preferences (e.g. elders), with the daily users' routines while moving in the BE spaces [25]. By doing so, outdoor behavioral patterns are expected to show attraction to trees, and/or shaded areas. This aspect is crucial above all in the use of squares and forecourts, while it can affect the volumes of pedestrian traffic in urban canyons.

However, the present work did not consider how the opening and closing time of some activities affect traffic levels, thus released anthropogenic heat (i.e. motor vehicles). Utilized weather datasets were limited, motivating gross assumptions generating higher variance of the allocated risk (i.e. employing RiskT instead of UTCI). Moreover, full or no occupancy rates were inserted in the occupancy profile, thus possibly overestimating exposure, and generating a possible shift in the timeframes selected.

## 6 Conclusion

A relevant case study in Milan, Italy has been studied with a rapid methodology for identifying significant scenarios for future studies on risk conditions of increasing temperature SLOD. The methodology focuses on the interaction between exposure and hazard factors, identifying extreme and recurring risk scenarios in the BE.

Identifying relevant scenarios related to main drivers of users' behaviors in the built environment (in this case, heat), can facilitate further BE analyses aimed at adopting simulation-based risk assessment techniques (e.g. seismic evacuation). Another area, area size or type of SLOD can be rapidly assessed by researchers with the same methodology, such as the concentration and distribution of air pollution.

These methodology is foreseen to help provide information to planners and citizens for making the BE more secure and resilient throughout testing of targeted mitigation strategies on BE users' exposure and/or environmental hazard.

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## References

1. Dyurgerov, M.B., Meier, M.F.: Twentieth century climate change: evidence from small glaciers. Proc. Natl. Acad. Sci. **97**, 1406–1411 (2000)
2. Oke, T.R., Johnson, G.T., Steyn, D.G., Watson, I.D.: Simulation of surface urban heat islands under 'ideal' conditions at night part 2: diagnosis of causation. Boundary-layer Meteorol. **56**, 339–358 (1991)
3. Salvalai, G., Moretti, N., Blanco Cadena, J.D., Quagliarini, E.: SLow Onset Disaster events factors in Italian built environment archetypes. In: Littlewood, J. (ed.) Sustainability in Energy and Buildings 2020, pp. 333–343. Springer Nature Singapore Pte Ltd., Singapore (2021)
4. CEM-DAT: EM-DAT: The OFDA/CRED International Disaster Database (2020)
5. Meehl, G.A., Tebaldi, C.: More intense, more frequent, and longer lasting heat waves in the 21st century. Science **305**, 994–997 (2004)
6. Schwartz, J., Samet, J.M., Patz, J.A.: Hospital admissions for heart disease: the effects of temperature and humidity. Epidemiology **15**, 755–761 (2004)
7. Hoffman, J.L.: Heat-related illness in children. Clin. Pediatr. Emerg. Med. **2**, 203–210 (2001)
8. Kenney, W.L., Munce, T.A.: Invited review: aging and human temperature regulation. J. Appl. Physiol. **95**, 2598–2603 (2003)
9. Melnikov, V.R., Krzhizhanovskaya, V.V., Lees, M.H., Sloot, P.M.A.: The impact of pace of life on pedestrian heat stress: a computational modelling approach. Environ. Res. **186**, 109397 (2020)
10. Villagràn De León, J.C.: Vulnerability: a conceptual and methodological review (2006)
11. Choi, Y., Yoon, H., Kim, D.: Where do people spend their leisure time on dusty days? Application of spatiotemporal behavioral responses to particulate matter pollution. Ann. Reg. Sci. **63**, 317–339 (2019)
12. Huang, B., Hong, B., Tian, Y., Yuan, T., Su, M.: Outdoor thermal benchmarks and thermal safety for children: a study in China's cold region. Sci. Total Environ. **787**, 147603 (2021)
13. Cheung, P.K., Jim, C.Y.: Improved assessment of outdoor thermal comfort: 1-hour acceptable temperature range. Build. Environ. **151**, 303–317 (2019)
14. Mackey, C., Galanos, T., Norford, L., Roudsari, M.S., Bhd, N.S.: Wind, sun, surface temperature, and heat island: critical variables for high-resolution outdoor thermal comfort payette architects. In: Proceedings of 15th IBPSA Conference. United States of America Massachusetts Institute of Technology, United States of America University of Pennsylvania, pp. 985–993 (2017)

15. Sangiorgio, V., Fiorito, F., Santamouris, M.: Development of a holistic urban heat island evaluation methodology. Sci. Rep. 1–13 (2020)
16. Yıldız, B., Çağdaş, G.: Fuzzy logic in agent-based modeling of user movement in urban space: definition and application to a case study of a square. Build. Environ. **169** (2020). http://doi.org/10.1016/j.buildenv.2019.106597
17. Santamouris, M., Synnefa, A., Karlessi, T.: Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. Sol. Energy **85**, 3085–3102 (2011)
18. Huttner, S.: Further development and application of the 3D microclimate simulation ENVI-met (2012)
19. Elwy, I., Ibrahim, Y., Fahmy, M., Mahdy, M.: Outdoor microclimatic validation for hybrid simulation workflow in hot arid climates against ENVI-met and field measurements. Energy Procedia **153**, 29–34 (2018)
20. Fernández-González, Á., Rosillo, R., Miguel-Dávila, J.Á., Matellán, V.: Historical review and future challenges in supercomputing and networks of scientific communication. J. Supercomput. **71**, 4476–4503 (2015)
21. Salvalai, G., Enrico, Q., Blanco Cadena, J.D.: Built environment and human behavior boosting slow-onset disaster risk. In: Amoeda, R., Lira, S., Pinheiro, C. (eds.) Heritage 2020, pp. 199–209. Coimbra, Portugal (2020)
22. ISO: ISO 17772-1: Energy performance of buildings—indoor environmental quality—parameters for the design (2017)
23. Bloomberg, M., Burden, A.: New York City Pedestrian Level of Service Study—Phase 1. New York, NY, USA (2006)
24. Blanco Cadena, J.D., Moretti, N., Salvalai, G., Quagliarini, E., Re Cecconi, F., Poli, T.: A new approach to assess the built environment risk under the conjunct effect of critical slow onset disasters: a case study in Milan, Italy. Appl. Sci. **11**, 1186 (2021)
25. Yang, L., Hoffmann, P., Scheffran, J., Rühe, S., Fischereit, J., Gasser, I.: An agent-based modeling framework for simulating human exposure to environmental stresses in urban areas. Urban Sci. **2**, 36 (2018)

# A Numerical Investigation of Repeating Thermal Bridges from Metal Fasteners in Offsite Manufactured Timber Frame Closed Panels for Exterior Walls

**F. Zaccaro and J. R. Littlewood**

**Abstract** Calculating repeating Thermal Bridges (TBs) in Timber Frame (TF) closed panels for exterior walls represents an opportunity to close the Performance Gap (PG) occuring in the Off-Site Manufacture (OSM) of Modern Method of Constructions (MMC). Despite the high precision reached by the OSM, neglecting repeating TBs from metal fasteners could add further uncertainty to the thermal transmittance of the construction, leading inexorably to real and predicted U-value differences. The paper discusses the TB calculation process for three dimensional (3D) Finite Element Analysis (FEA) models to assess the impact of fixings χ-values on the U-value of exterior wall TF MMC system. Five widely used fastener types have been analysed in 96-panel typologies differing for insulation materials, core and/or flanking insulation thickness, and reflective membranes. Results show that χ-values are reduced when the U-value decreases but, after accounting for the relative fastening density, the final U-value correction (resultant of all the fasteners) has a higher percentage detrimental impact on low U-value MMC systems such as those designed to meet near-to-zero and zero operational energy, ranging from 7 to 22%. Greater attention to repeating TBs should be paid with high performing constructions because high detrimental factors could be introduced by the metal connections.

## 1 Introduction

To reduce building operational energy consumption and achieve carbon reduction targets, the United Kingdom (UK) Government imposes, through the building regulations, increasingly stricter U-values to be achieved with highly insulated construction fabric [1]. The efficacy of OSM wall, roof and floor constructions are threatened by defects that can be caused by deficiencies in design and workmanship [2], which can contribute significantly to the PG between as-designed and actual performance [3].

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Appropriate thermal insulation is essential to reduce energy consumption in buildings, besides great attention must be paid to TB which can substantially increase heat losses, risk of mould growth and discomfort [4]. Heat losses from TBs are caused by the increment of heat flow when compared to the surrounding uninfluenced areas, essentially due to change of materials, geometry or penetration of different conductivity materials [5]. TB can detrimentally impact the U-value of high-performing MMC systems, such as TF closed panels, because of their framed structure composed of insulation pockets alternated by timber structural studs. The structural timber availability, or TF Fraction (TFF), has already been analysed in a previous study of the authors [1] which underlines the importance of accurate calculations based on the real wood quantities of framing elements over the common use of standards. An excessive timber to insulation ratio can be classed as a defect, which can result in repeating linear TB [ibid], while point TBs from fasteners are often neglected. Metal fasteners are the preferred system used by the OSM sector in the UK, for their quick installation and their bonding strength. These connecting systems include nails and screws that are inserted into TF MMC to secure consecutive layers to give bonding stability. The use of fasteners is rarely seen as a potential issue for the performance of the construction, thus not often considered by the designers and manufacturers because the connectors used do not pierce, nor connect the cold side (exposed to the external environment) with the warm side (at room temperature) of the construction. However, metal is a higher conductor of heat when compared with the other homogeneous materials used in the TF construction detail and thus, creates an increase in heat loss and so a TB can occur in the connected materials.

The research discussed in this paper has been undertaken in collaboration with one of Wales', UK, Offsite Manufacturers (company hereafter) of TF MMC systems including exterior and interior walls, roof trusses and floor cassettes. Note, the company wish to remain anonymous, hence there is no citation to their technical details. Findings from an ethnographic study on the company's production line of TF exterior walls systems included random and overuse of fasteners, which could have a detrimental impact on the effectiveness of the thermal insulation. Despite the spacing rules specified by the designers, some of the production line operatives did not always appear precise when installing the fasteners, which subsequently led to increased use than as-designed.

## 2 Repetitive Thermal Bridging and Impacts upon U Values

The push to increase the OSM of MMC in the UK is a direct result of the UK Government commissioned Farmer Report entitled 'Modernise or Die' [6], and also ambitious target to construct 300,000 new homes annually by the mid-2020s [7]. TF MMC appear to satisfy the level of insulation, required by ever-stricter building regulations, whilst speeding up the delivery of homes that can be weather tight in just a few days [8]. Prefabricated buildings also ensure a significant increase in accuracy of building components and reduction of carbon emission, besides reducing cost and minimizing waste [9]. The adoption of TF MMC requires a clear process that should be established throughout the design, manufacturing, and erection phases, avoiding where possible design changes and alteration which could affect the costs and building performance [10]. Consequently, an increased level of precision in design from the concept stage could help to prevent unexpected impacts on final building performance and costs.

TF closed panels are a source of both linear and point repeating TBs. Linear TBs are accounted for by the TFF, defined as the percentage of the surface area of the wall occupied by the wooden framing members repeatedly short-circuiting the insulation and so, causing an extra heat flow due to the difference of thermal conductivity between materials [1]. Point TBs are constituted by metallic high-conductive fasteners (principally nails, screws and staples) connecting the different layers composing the TF panel.

The effect of repeating point TBs could be relevant for the calculation of construction detail thermal transmission and building heat losses in MMC. This is evident for diagonal tie connectors in a precast concrete sandwich, which could lead to an increase of the heating demand by 10.3% [11]. A similar investigation from Yu et al. [9] emphasized the importance of the thermal performance of connectors used in precast concrete sandwich walls, where the substitution of the metallic ties with nylon-wrapped connectors or glass fibre reinforced polymer help to reduce the conductivity of the wall. Point TBs are also a relevant issue for the installation of cladding facades where the aluminium fasteners could affect the U-value by reducing the efficacy of high insulated solutions [12, 13]. Berardi and Ákos [14] discussed the impact of point TBs from fasteners piercing an aerogel-enhanced blanket on a brick wall, concluding that the reduction of thermal resistance can span between 15% (three anchors/$m^2$) and 45% (six anchors/$m^2$). As a consequence, point TBs can affect both traditional and MMC and their impact might be high for nearly-zero energy building constructions. TF MMC is not excluded by point TBs issues and the evidence is presented in a study of Christensen [15] on the impact of metal fastening (drywall screws and nails) on high-performing TF walls. The research used FEA to quantify the additional heat losses introduced by the metal fasteners and demonstrated how the insulation performance can be reduced by approximately three per cent or more if the TFF increases.

The evaluation of point TBs during the design stage is often neglected because of the lack of trained personnel and the difficulty of the assessment [16] so that many qualified operational energy modellers, with many years of experience, are still not able to improve the accuracy of energy predictions causing an intrinsic PG [17]. Therefore, to improve the design predictions and broader understanding of the point TB problem, it is necessary to model in greater detail closed panel TF exterior walls, including all the fastenings. In this respect, the metal fixings that cross, or partially cross the different layers (to secure the layers) constituting the TF MMC system will be evaluated, recognizing the magnitude of the U-value reduction that can be accounted for in building operational carbon/energy simulation models.

## 3 Methodology for Measuring Impacts of Metal Fixings

The Case Study (CS) for the research documented in this paper is a TF closed panel exterior wall system, manufactured by the company in Wales, UK. The CS is manufactured with different TF stud widths [140/197/220 mm (mm)] spaced at 600 mm intervals and consists of core insulation, generally synthetic and non-breathable pumped into the panels in the factory between two Oriented Strand Boards (OSBs); flanking insulation, with variable thickness depending on the as-designed U value; two types of breather membranes (with high or low emissivity) and suitable lining. By selecting the design variables and their respective values, as shown in Table 1/Fig. 1, most panels sizes of the CS that the company supplies are assessed.

The variables investigated are of three typologies: Geometrical, referring to layer thicknesses; Material thermal conductivities and surface resistances, to account for the external reflective membrane. Reflective membranes have been accounted accordingly the Annex C and D of the ISO 6496, but treated differently according to their positioning: the service air void (unventilated cavity) with reflective membrane increases the thermal resistance (otherwise called equivalent thermal conductivity); the flanking insulation (ventilated) incorporating an outer reflective layer facing the external air gap, modifies the surface resistance of the external boundary condition. All the chosen variables have to assume a unique value to define a CS combination.

Ordinarily, the one-dimensional heat loss through a homogeneous building component (or U-value) is calculated according to the ISO 6946 [18] based on thermal conductivity values of the materials constituting the layered construction. The U-value, with the opportune adjustments, can be inclusive of repeating TB, both linear and point. Repetitive linear TBs introduced by the TF studs are evaluated with the simplified or detailed method described in the ISO 6946 [ibid]. The simplified method bases the calculation of the U-value on the average of upper resistance (considering all resistances of the possible thermal heat flow path through the building element multiplied by their fractional area) and lower resistance (evaluated combining the conductivity of each material composing the bridged layer, and then summing the resistances of the other non-bridged layers). The detailed method calculates the U-value of the construction element from a numerical FEA simulation, following the recommendations for non-repetitive TB set out by ISO 10211 [5]. The result of one of the two methods is a U-value which includes the TFF, otherwise called undisturbed or base U-value ($U_0$). In this paper, the calculation of the $U_0$ follows the simplified method for the linear TBs introduced by TFF, which has been assumed to be 6.3%. The TFF is evaluated considering a rectangular stud 38 mm wide, spaced regularly at 600 mm. The $U_0$ calculation methodology has been created in Microsoft Excel and accounts for the two bridged layers (core insulation and service void) of CS, a feature not always available in the tools used in the TF industry causing a minor discrepancy. Furthermore, some U-value calculators give outputs to the third decimal place, most of the times not enough to analyse small variations due to a single non-piercing fastener [19].

**Table 1** CS combinations analysed

| Name | Variable | Values | | | |
|---|---|---|---|---|---|
| 1–7 | Wood (Thermal conductivity—W/m K) | 0.13 Softwood | | | |
| 2 | OSB (Thermal conductivity—W/m K) | 0.13 Oriented strained board | | | |
| 3 | Core insulation (Thermal conductivity—W/m K) | 0.032 PUR Insulation | | 0.038 Paper recycled | |
| 4 | Air void (Equivalent thermal conductivity—W/m K) | 0.035 Reflective membrane | | 0.1389 Non-reflective membrane | |
| 5 | Plasterboard (Thermal conductivity—W/m K) | 0.21 Gypsum | | | |
| 6 | Flanking insulation (Thermal conductivity—W/m K) | 0.022 Polyurethane | | 0.042 Woodfibre | |
| 8 | Fasteners (Thermal conductivity—W/m K) | 55 Galvanized steel | | | |
| C | Core insulation (Thickness—mm) | 140 Standard frame | | 220 Thick frame | |
| G | Flanking insulation (Thickness—mm) | 50 Standard | 100 Improved | | 150 Thick |
| I | Internal boundary (T = 20 °C) (Surface resistance—$m^2$ K/W) | 0.13 Standard ISO 6946 | | | |
| E | External boundary (T = 0 °C) (Surface resistance—$m^2$ K/W) | 2.6387 Reflective membrane | | 25 Non-reflective membrane | |

Repetitive point TBs occur systematically when an insulation material is penetrated, fully or partially, by a highly conductive material. To measure the impact of metal fasteners on CS, this research uses a 3D Finite Elemental Analysis (FEA), deemed to be the best method to model complex geometries such as metal connections. The geometric input of the FEA consisted of a succession of layers composing the CS, with the insulation and air void bridging timber elements where all the metal connections summarized in Table 2/Fig. 2 are inserted:

Fasteners have been defined in the FEA as cylindrical extrusions of the head and body diameters along the respective lengths, as shown in Table 2. Each fastener was modelled with the head fully embedded and flush with the material surface,

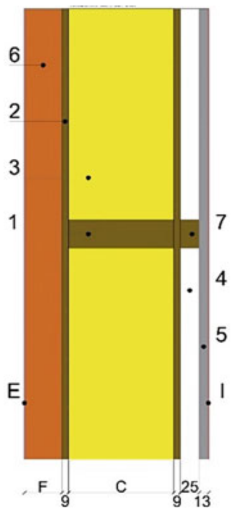


**Fig. 1** CS combinations analysed

**Table 2** Repeating TBs from fastening in the CS TF closed panel

| POS | Connection | Spacing (mm) | No./m$^2$ | Dimension (mm) | |
|---|---|---|---|---|---|
| | | | | Diameter | Length |
| 1–2 | Nail | 50–300 | 5–33 | Body ∅ 2.8 | 49 |
| | | | | Head ∅ 7 | 1 |
| 3 | Nail | Standard 300 | 5–6 | Body ∅ 2.8 | 69 |
| | | | | Head ∅ 7 | 1 |
| 4 | Screw | Standard 150 | 11–12 | Body ∅ 2.25 | 37 |
| | | | | Head ∅ 8.5 | 1 |
| / | Staple | According to manufacturer specs | N/A | N/A | N/A |
| 5 | Twisted nail | Standard 225 | 7–8 | Body ∅ 4.6 | Variable |
| | | | | Headless | N/A |

centred on the supporting structural timber stud. The twisted nail, which secures the exterior insulation, has generally a plastic retainer, which has been omitted to simplify the FEA calculation. The length of this last fastening varies with the thickness of the external insulation and is calculated accounting for 35 mm minimum grip into the timber stud, 9 mm (necessary to pierce the OSB) and the thickness of the flanking insulation itself. The thermal conductivities of materials have been considered isotropic and without any dependence on temperature and moisture content.

Each CS combination has been reiterated five times to evaluate the heat losses due to each fastening separately, producing as result five FEA models: POS 1-2, OSB board nails (interior and exterior); POS 3, noggin nails; POS 4, plasterboard

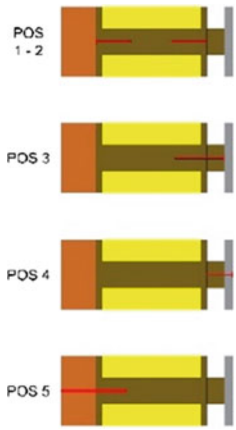


**Fig. 2** Repeating TBs from fastening in the CS TF closed panel

screws, and POS 5, external insulation retainers The additional heat flow caused by the point TB, named point thermal transmittance (or $\chi$-value), is then evaluated in steady-state as established by ISO 10211. The $\chi$-value is evaluated by comparing the heat flow through the specific CS combination with and without fastenings by using the following equation:

$$\chi = L^{3D} - U_0 * A \tag{1}$$

where $L^{3D}$ is the coupling coefficient obtained from the heat flux result of the FEA calculation, divided by the difference in temperature applied at the internal and external surface of the construction detail. A is the area where the $U_0$ applies. The correction ($\Delta U_f$) given by the presence of the point TB is hence calculated as:

$$\Delta U_f = n_f * \chi \tag{2}$$

where $n_f$ is the number of the fixings inserted in the TF panel on a $m^2$. The effective U-value, inclusive of all point TBs, is then calculated as:

$$U_{eff} = U_0 + \sum_{i=1}^{n} \Delta U_{f,i} \tag{3}$$

$U_{eff}$ represents the final U-value, inclusive of all the point TBs corrections calculated singularly. $U_{eff}$ is the value to be checked against the building regulation benchmarks and to be used in the building energy simulation tools to calculate energy consumption and carbon emissions. By omitting the point TBs contribute, $U_{eff}$ is not accurately calculated, making the heat losses smaller than the actual and as such, generating a PG.

The FEA software used is capable of changing autonomously and parametrically the thermal conductivity of the materials, surface resistance and geometric thickness of the insulation layers (core and flanking insulation) before running the calculation algorithms. The process ensures that all simulations are run with the same solving mesh settings, guaranteeing consistency of results. The FEA software subdivides the geometric model, consisting of a CS combination and one fastener, into a number of adjacent cells with homogenous thermal conductivity, all meeting the conservation of energy equations with the imposed boundary conditions. Some initial simulations have been run to correctly set the tetrahedral solving mesh and to understand the sensitivity of the model to finer meshes as underlined by ISO 10211: the accuracy of the results was determined as the difference between the heat flow evaluated when the mesh is composed by n nodes and 2n nodes. The difference must be lower than 1%, otherwise, further subdivisions shall be made until meeting the criterion.

The total number of CS combinations derived from the variables analysed has produced a total of 96 different construction typologies, iterated for each of the five fastening objects of the study. The resulting five χ-values, obtained applying Eq. (1), are then multiplied by their respective number per $m^2$ of TF closed panel (derived from the spacing rules suggested by the company) shown in Table 2. Finally, the calculation returns the total increase in U-value given by the total point TBs in a CS combination, defining the increment $\Delta U_f$ to be applied to $U_0$.

## 4 Results and Discussion

The use of metal fasteners is a frequent practice in the UK for the installation of TF structural layers (OSB boards, frame elements, noggings), internal lining and external insulation. Point TBs are caused by either piercing or non-piercing fasteners systems, increasing the thermal transmittance of the insulation layer [20], especially when applied copiously in common practice when production line operatives do not measure the distances prescribed by the designers or around complex geometries, such as windows or doors. The 96 CS combinations derived by the exploration of values introduced by Table 1. have been iterated for each of the five point TBs introduced in Table 2. A total of 480 different FEA models have been simulated to evaluate the fastenings χ-value in each CS combination. For example, the χ-values for the 96 CS combinations produced for the nail in POS.3 (see Table 2) are plotted in Fig. 3 as a function of the base U-value of the unbridged wall, $U_0$.

Figure 3 evidences that the point TBs magnitude is reduced when the U-value decreases. The same behaviour is noted for all five fastening types. The total reduction of the final U-value for a single fastening type, $\Delta U_f$, depends on the fastener density ($n_f$) as underlined in Eq. (2). To further understand the impact of the specific fastening type, Fig. 4 summarize the plot of the χ-values calculated on the 96 CS combinations, multiplied by the number of fasters per $m^2$.

The box and whisker plot is used to represent the distribution of the $\Delta U_f$. The graph shows the minimum and maximum of the distribution at the end of the whiskers while, the lower and upper lines of the box are the first and the third quartiles. The line in the middle represents the median and the cross shows the mean χ-value for a

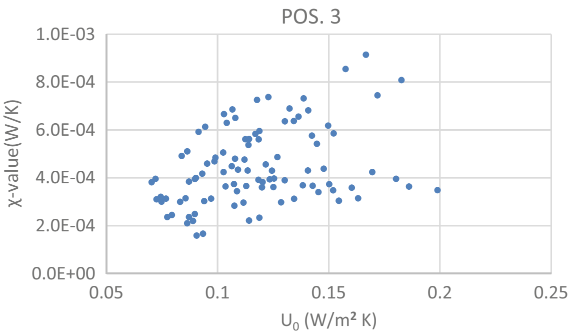


**Fig. 3** The plot of the 96 combinations χ-values depending on the base U-value for fastening

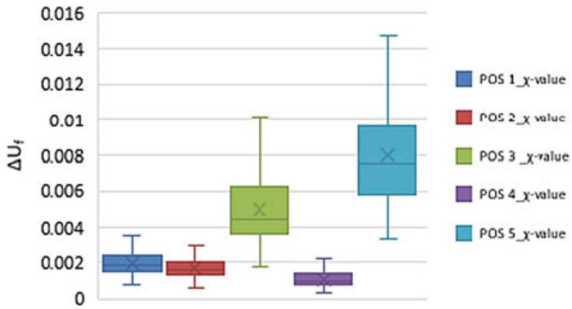


**Fig. 4** Box and whiskers plot of $\Delta U_f$ by fastening type

specified fastening. It is noted that the fastening in POS.1, POS.2 and POS.4 (refer to Table 2) have an average $\Delta U_f$ low, therefore their effect on the final U-value is limited. As opposite, POS. 3 and POS. 5 represent the main issue for the panel thermal transmittance. This establishes that longer nails/screws have a higher impact on the thermal conductivity and as such, they need to be carefully positioned and distanced when used by the manufacturing operatives, especially as the effect of the fastening density increases linearly the thermal conductivity of the construction, as already shown in previous research [20]. Notwithstanding the reduction of the magnitude of the single fastening χ-value when low U-values occur, it is important to underline that the total percentual reduction of U-value given by the sum of all fastenings used in a CS combination, increases inversely with $U_0$ as shown in Fig. 5.

The percentage detrimental reduction of the base U-value due to fastenings is included between 7 and 22%. Therefore, metal fastening use can significantly reduce the performance of the TF closed panels and as such, the PG is not resolved by OSM because the use of metal fixings lower significantly the U-values as calculated by the designers, without consideration for point TBs. For example, if the PassiveHouse design standard specification includes exterior walls with a U-value of 0.15 W/(m$^2$ K), the TF OSMs specifies a particular combination of core and flanking insulation thicknesses to match the limit, calculating the U-value as a succession of non-homogeneous layers with the simplified method of ISO 6946. The results of this research suggest that the real U-value ($U_{eff}$) is likely to be higher than the

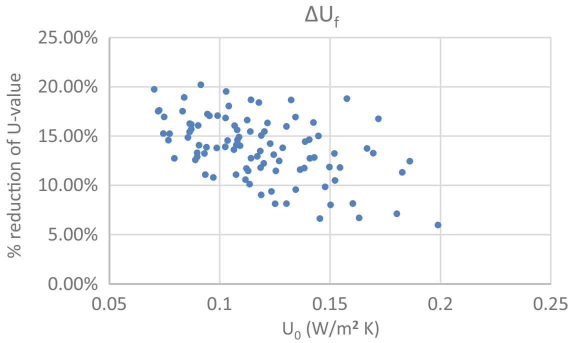


**Fig. 5** Total percentage reduction of U-value on the base U-value

one calculated by the designers because of the presence of point TBs. These findings could have implications for all new buildings that use OSM TF panels with steel fasteners, especially because the observation of increased fastener use has also been identified in another research project with the company [21] and, following the researches outcomes, the company has made changes to operator use of fasteners.

This research suggests that further investigation into repetitive point TBs for TF OSM of MMC is necessary because their impact could reduce the performance of all buildings adopting those systems, specifically the ones with high performing U-value constructions. For this reason, a sensitivity analysis of the design parameters influencing the χ-value will introduce to the industry a ranking of design variables, convertible into direct actions to put in place when reducing the effect of point TBs on OSM TF panels.

## 5 Conclusion

The analysis of repetitive linear and point TB becomes crucial in relation to the manufacture of TF, where a serious lack of understanding of the effect of extra wood and extra steel is observed. Actual U-values adopted by the manufacturers are not meticulously calculated and for this reason TF closed panel systems may not perform as designed. Many experts suggest that OSM could perform better than on-site construction systems, however, their expectations could be impacted by the findings of the authors. In this work a series of TF constructions used for exterior wall have been simulated with 3D FEA methods, suggesting that the metal fasteners could detrimentally impact the final U-value of high-performing construction particularly when there is no precision and respect for the designed fastener span.

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## References


1. Zaccaro, F., Littlewood, J.R., Hayles, C.: An analysis of repeating thermal bridges from timber frame fraction in closed panel timber frame walls: a case study (2021)
2. Aoul, K.A.T., Hagi, R., Abdelghani, R., Syam, M., Akhozheya, B.: Building envelope thermal defects in existing and under-construction housing in the UAE; infrared thermography diagnosis and qualitative impacts analysis. Sustainability (Switzerland) **13**, 1–23 (2021)
3. Gupta, R., Kotopouleas, A.: Magnitude and extent of building fabric thermal performance gap in UK low energy housing. Appl. Energy **222**, 673–686 (2018). http://doi.org/10.1016/j.apenergy.2018.03.096
4. Citterio, M., Cocco, M., Erhorn-Kluttig, H.: Thermal bridges in the EBPD context: overview on MS approaches in regulations (2008)
5. CEN. BS EN ISO 10211: 2017 BSI Standards Publication: Thermal bridges in building construction—heat flows and surface temperatures—detailed calculations (2017)
6. Farmer, M.: The Farmer review of the UK construction labour model [Internet] (2016). Available from: https://www.gov.uk/government/publications/constructionlabour-%0Amarket-in-the-uk-farmer-review
7. HM Treasury: Autumn budget 2017 building the homes the country needs. Department of Energy [Internet], 2 (2017). Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/661430/Building_the_homes_the_country_needs.pdf
8. STA: Timber Frame Construction Market UK (2019)
9. Yu, S., Liu, Y., Wang, D., Bahaj, A.B.S., Wu, Y., Liu, J.: Review of thermal and environmental performance of prefabricated buildings: implications to emission reductions in China. Renew. Sustain. Energy Rev. **137**, 110472 (2021). http://doi.org/10.1016/j.rser.2020.110472
10. Palmer, J., Godoy-Shimizu, D., Tillson, A., Mawditt, I.: Building performance evaluation programme: findings from domestic projects—making reality match design. Innovate UK [Internet], 38 (2016). Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/497758/Domestic_Building_Performance_full_report_2016.pdf
11. Kiil, M., Käärid, M.S., Klõšeiko, P., Võsa, K.V., Simson, R., Sarevet, H., et al.: PCSP's diagonal tie connectors thermal bridges impact on energy performance and operational cost: case study of a high-rise residential building in Estonia. In: E3S Web of Conferences, vol. 172, pp. 1–8 (2020)
12. Šadauskiene, J., Ramanauskas, J., Šeduikyte, L., Daukšys, M., Vasylius, A.: A simplified methodology for evaluating the impact of point thermal bridges on the high-energy performance of a passive house. Sustainability (Switzerland) **7**, 16687–16702 (2015)
13. Theodosiou, T.G., Tsikaloudaki, A.G., Kontoleon, K.J., Bikas, D.K.: Thermal bridging analysis on cladding systems for building facades. Energy Build. **109**, 377–384. http://doi.org/10.1016/j.enbuild.2015.10.037
14. Berardi, U., Ákos, L.: Thermal bridges of metal fasteners for aerogel-enhanced blankets. Energy Build. **185**, 307–315 (2019)
15. Christensen, D.: Thermal impact of fasteners in high-performance wood-framed walls. In: Thermal Performance of the Exterior Envelopes of Whole Buildings—11th International Conference (2010)
16. Theodosiou, T.G., Papadopoulos, A.M.: The impact of thermal bridges on the energy demand of buildings with double brick wall constructions. Energy Build. **40**, 2083–2089 (2008)
17. Imam, S., Coley, D.A., Walker, I.: The building performance gap: Are modellers literate? Build. Serv. Eng. Res. Technol. **38**, 351–375 (2017)
18. CEN. BS EN ISO 6946: 2017 BSI Standards Publication: Building components and building elements—thermal resistance and thermal transmittance—calculation methods (2017)
19. Viot, H., Sempey, A., Pauly, M., Mora, L.: Comparison of different methods for calculating thermal bridges: application to wood-frame buildings. Build. Environ. **93**, 339–348 (2015)

20. Ji, R., Zhang, Z., He, Y., Liu, J., Qu, S.: Simulating the effects of anchors on the thermal performance of building insulation systems. Energy Build. **140**, 501–507 (2017)
21. Moorhouse, V., Littlewood, J.R., Hale, E.: A pilot study evaluating offsite manufacturing of timber frame panels using lean manufacturing principles for dwellings. In: Littlewood, J., Howlett, R.J., Jain, L.C. (eds.) Sustainability in Energy and Buildings 2020, pp. 503–514. Springer, Singapore (2021)

# Smart Grid for Sustainable Cities: Strategies and Pathways for Energy Efficiency Solutions

**Abdellah Chehri, Rachid Saadane, Issouf Fofana, and Gwanggil Jeon**

**Abstract** Smart Cities are making massive use of information and communication technologies, which are leading to significant digitization. However, the rate at which technology is currently being implemented is on the increase. Modern cities play a leading role in sustainable strategic development. They have a central position in developing and applying advanced technologies to support environmental sustainability in the face of the escalating urbanization trend. Smart grid specifics are finally starting to emerge from the marketing haze. In a smart grid, utilities manage their electrical supply and productivity cost-effectively, and energy customers benefit from a more efficient power system. This article focuses on the main strategies of the resource efficiency management associated with smart grid and sustainable cities.

## 1 Introduction

With the constant rise in world population causing increased consumption of resources and leading to resource shortages and climate change, the need for ground-breaking solutions is clear to see.

The concept of Smart Cities appeared in 1992. It is used to improve the future cities, not to improve the functioning of these cities as well, economically, that of management, or even ecologically, this in a sustainable development perspective. The objective of Smart Cities is also to bequeath to future generations something

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sustainable to enable them to build their future on good foundations. The smart technologies implemented in these smart cities are aimed at residents, and the objective is to improve comfort, their standard of living, and even their safety [1].

Both smart cities and sustainable cities are increasingly investing in and implementing smart meters, sensor networks, automated control systems, and cyber-physical systems in smart energy and smart environments within the framework of the Internet of Things (IoT).

As stated by Mosannenzadeh and Vettorato [2], the issues addressed by sustainable urban development strategies are:

- The city's economic development, including job creation.
- The creation of an environment conducive to the creation of new businesses.
- Improving the level of education in the city.
- Increasing the quality of life in the city, with the improvement and maintenance of green spaces, the quality of medical and social support services, and making life safer on the city's streets.
- Modernization and expansion of the city's technical and IT infrastructure.
- The increase in the leisure offer in the city and the improvement of its tourist attractiveness.

Several definitions of smart cities have been studied [3], to conclude that the axes around which smart cities are developing are:

- Industry
- The academic
- The government aspect.

The "Smart" aspect takes several forms in these fields. For the industry, it is a question of designing products or services that are smarter in particular regarding the user and not only integrated technology for technology. For the academic, it is about improving existing technologies, finally for the governmental aspect that may seem vague. It refers to smart, sustainable growth, for example, to prevent urban sprawl.

Six basic components making it possible to create a smart city have been identified, these are:

- An intelligent governance system, with transparent information exchange between residents, the city, municipal services, emergency services (police, firefighter).
- A smart economy, enabling the efficient flow of products, services, and knowledge at the city level and between cities.
- Intelligent mobility as an interconnected, safe, and efficient system for managing transport, logistics, parking lots, public transport.
- The intelligent environment is a smart management system of resources such as devices allowing energy storage, reducing energy consumption, managing electricity supply, intelligent lighting system, developing renewable energies, or even Waste Management.
- Smart residents: access to education, training through modern telecommunications and information technologies, supporting residents in terms of resources,

creativity and human potential and encouraging the active participation of participants in the life of the city.
- An intelligent way of life, making it possible to improve the quality of life, develop better health services and infrastructure, and expand and diversify the cultural and service offer.

The rest of the paper is organized as follows; the management of electricity production and distribution are described in Sect. 2. The smart grid architecture is given in Sect. 3. Section 4 puts the light on the cyber security in smart grid networks. The conclusion is given in Sect. 5.

## 2 Management of Electricity Production and Distribution

Among the key systems of Smart Cities, clean, renewable energies and the operation of sustainable distribution systems are widely discussed. The three main reasons why it is necessary to develop a sustainable distribution system are [3]:

- The number of people residing in cities and their surroundings continues to grow and is expected to continue in the coming years to reach 68% of the population living in cities, resulting in a greater need for energy in these regions.
- Smart Cities making massive use of information and communication technologies, and the advances in everyday technology, are leading to significant digitization. And therefore, an increase in the need for electricity. This increase is also due to the electrification transport and the increase in data servers, equipment, or applications, which causes an intense load on the electrical network.
- Climate change makes it compulsory to use alternative, clean, and renewable energy sources. The limitations of renewable energies, such as wind or solar, which are not available all the time or do not produce the same quantity depending on the moment, are a real challenge for storing, managing, distributing energy.

Thus, digital technologies and their energy needs show the need to strengthen electricity management and distribution systems because, without electricity, Smart Cities become entirely obsolete. It is also essential to have a reliable, stable distribution system. Otherwise, it has a significant impact on daily life.

The Smart Grid is an advanced, two-way, sustainable, self-managed, adaptive distribution system that can predict when uncertain. It is designed to work with the standards of existing infrastructures, and with future standards, it is also secure against cyberattacks [4].

The Smart Grid works with the same infrastructure, with the same transmission as the conventional distribution networks used in most cities today. The main difference is that the Smart Grid divides the electrical network into two systems (see Fig. 1). The transmission system sends energy from the power stations to the distribution system, which delivers energy to residents, industries, public infrastructure, etc.

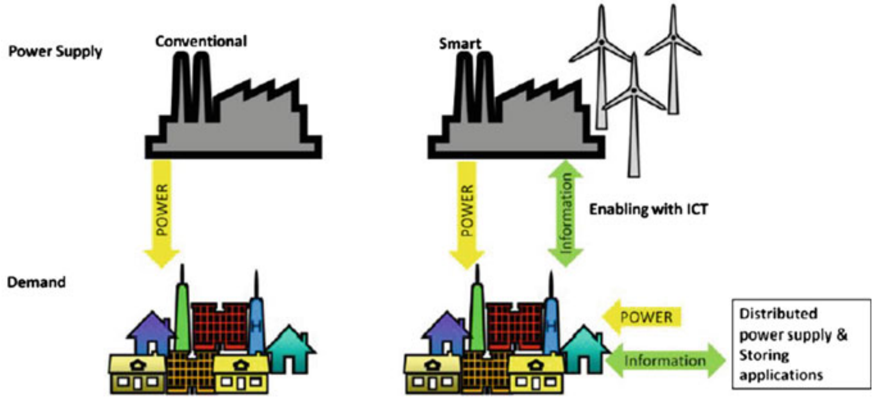


**Fig. 1** Differences between classic grid and smart grid [3]

Unlike conventional distribution systems, the Smart Grid uses the network intelligently. In fact, the SG uses an information flow between consumer and producer, and on the other hand, energy is produced, stored, and injected at different points of the network. In addition to these main concepts of an SG, it can detect problems independently, perform network analysis, and self-adjust if necessary, thus increasing the safety and reliability of the network. Smart grid technology makes it possible in particular to manage consumption peaks, supervise the electrical quality. Also, the smart grids must manage several different energy sources that may or may not be active or storage areas.

According to [3], the complex technologies of Smart Grids can be divided into four categories:

- Communication systems must be standardized and open-source so that energy needs can be addressed, but also errors can be anticipated.
- Demand management through an advanced measurement system to always balance demand and production. Allowing to control the power in the SG and to apply dynamic billing methods.
- Advanced and intelligent control units that play a vital role in the generation, transmission, distribution, and consumption of electricity through the Smart Grid.
- Greater automation of the distribution and transmission of electricity.

Among the possible applications are:

- Smart meters that measure electricity consumption but can also communicate. This allows the user to view and analyze his energy consumption on a digital terminal, allowing the supplier to analyze the data to anticipate possible peaks in consumption or even set up dynamic costs. Of course, this type of equipment is closely linked to the field of IoT, which aims to connect equipment so that they can communicate independently.

- The inclusion of electric vehicles in the city and the electricity network these vehicles lead to an increase in electricity consumption for each housing equipped, so there is a great challenge in managing the load imposed on the network. In addition, these vehicles can be used as energy storage or sometimes even as an energy source.
- Information sharing between all the different players and members/equipment connected to the smart grid.

The ability to communicate in real-time between all network members is the most exciting concept to develop for smart grids, but it is also the most technical point. Indeed, for this one, there is a real challenge to face for this one to develop a two-way communication system that allows control, supervision and measurement, and an efficient low-consumption communication system [4].

On the other hand, to implement these technologies, there will be a need to invest heavily in the existing network and infrastructure and the deployment of smart meters to supervise the network correctly. However, a significant investment will be necessary to develop further connected devices allowing the supervision of household consumption [4].

An important aspect that will need to be developed technologically and economically is the cloud technology associated with smart grids. The flexibility and scalability of this technology make it the perfect candidate. Nevertheless, it is necessary to increase the calculation capacities to manage the immense data flow of the sets of intelligent sensors of the smart grid. Finally, it is important to consider that the calculation and storage units lead to additional consumption of electricity, which is why it is necessary to take this into account to balance between the benefits provided and their associated costs [5].

Currently, we can identify two ways to set up a smart grid:

1. The TOP-DOWN method starts from the highest level of the smart grid.
2. The BOTTOM-UP method starts with consumers, households, industry, public infrastructure, making intelligent at their level to allow efficient electricity consumption.

It is possible to affirm that the concept of smart grid will be an essential point for the development of smart cities. Several players have an interest in the development of smart grids:

- First, power producers can use these technologies to acquire data on energy consumption and, therefore, better manage distribution to compensate for current peaks and improve the stability of their grid. Nevertheless, these could see their sales reduced due to the independent production of the inhabitants.
- On the other hand, consumers for whom the smart grid would be an advantage in many aspects. The main benefit for consumers is the reduction in electricity costs, thanks to a dynamic pricing system that allows them to pay less during off-peak periods. In addition, thanks to the IoT, it would be possible to automate this behavior, allowing devices with high consumption to start automatically.

- For the planet, using a smart grid seems to allow people to become more aware of their energy consumption and adapt their behavior, leading to more sustainable energy use. In addition, the decentralized generation of energy and its efficient use allows a significant reduction in greenhouse gas emissions.

## 3 Smart Grid Architecture

The model is to build block and referred to as Smart Grid Architecture Model [5]. The main functionalities, or domains, of the smart grid architecture, are (1) Energy Production, (2) Energy Transmission, (3) Energy Distribution, (4) DER—Distributed Energy Resources (5) Customers.

### *3.1 Architecture Description*

The aim of developing an architecture for the smart grid is to create a common standard based on which intelligent grids can be planned and implemented in the future [6]. That includes, among other things, the survey of existing standards and the development of new standards. The result of the development process is a framework based on the criteria for developing reference architectures.

Renewable energies are on the rise. More and more electricity are generated by e.g., Solar or wind energy generated. Such systems are also referred to as Distributed Energy Resources (DER), i.e., energy resources that occur distributed in the power grid [7, 8]. Their dynamic behavior concerning power generation characterizes such systems. The generation of electricity by photovoltaic or wind power plants is very dependent on the prevailing weather conditions. The resulting irregular and decentralized feed-in of the generated electricity leads to fluctuations in the power grid.

A study of households using smart washing machine automation has seen demand automatically shift to periods when electricity supply is abundant. This was possible with the implementation of a home area network of wireless sensors that uses the ZigBee protocol, used to relay messages between different entities.

For the consumer, significant energy savings could be achieved, equivalent to paying less on the electricity bill, that is, excellent news. This would be achieved thanks to applying new technologies that would help us make more efficient consumption. Systems capable of turning off the devices that we are not using automatically, informing us at all times of the electricity consumption that we are doing, of detecting what consumes the most so that we try to reduce or optimize its use.

Its defenders also assure that these new networks would reduce carbon dioxide ($CO_2$) emissions by up to 15% and combat climate change by substituting fossil fuels for renewable energies integrated into the architecture itself. In other words, solar panels and other systems based on these energies would cease to be the alternative to become protagonists of the electricity supply.

Many of the current solutions related to Smart grids come from large companies related to the electricity sector companies and the monitoring and control of the systems. Even so, other types of initiatives related to the subject, such as the one carried out in the Institute of Electrical and Electronic Engineering (IEEE), an international non-profit organization, are rising strongly.

There are different projects on the table, and little by little, the necessary infrastructures are being developed to make them a reality in the not too distant future.

This requires expanding the distribution network level to include information and communication technology infrastructure (ICT infrastructure). This requirement has defined three integrated architectural perspectives: energy systems, communications technology, and information technology, which indicate the main guidelines for the interoperability of the Smart grid.

According to [9], a smart grid is an electrical network that integrates all participants and their actions and behavior in a cost-efficient manner. It also allows users to feed in and sell their electricity. In addition to producers and consumers, there are also electricity storage systems such as storage power plants and electric vehicles.

In addition to the domains, a second dimension was introduced. The so-called zones represent the control levels of the individual fields. They were derived from the SCADA automation pyramid [10, 11]. The merging of the zones with the domains results in a two-dimensional view of the smart grid (see Fig. 2).

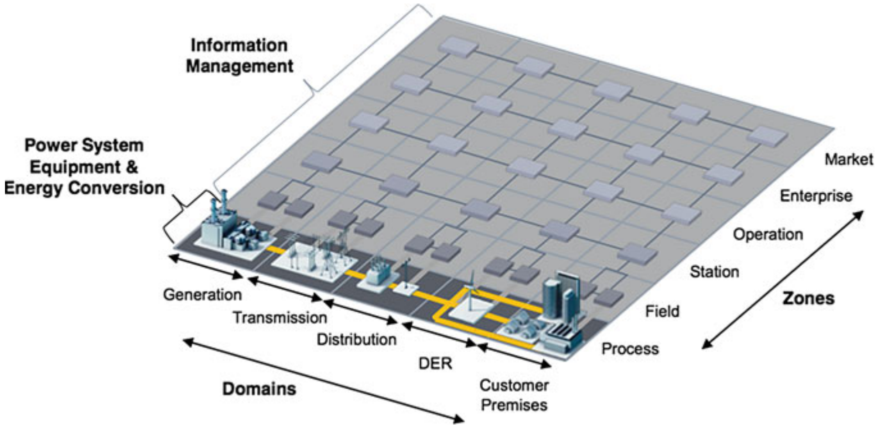


**Fig. 2** Smart grid architecture—domains and hierarchical zones [9]

### 3.2 Standardization in Smart Grids

To be able to operate a system like the smart grid, standards have to be created. The aim is to achieve broad acceptance. Existing measures from different domains must also be taken into account [12].

According to [13], the interoperability stack represents the basis for requirements engineering in pre-registration and management. In the context of the smart grid, the stack was summarized on five levels. These expand the framework by a third dimension, the so-called interoperability dimension. The individual layers of this dimension are listed below as an overview. A more detailed description can be found in [9].

- Business layer: The layer represents the view for stakeholders interested in the market economy. In the area of the electricity market are supported via this layer. Official regulations must also be taken into account here.
- Function layer: In this layer, the description is derived from use cases. This layer describes the Functions, services, and relationships from the architecture perspective.
- Information layer: This layer defines the information exchanged between the systems as well as the underlying data model.
- Communication Layer: The mechanisms and protocols necessary for exchanging technical information are described in this layer.
- Component Layer: It represents all physical components that are located in the smart grid (e.g., system actors, network components, applications).

By combining the three dimensions, the domains, the zones, and the interoperability, the smart grid architecture framework was created.

While smart grid technology addresses many issues, many challenges and issues need to be addressed. These problems are divided into three categories, technical, regulatory, and security issues. The technical challenges are divided into three areas: information and telecommunications technologies, measurement and automation technologies, and technologies for the storage and production of electricity. However, these subjects are the source of much research, and technical progress will make it possible to respond to these challenges.

Even if it is clear that the technical issues are indeed present, the legislative and regulatory aspect around smart Grids is the biggest challenge. Today, nothing is planned to supervise this type of project. Notably, energy policies differ significantly from one country to another but even more locally from one region to another. So if we want to be able to set up a sustainable and intelligent electricity grid, we must already focus on standardizing strategies and regulations.

Finally, security occupies a significant and strategic place because an attack on the network will jeopardize the entire city. Because the electricity network is fully connected, it would be possible to control it to cause harm. In addition, the Smart Grid is quite vulnerable because having several points where it is possible to enter. Moreover, these points being different, there will be more possibilities to join, and it would be more challenging to find and correct the flaws. Also, the problem of using user data arises. Indeed, power producers could use the data for a purpose other than optimizing the distribution and consumption of energy. Against this, no measures are discussed, shared; again, the legislative aspect shows how essential it is.

## 4 Cyber Security in Smart Grid Networks

Smart grids' cybernetic infrastructure includes electronic information systems and services and communication and the information contained therein. Sayings systems and services are made up of hardware and software used to process (access, create, modify, and destroy), store, and transmit (exchange and distribute) information [14]. Attacks on cyberinfrastructure can cause operational failures and timing that would affect critical components, interrupting the power supply, and causing economic loss. Therefore, it is essential to involve cybersecurity in the smart grid design process [15].

The incorporation of new technologies to the current electricity grid increases its complexity and, with it, also increases the number of risks. For example, new nodes in the power grid they generate new entry points that attackers could exploit.

New threats to computer systems appear day by day due to the rapid increase in hacking tools sophisticated. Therefore, any telecommunications link within the electrical network represents a potentially perilous path in the same operation.

Although the direct physical destruction of generators, substations, and power lines may be the most obvious to cause blackouts, other activities that endanger sensors' operation, communication devices, through sending wrong commands to control centers. These "unwanted" commands could disrupt the system, cause power outages, and cause physical damage to critical system components. Also, the digitization of the electricity grid enables the possibility of attacks remotely. For example, the implementation of the Advanced Metering Infrastructure (AMI) widely regarded as one of the first steps in the digitization of the electrical grid control systems, generates new threats to the network, such as the fabrication of reads energy meter, manipulation of energy costs, the sending false control signals and malicious code [16–18].

Consequently, cybersecurity is a priority key and should be included in all stages or phases of the life cycle of the development of smart electrical grids, from the design phase, up to the implementation and maintenance phases. Planning and implementing cybersecurity strategies can reduce the probabilities of successful attacks and minimize the impacts of those who manage to run [19].

Scenarios caused by cyber-attacks are, unfortunately, no longer theoretical ideas. As already explained, the smart grid is made up of a myriad of interconnecting devices. In addition, the network transition between the office IT and the production network is a gateway for cybercriminals [20–23]. For example, worms, Trojans, or other unwanted programs can get into the production environment from the conventional infrastructure and significantly impair the production process.

## 5 Conclusion

The emergence of information and communication technologies associated with IoT opens up new possibilities, with these possibilities appearing Smart Cities concepts. These concepts are widely discussed within the scientific community and are starting to gain the attention of major players. Among the axes developed by smart cities, smart grids are the most discussed in the scientific community, aiming to optimize the production and transmission of electricity within the city.

The technologies presented are up-and-coming and will bring cities and the daily lives of their residents to another level. The city of tomorrow will be more innovative more sustainable. It will not be limited to the management of its electrical needs: it will include all forms of energy, but also the management of human flows (transport), information flows, and the development of communicating infrastructures with the primary goal of improving the comfort and quality of life of its fellow citizens while respecting the environment.

## References

1. Kos, B.: Intelligent transport systems (ITS) in smart city. In: Suchanek, M. (ed.) Challenges of Urban Mobility, Transport Companies and Systems, pp. 115–126. Springer Proceedings in Business and Economics. Springer, Berlin (2019)
2. Mosannenzadeh, F., Vettorato, D.: Defining smart city. A conceptual framework based on keyword analysis. J. Land Use Mobility Environ. (2014)
3. Igelmann, M., Kovalchuk, V.: Project Research Report: Smart Sustainable City: Smart Grids (2020)
4. Dileep, G.: A survey on smart grid technologies and applications. Renew. Energy **146** (2019)
5. Chakraborty, N., Mondal, A., Mondal, S.: Efficient load control based demand side management schemes towards a smart energy grid system. Sustain. Cities Soc. **59** (2020). ISSN 2210-6707
6. Kumar, K., Indra Gandhi, V., Ravi, L., Vijayakumar, V., Subramaniyaswamy, V.: Improving security for wind energy systems in smart grid applications using digital protection technique. Sustain. Cities Soc. **60** (2020)
7. Chehri, A., Mouftah, H.T.: Service-oriented architecture for smart building energy management. In: 2013 IEEE International Conference on Communications (ICC), Budapest, pp. 4099–4103 (2013). http://doi.org/10.1109/ICC.2013.6655203
8. Chehri, A., Mouftah, H.T.: FEMAN: fuzzy-based energy management system for green houses using hybrid grid solar power. J. Renew. Energy (Article ID 785636) (2013)
9. Smart Grid Coordination Group: Smart Grid Reference Architecture. CEN-CENELECETSI, Smart Grid Coordination Group, Technical Report (2012)
10. Neureiter, C., et al.: A standards-based approach for domain specific modelling of smart grid system architecture. In: 11th International Conference on System of Systems Engineering, pp. 12–16 (2016)
11. Ferreira, A., Leitão, P., Vrba, P.: Challenges of ICT and artificial intelligence in smart grids. In: 2014 IEEE International Workshop on Intelligent Energy Systems (IWIES), San Diego, CA, pp. 6–11 (2014). http://doi.org/10.1109/IWIES.2014.6957039
12. Specht, M., Rosinger, C.: Standards in the electro mobility domain—vehicle 2 grid. In: Standardization in Smart Grids, pp. 163–177. Springer, Berlin (2013)
13. Uslar, M., et al.: Standardization in Smart Grid. Springer, Berlin (2013)

14. Ghansah, I.: Smart grid cyber security potential threats, vulnerabilities and risks. California Energy Commission, PIER Energy-Related Environmental Research Program, Sacramento, CA, CEC-500-2012-047 (2009)
15. Chehri, A., Fofana, I., Yang, X.: Security risk modeling in smart grid critical infrastructures in the era of big data and artificial intelligence. Sustainability **13**, 3196 (2021). https://doi.org/10.3390/su13063196
16. Karnouskos, S., Terzidis, O., Karnouskos, P.: An advanced metering infrastructure for future energy networks. In: New Technologies, Mobility and Security, pp. 597–606. Springer, Netherlands (2007)
17. Depuru, S.S.S.R., Wang, L., Devabhaktuni, V.: Smart meters for power grid: challenges, issues, advantages and status. Renew. Sustain. Energy Rev. **15**(6), 2736–2742 (2011)
18. Shipman, C.M., Hopkinson, K.M., Lopez, J.: Con-resistant trust for improved reliability in a smart-grid special protection system. IEEE Trans. Power Deliv. **30**(1), 455–462 (2014)
19. McDaniel, P., McLaughlin, S.: Security and privacy challenges in the smart grid. IEEE Secur. Priv. **7**(3), 75–77 (2009)
20. Nordell, D.E.: Terms of protection: the many faces of smart grid security. IEEE Power Energy Mag. **10**(1), 18–23 (2012)
21. Khurana, H., Hadley, M., Lu, N., Frincke, D.A.: Smart-grid security issues. IEEE Secur. Priv. **8**(1), 81–85 (2010). http://doi.org/10.1109/MSP.2010.49
22. Rossebø, J.E.Y., et al.: An enhanced risk-assessment methodology for smart grids. Computer **50**(4), 62–71 (2017). https://doi.org/10.1109/MC.2017.106
23. Dechesne, F., Hadziosmanovic, D., Pieters, W.: Experimenting with incentives: security in pilots for future grids. IEEE Secur. Priv. **12**(6), 59–66 (2014)

# Energy Management of a Residential Heating System Through Deep Reinforcement Learning

**Silvio Brandi, Davide Coraci, Davide Borello, and Alfonso Capozzoli**

**Abstract** In this study, a controller based on deep reinforcement learning was tested for a residential building equipped with a radiant heating system. In detail, a Soft Actor-Critic (SAC) algorithm was implemented to optimize the operation of the heating system while ensuring adequate levels of indoor temperature. A probabilistic window opening behavior model was implemented within the simulation framework in order to emulate the interaction of the occupants with the building. A sensitivity analysis on SAC hyperparameters was carried out to determine the best configuration that was then deployed in four different scenarios in order to analyze the adaptability of the controller to different boundary conditions. The performance of the reinforcement learning agent was evaluated against a baseline strategy which combines rule-based and climatic control. The developed agent was able to achieve a saving of heating energy provided to the building in the range between 2 and 6% while increasing temperature control performance up to 65% in the four scenarios investigated.

## 1 Introduction

The energy consumption related to the operation of building systems accounts for 40% of the worldwide energy demand and 36% of $CO_2$ emissions [1]. Heating, Ventilation and Air Conditioning (HVAC) systems represent the most energy-intensive in buildings and significant improvements have been made in recent years to enhance their energy efficiency [2]. However, the optimal management of these systems is challenging due to the influence of stochastic endogenous and exogenous factors which cause the non-linearity of the control problem [3]. Traditionally, ON/OFF or Proportional-Integrative-Derivative (PID) controllers are the most widely applied bottom-level control system. At the supervisory level Rule-Based Control agents

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(RBCs) are commonly employed. However, since these strategies are mainly reactive and unable to predict changes in weather or building conditions [4], or to take into account more than one control objective, their implementation results in sub-optimal control policies [5, 6]. Model-based control strategies, such as Model Predictive Control (MPC), were explored to overcome such limitations, showing an excellent ability in improving comfort conditions and energy efficiency in buildings [7–9]. However, despite the promising results, MPCs are not widely adopted in real-world applications due to their strong dependence from the accuracy of the underlying model of the system [10] and from the robustness of the optimization algorithm [11]. As a consequence, Reinforcement Learning (RL), specifically Deep-RL (DRL), has emerged as a promising control algorithm due to its model-free approach for the optimization of building performance [12]. Recent works in literature have proven the feasibility in the application of DRL strategies to control supply water temperature [13–15] and indoor temperature setpoint [16, 17].

In this paper, an off-policy DRL algorithm named Soft Actor-Critic [18], was implemented to control the supply heating power for a residential building located in Turin, Italy. The experiment was carried out in a simulation environment which combines Python and EnergyPlus. The control agent is designed to reduce heating energy supplied to the building while maintaining the desired indoor temperature values. Moreover, it was implemented a probabilistic model for the operation of the windows (open/close) to simulate the interaction of occupants with the residential building.

## 2 Methods

Reinforcement learning (RL) can be formalized as a Markov Decision Process (MDP), defined by a four-values tuple, including a set of state S, a set of action A, transition probabilities between the states and a reward function r. The goal of the RL agent is to learn an optimal control policy (π), a mapping between states and actions that maximizes the cumulative sum of future rewards [19]. The problem can be defined by two functions, namely state-value $v_\pi(s)$ and action-value $q_\pi(s)$. These functions determine the optimal policy of the RL agent and are used to show the expected return of a control policy π starting from a specific state or a state, action pair, as follows:

$$\mathrm{v}_\pi(\mathrm{s}) = \mathrm{E}[\mathrm{r}_{t+1} + \gamma \mathrm{v}_\pi(\mathrm{s}')|\mathrm{S}_t = \mathrm{s}, \mathrm{S}_{t+1} = \mathrm{s}'] \quad (1)$$

$$q_\pi(s, a) = E[r_{t+1} + \gamma q_\pi(s', a')|S_t = s, A_t = \mathrm{a}] \quad (2)$$

where γ[0, 1] is the discount factor for future rewards. For $\gamma = 1$ the agent will consider future rewards more important than current ones. Contrarily, for $\gamma = 0$ the agent will give greater importance to immediate rewards. The most widely applied approach among RL algorithms is the Q-Learning. Q-Learning exploits a tabular approach to map the relationships between states and action pairs [13]. These relationships are formalised as Q-values, which are updated according to the following formula:

$$Q(s, a) \leftarrow Q(s, a) + \mu\left[r_t + \gamma \max_{a'} Q\left(s', a'\right) - Q(s, a)\right] \tag{3}$$

where $\mu[0, 1]$ is the learning rate, which determines the degree of overwriting of old knowledge with the new one. For $\mu = 1$ new knowledge completely substitutes old knowledge.

**Soft Actor-Critic**

Deep Neural Networks, and their combination with RL algorithms [i.e., Deep Reinforcement Learning (DRL)] seemed to overcome Q-Learning limitations. Therefore, DRL resulted more suitable for complex problems. In this paper, it was implemented the Soft-Actor Critic (SAC), an off-policy algorithm introduced by Haarnoja et al. [18] capable of handling continuous action spaces. The adopted actor-critic architecture employs two different deep neural networks: the *Actor* maps the current state based on the estimated optimal action, while the *Critic* evaluates the actions by calculating the value-function. The entropy regularization represents a key-feature in SAC, ensuring that the agent is pushed towards the exploration of new policies while avoiding that it gets stuck in sub-optimal behavior [3]. Therefore, in SAC algorithm the objective is to maximize both expected reward and entropy [20] as follows:

$$\pi^* = \arg\max_{\pi} \mathbb{E}_{\pi} \sum_{t=0}^{\infty} \left[r_t + \alpha H_t^{\pi}\right] \tag{4}$$

where H is the Shannon entropy term, expressing the attitude of the agent in taking random actions, and α is the temperature parameter, a regularization coefficient that determines the importance of the entropy term against the reward.

## 3 Case Study and Methodology

The proposed control strategy was developed for a five stories residential building located in Turin, Italy. The building is characterized by a net heated surface of 527 m$^2$ organized into five different thermal zones, one for each floor. The average transmittance values of the opaque and transparent envelope components are 0.985 and 2.681 W/m$^2$ K respectively. The thermal zones are served by a radiant floor heating system equipped with a variable speed circulation pump. The amount of heat delivered to each zone can be controlled by three-way circulation valves. The objective of the developed DRL controller is to maintain the indoor temperature into an acceptability range, defined between [−1, 1] °C from the desired temperature value of 21 °C, while reducing the heating energy provided to the building through the regulation of the heating power supply to each radiant floor. The design value of supply heating power per each floor is respectively equal to 11 kW, 6.5 kW, 5.0 kW, 5.0 kW and 6.5 kW. The interaction between the control agent and the building energy model was simulated through Building Control Virtual Test Bed (BCVTB), that allows the information exchange between the building model (developed in EnergyPlus) and the SAC control agent (developed in Python). Simulation time step and control time step was equally set to 30 min.

## 3.1 Occupancy Schedules and Modeling of Window Opening Behavior

Different occupancy schedules were implemented for each floor in the building. Moreover, in order to better characterize the behavior of the occupants and, in particular, their interactions with the building a probabilistic model for window opening/closing was implemented within the simulation environment. The model developed in [21] employs indoor temperature, relative humidity and $CO_2$ along with outdoor air temperature, relative humidity, wind speed and solar radiation to estimate probabilities of opening and closing of the windows in the building. The model is based on logistic regression which coefficients depends on the day of the week and the time of the day and was implemented in Python. The open/close state of windows was passed as an additional binary "control-signal" (i.e., 0 = closed, 1 = open) to EnergyPlus at each control time step.

## 3.2 Baseline Control Logic

The performance of the DRL controller was evaluated against a baseline controller consisting of a combination of rule-based and climatic-based logics for the control of the supply power of the heating system. The RBC controller manages the operation of the radiant heating systems according to the indoor temperature values and occupancy schedules separately for each floor. The heating energy to each floor is supplied two hours before the arrival of the occupants or when the indoor temperature is lower than the lower threshold of the acceptability range during occupancy period. Contrarily, during unoccupied hours or when the indoor temperature is higher than the upper threshold of the acceptability range during occupancy period the heating energy is not supplied. The opening degree of the valves, which determines the fraction of the nominal heating power provided to each floor, is managed through a climatic-based curve implemented in the real building on which this case study is based on. Nominal heating power is provided when outdoor air temperature values fall below 6 °C, while when outdoor temperature rises above 19 °C the system is switched off.

### 3.3 Design of Reinforcement Learning Control Agent

This section discusses the design of the action-space, state-space and reward function of the DRL controller.

**Design of the action-space**. Since SAC was selected as the control algorithm, the action-space was expressed as a continuous space of 5 different actions, related to the supply power per each thermal zone, expressed in kW:

$$At = [A_{ground floor}, A_{first floor}, A_{second floor}, A_{third floor}, A_{fourth floor}] \quad (5)$$

The supply power was limited between 0 and the design value for each floor.

**Design of the state-space**. The state-space is composed of 26 observed variables, reported in Table 1 with their lower and upper bounds, and the time step at which they are evaluated. The variables chosen are feasible to be collected in a real-world implementation and provide the necessary information required by the agent to predict immediate future rewards.

Observations were scaled in the (0, 1) range according to a min–max normalization in order to be fed to the neural network.

**Design of the reward function**. The reward function was formulated as a linear combination of two competing terms. The first term is related to the heating energy supplied to the building expressed in kWh that is directly proportional to the control

**Table 1** State-space variables

| Variable | Timestep | Min value | Max value | Unit |
|---|---|---|---|---|
| Hour of the day | t | 1 | 24 | H |
| Day of the week | t | 1 | 7 | – |
| Outdoor air temperature | t | −8 | 32 | °C |
| Direct solar radiation | t | 0 | 1100 | W/m$^2$ |
| Time to occupancy start | t | 0 | 10 | H |
| Time to occupancy end | t | 0 | 15 | H |
| Indoor $\Delta T_{\text{ground floor}}$ | t, t − 1, t − 2, t − 4 | −5 | 10 | °C |
| Indoor $\Delta T_{\text{first floor}}$ | t, t − 1, t − 2, t − 4 | −5 | 10 | °C |
| Indoor $\Delta T_{\text{second floor}}$ | t, t − 1, t − 2, t − 4 | −5 | 10 | °C |
| Indoor $\Delta T_{\text{third floor}}$ | t, t − 1, t − 2, t − 4 | −5 | 10 | °C |
| Indoor $\Delta T_{\text{fourth floor}}$ | t, t − 1, t − 2, t − 4 | −5 | 10 | °C |

action. The second term is defined as quadratically proportional to the difference between the measured indoor temperature ($T_i$) and the desired setpoint ($T_{SP}$).

These terms were combined through the introduction of two weight factors (δ and β) that determine respectively the relative importance of heating energy consumption and indoor temperature requirements.

The resulting reward function depends by the presence of the occupants and it is expressed as follows:

$$R = \begin{cases} -\delta * \sum_{i=1}^{N} E_{HEATING,i} - \beta * (T_{SP} - T_i)^2, & if\ OCC = 1 \\ -\delta * \sum_{i=1}^{N} E_{HEATING,i}, & if\ OCC = 0 \end{cases} \quad (6)$$

where $E_{HEATING,i}$ is the energy provided to each floor and N is the number of floors.

## 3.4 Training and Deployment Phase

**Training phase**. The performance of the DRL agent is highly influenced by several hyperparameters. To assess their influence, a sensitivity analysis was performed to select the value of the following hyperparameters: discount factor $\gamma$, learning rate $\mu$, weight factors of the reward terms $\beta$ and $\delta$, batch size, number of neurons per hidden layer and number of training episodes. The different tested configurations are shown in Table 2. A training episode lasts 61 days and includes two months, from 1 November to 31 December, for a total of 2928 control time-steps. The weather file used in this phase refers to the heating season 2018/2019 for Turin, Italy.

**Deployment phase**. The best configuration of hyperparameters, retrieved from the sensitivity analysis performed during the training phase, was deployed in four different scenarios to evaluate the adaptability of the learned control policy. The deployment period last one episode including two months, from 1 January to 28 February, considering the same weather file as in the training phase. The proposed scenarios are the following:

- Scenario 1: this is the base case with no implemented changes in the controlled environment. This scenario aims to evaluate the adaptability of the control agent to different patterns of outdoor conditions.
- Scenario 2: in this scenario the indoor temperature setpoint was decreased from 21 to 20 °C to assess the performance of the agent in satisfying different temperature requirements from the one assumed in the training phase.
- Scenario 3: in this case was evaluated the performance of the agent considering thermal transmittance $U_w$ and the solar factor *g* of windows reduced to 1.1 W/m$^2$ K and 0.33 respectively.

**Table 2** Tested hyperparameters configurations for the DRL controller during the training phase

| Configuration | $\gamma$ | $\mu$ | $\beta$ | $\delta$ | Batch size | Neurons | Episodes |
|---|---|---|---|---|---|---|---|
| 1 | 0.9 | 0.001 | 1 | 0.1 | 256 | 256 | 10 |
| 2 | 0.95 | 0.001 | 1 | 0.1 | 256 | 256 | 10 |
| 3 | 0.99 | 0.001 | 1 | 0.1 | 256 | 256 | 10 |
| 4 | 0.9 | 0.001 | 1 | 0.5 | 256 | 256 | 10 |
| 5 | 0.9 | 0.001 | 1 | 0.1 | 512 | 256 | 10 |
| 6 | 0.9 | 0.001 | 1 | 0.1 | 128 | 256 | 10 |
| 7 | 0.9 | 0.0001 | 1 | 0.1 | 128 | 256 | 10 |
| 8 | 0.9 | 0.0001 | 1 | 0.1 | 256 | 256 | 25 |
| 9 | 0.9 | 0.001 | 1 | 0.1 | 256 | 256 | 25 |
| 10 | 0.9 | 0.0001 | 1 | 0.01 | 256 | 256 | 25 |
| 11 | 0.9 | 0.0001 | 5 | 0.1 | 256 | 256 | 25 |
| 12 | 0.9 | 0.0005 | 1 | 0.1 | 256 | 256 | 25 |
| 13 | 0.9 | 0.0001 | 10 | 0.1 | 256 | 256 | 25 |
| 14 | 0.9 | 0.0001 | 1 | 0.1 | 256 | 128 | 25 |
| 15 | 0.9 | 0.0001 | 1 | 0.1 | 256 | 512 | 25 |

- Scenario 4: in the last scenario it was assessed the adaptability of the agent considering the internal mass doubled to rise the thermal inertia and internal heat capacity of the building.

The best trained agent was deployed statically, then it was not updated during the deployment and was used as static function. This process requires less computational time at the cost of a lower capability to adapt to changes in the controlled system [14].

## 4 Results and Discussion

In order to consider the influence of the hyperparameters on the DRL control logic performances, a sensitivity analysis was performed. Two metrics were used to compare the different hyperparameters configuration: the energy saving with respect to the baseline and the cumulative sum of temperature violations during the occupancy hours. These metrics were summed up at the end of the training episode. The temperature violations, evaluated in °C, were calculated as the absolute difference between the indoor temperature and the lower or upper limit of the temperature acceptability range [19, 21], when the internal temperature was lower or higher than these limits. Figure 1 shows the cumulative sum of temperature violations (on y-axis, defined on a logarithmic scale for the sake of legibility) for the last training episode as a function of the energy saving. The performance of the baseline is reported with

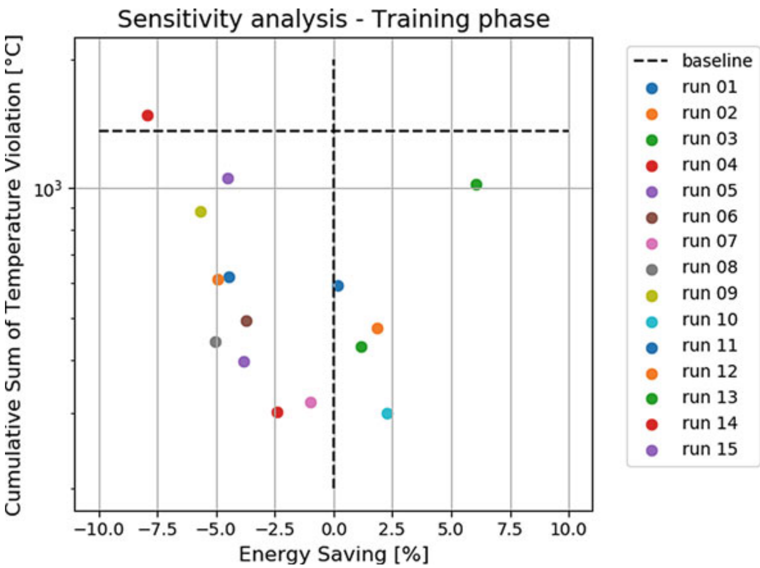


**Fig. 1** SAC control agent performance in the last episode of the training phase

black dashed lines that divides the plot into four quadrants. The left-bottom quadrant includes the configurations in which the DRL agent reduced both the supplied heating energy and the temperature violations.

The configuration eight (i.e. run 08 in the figure) showed the best trade-off between energy saving (−5%) and temperature violations (−65%). The agent trained with this configuration was successively statically deployed in the four deployment scenarios.

Table 3 shows the results obtained for the DRL agent in the four deployment scenarios, considering the energy savings and the reduction of the cumulative sum of temperature violations with respect to the RBC control selected as baseline. In all scenarios, the DRL controller leads to a reduction of heating energy supplied and temperature violations. The SAC control logic achieves the highest energy saving (i.e., about 5%) in the fourth scenario without reducing the temperature violations with respect to the baseline. In contrast, in the third scenario the DRL controller shows the highest reduction of temperature violations (60%) with the lowest energy saving

**Table 3** Performance comparison between DRL and RBC agents for all deployment scenarios

| Scenario | Energy consumption [MWh] | | Temperature violations [°C]2 | |
|---|---|---|---|---|
| | DRL agent | Baseline | DRL agent | Baseline |
| 1 | 20.6 | 21.2 | 592.2 | 1447.8 |
| 2 | 22.6 | 23.6 | 395.3 | 1158.6 |
| 3 | 20.0 | 20.3 | 603.2 | 1553.1 |
| 4 | 20.8 | 22.0 | 505.6 | 508.9 |

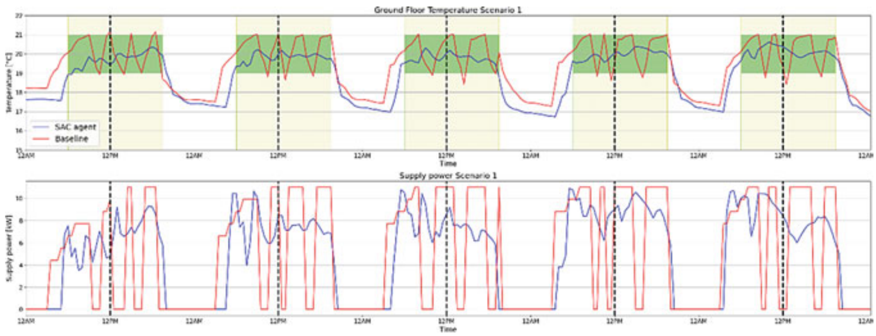


**Fig. 2** Comparison between SAC and baseline controllers in Scenario 1

with respect to the baseline (around 2%). Overall, the SAC control agent ensures better performance than the baseline. In addition, the definition of a carefully designed state-space allows the developed agent to adapt to each scenario even if statically deployed, avoiding control instability issues and reducing the computational time.

Figure 2 reports the comparison between the SAC and RBC controllers in the first scenario during 5 days of the deployment period. The figure shows the indoor temperature and supply power patterns for the ground floors. The adaptive control agent is capable to reduce the temperature violations and energy supplied through an optimal management of the heating system. The SAC controller optimizes the pre-heating phase. In particular, the developed agent switches-ON the heating system later than the baseline, reducing the corresponding energy supplied and ensuring that indoor comfort requirements are met.

## 5 Conclusions

In this paper, a DRL agent was implemented to control the heating power supplied to each floor zone of a residential building. To represent the occupants' behavior as close as possible to the reality, it was adopted a model presented in literature based on logistic regression to simulate the windows opening and closing. The control agent was designed to enhance the energy efficiency while maintaining the indoor temperature within an acceptability range. A sensitivity analysis on the hyperparameters of the SAC algorithm was performed during the training phase to choose the DRL agent ensuring the best performance with respect to the baseline controller. The best trained agent was able to reduce the cumulative sum of temperature violations by more than 65%, while ensuring a reduction in the heating energy supplied. Furthermore, the agent was found effective in adapting to modification in the controlled system such as weather conditions, indoor temperature requirements and physical characteristics even if statically deployed. In particular, the developed controller reduced the heating energy supplied up to a maximum of 6% compared to the baseline controller, while ensuring better indoor temperature conditions.

Future works will be focused on the aspects of reproducibility and standardization of the developed controller, since it could perform differently in other buildings or HVAC systems. Moreover, the evaluation of indoor thermal comfort could be performed, by introducing parameters such as Predicted Percentage of Dissatisfied (PPD) and Predicted Mean Vote (PMV) in the reward function.

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## References


1. Yang, L., Nagy, Z., Goffin, P., Schlueter, A.: Reinforcement learning for optimal control of low exergy buildings. Appl. Energy **156**, 577–586 (2015). https://doi.org/10.1016/j.apenergy.2015.07.050
2. Martinopoulos, G., Papakostas, K.T., Papadopoulos, A.M.: A comparative review of heating systems in EU countries, based on efficiency and fuel cost. Renew. Sustain. Energy Rev. **90**, 687–699 (2018). https://doi.org/10.1016/j.rser.2018.03.060
3. Coraci, D., Brandi, S., Piscitelli, M.S., Capozzoli, A.: Online implementation of a soft actor-critic agent to enhance indoor temperature control and energy efficiency in buildings. Energies **14** (2021). http://doi.org/10.3390/en14040997
4. Wang, Z., Hong, T.: Reinforcement learning for building controls: the opportunities and challenges. Appl. Energy **269**, 115036 (2020). http://doi.org/10.1016/j.apenergy.2020.115036
5. Mechri, H.E., Capozzoli, A., Corrado, V.: USE of the ANOVA approach for sensitive building energy design. Appl. Energy **87**, 3073–3083 (2010). https://doi.org/10.1016/j.apenergy.2010.04.001
6. Aghemo, C., Virgone, J., Fracastoro, G.V., Pellegrino, A., Blaso, L., Savoyat, J., Johannes, K.: Management and monitoring of public buildings through ICT based systems: control rules for energy saving with lighting and HVAC services. Front. Archit. Res. **2**, 147–161 (2013). https://doi.org/10.1016/j.foar.2012.11.001
7. Ma, Y., Borrelli, F., Hencey, B., Packard, A., Bortoff, S., Sturzenegger, D., Gyalistras, D., Morari, M., Smith, R.S., Oldewurtel, F., et al.: Model predictive control of thermal energy storage in building cooling systems. IEEE Trans. Control Syst. Technol. **24**, 1–12 (2009). https://doi.org/10.1109/CDC.2009.5400677
8. Oldewurtel, F., Parisio, A., Jones, C.N., Gyalistras, D., Gwerder, M., Stauch, V., Lehmann, B., Morari, M.: Use of model predictive control and weather forecasts for energy efficient building climate control. Energy Build. **45**, 15–27 (2012). https://doi.org/10.1016/j.enbuild.2011.09.022
9. Sturzenegger, D., Gyalistras, D., Morari, M., Smith, R.S.: Model predictive climate control of a Swiss office building: implementation, results, and cost-benefit analysis. IEEE Trans. Control Syst. Technol. **24**, 1–12 (2016). https://doi.org/10.1109/TCST.2015.2415411
10. Killian, M., Ten, K.M.: Questions concerning model predictive control for energy efficient buildings. Build. Environ. **105**, 403–412 (2016). https://doi.org/10.1016/j.buildenv.2016.05.034
11. Wang, Y., Boyd, S.: Fast model predictive control using online optimization. IEEE Trans. Control Syst. Technol. **18**, 267–278 (2010). https://doi.org/10.1109/TCST.2009.2017934

12. Hong, T., Wang, Z., Luo, X., Zhang, W.: State-of-the-art on research and applications of machine learning in the building life cycle. Energy Build. **212**, 109831 (2020). http://doi.org/10.1016/j.enbuild.2020.109831
13. Ahn, K.U., Park, C.S.: Application of deep Q-networks for model-free optimal control balancing between different HVAC systems. Sci. Technol. Built Environ. **26**, 61–74 (2020). https://doi.org/10.1080/23744731.2019.1680234
14. Brandi, S., Piscitelli, M.S., Martellacci, M., Capozzoli, A.: Deep reinforcement learning to optimise indoor temperature control and heating energy consumption in buildings. Energy Build. **224**, 110225 (2020). http://doi.org/10.1016/j.enbuild.2020.110225
15. Zhang, Z., Chong, A., Pan, Y., Zhang, C., Lam, K.P.: Whole building energy model for HVAC optimal control: a practical framework based on deep reinforcement learning. Energy Build. **199**, 472–490 (2019). https://doi.org/10.1016/j.enbuild.2019.07.029
16. Lu, S., Wang, W., Lin, C., Hameen, E.C.: Data-driven simulation of a thermal comfort-based temperature set-point control with ASHRAE RP884. Build. Environ. **156**, 137–146 (2019). https://doi.org/10.1016/j.buildenv.2019.03.010
17. Park, J.Y., Nagy, Z.: HVACLearn: a reinforcement learning based occupant-centric control for thermostat set-points. In: Proceedings of the Eleventh ACM International Conference on Future Energy Systems, pp. 434–437. Association for Computing Machinery, New York, NY, USA (2020)
18. Haarnoja, T., Zhou, A., Hartikainen, K., Tucker, G., Ha, S., Tan, J., Kumar, V., Zhu, H., Gupta, A., Abbeel, P., et al.: Soft Actor-Critic Algorithms and Applications. arXiv (2018)
19. Sutton, R.S., Barto, A.G.: Reinforcement Learning: An Introduction. MIT Press, Cambridge (1998). http://doi.org/10.1016/S0140-6736(51)92942-X
20. Pinto, G., Piscitelli, M.S., Vázquez-Canteli, J.R., Nagy, Z., Capozzoli, A.: Coordinated energy management for a cluster of buildings through deep reinforcement learning. Energy 120725 (2021). http://doi.org/10.1016/j.energy.2021.120725
21. Andersen, R.V., Olesen, B.W., Toftum, J.: Modelling window opening behaviour in Danish dwellings. In: 12th International Conference on Indoor Air Quality and Climate, vol. 2, pp. 963–968 (2011)

# Daylighting Design for Refurbishment of Built Heritage: A Case Study

**Alessandro Lo Faro and Francesco Nocera**

**Abstract** This paper wants to present a study on natural light design for an historic lighthouse building. The design solution proposed for the old Capo Murro di Porco lighthouse (SR, Italy) starts from a deep knowledge of lighthouse typology, its history and technological characteristics. The refurbishment solution is based on solar radiation control and advanced daylight system application (new skylight) without modifying the external envelope of the building preserving its cultural heritage and complaining with architectural constraints. The main goals are to increase lighting energy savings due to less artificial lighting system utilization and to improve the uniformity of luminance distribution and levels at long indoor distances from the windows under variable sun and sky conditions throughout the year. A method and solution were also proposed for evaluating and improving daylight distribution in the atrium and adjacent rooms using a combination of skylight and light redirecting devices.

## 1 Introduction

The possibility of preserving historical buildings is fundamentally connected with their use and re-use in which is strong a demand for retrofit solutions able to improve indoor thermal conditions while reducing the use of energy sources and preserving the heritage significance [1]. Therefore, a better utilization of daylight assumes not negligible role, for reducing the need for artificial lighting and internal gains caused by solar energy and electric lighting. If daylighting issues are easy to manage in new buildings through an accurate design phase, it is not so on heritage buildings: here, it is the priority the respect of their cultural value and for this reason it is required

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more accurate and careful evaluations in order to reduce energy needs, guarantee visual perception of indoor spaces and visual comfort [2]. Acting on users' comfort and reducing the energy demand, are crucial to ensure the continued use of buildings over time and consequently their endurance. In addition, the built heritage values are sustained, by preserving the material of the historical fabric [3].

Daylight design is an important component of any retrofit [4]. Indeed the challenge is to optimize system delivery, daylight performance and minimize the size of the glare area [5]. Most adaptive reuse projects include changing the components that affect daylight penetration, above all windows. In addition to their thermal properties, today's windows have a different performance in terms of both quantity and quality of light compared to original single glazed windows. Internal organization of a building has to take into account this change in daylight levels, and often additional strategies should be applied to increase the daylight performance of a space to satisfactory level for different than original use. The papers want to propose a daylight design strategy for evaluating and improving daylight distribution on some underused buildings: the Sicilian lighthouses. This building typology makes use of light as a tool: therefore, it was almost obvious to reflect on the use of light even in the hypothesis of refurbishment.

## 2 Methodology

In order to maximize daylight inside a building and improve the well-being of building occupants and optimize the design solution, specific characteristics of daylight were considered. To this aim, daylighting metrics are useful to predict the daylight availability within a building and assess the performance of a suitable fenestration solution. The investigation was carried out considering the daylighting metrics currently most in use: Useful Daylight Illuminance (UDI), Daylight Factor (DF), and "point-in-time" Illuminance (PL). UDI is a set of three indicators for every point in the space. These indicators show the percentage of time that a point is below a minimum threshold, between a useful minimum and maximum value. DF is the ratio between the internal illuminance level at a specific point to exterior horizontal illuminance, under a CIE (Commission Internationale d'Eclairage) overcast sky. PL calculations measure light levels at a specific date and time, under a specific sky condition. The simulations of the case study were conducted with Plugins DIVA-for-Rhino [6, 7] with the interface Radiance for annual simulation and illuminance computation. In addition, the Grasshopper extension for Rhinoceros was also used to create the model geometry and perform simulations to assess all parameters that could influence the daylight performance. Some strategies that increase daylight levels without having a strong impact on building's heritage character were explored. The simulations were performed for the two extreme conditions of summer and winter (typical summer day with clear sky and typical winter day with overcast sky). Simulations were conducted both for the present state of the lighthouse and the new design proposal and performed on 21 December and 21 June from 7.00 a.m. to 7.00 p.m. using climatic data of the reference standard year for Syracuse, Italy.

## 3 Some Undervalued Built Heritage: The Sicilian Lighthouses

Sicily, the largest of the Mediterranean islands, is a territory whose coasts are dotted with lighthouses: we count 43 which sprawl themselves over 1152 km of coastline [8].

The Sicilian lighthouses belong to 2 different typologies: block lighthouse and tower lighthouse. In the tower lighthouse all the facilities (regency and living quarters) are located inside the tower with a variable geometry depending on the size.

The block lighthouse is most popular typology along Sicilian coasts and its appearance is based on the relation between the main building and the tower; generally, the main building accommodates the regency and the keeper's quartets. In this typology, towers are attached to a building from which it is possible to access the entire complex. The tower can be designed and built in different positions: along the central line or along a side. This solution gives the architectural appearance to the light. The staircase built in the tower, that brings upstairs to the room where alarm and timing devices are located, is usually made up of stone elements. The keeper's quarters are often part of a two storey building that includes the tower lantern system. The most frequent typology wants the tower along the central line. The tower is so integrated in the building and can be reached by crossing the main entrance and passing through a vestibule. After that, from the ground floor, it is necessary to get the staircase upstairs to the lantern [8].

Usually, the essential parts in the architecture of a lighthouse are the tower, the lantern with the external gallery for its maintenance, the guard room, the fuel stores, the cistern and the accommodation of the lighthouse-keepers.

## 4 The Case Study: Capo Murro di Porco Lighthouse

The Capo Murro di Porco lighthouse stands at the end of the Maddalena Peninsula, a strip of land that defines the Southern limit of the port of Syracuse.

The choice of the promontory as a lookout point goes back a long way: in fact, in the report by Captain Tiburzio Spannocchi, who circumnavigated Sicily in 1578 to survey the system of existing towers on the coast, the need to build a tower there was mentioned (see Fig. 1). Capo Murro di Porco and its lighthouse are now the heart of the Plemmirio Marine Reserve, the most protected area of the reserve due to the presence of beautiful sea beds and sea caves (see Fig. 2).

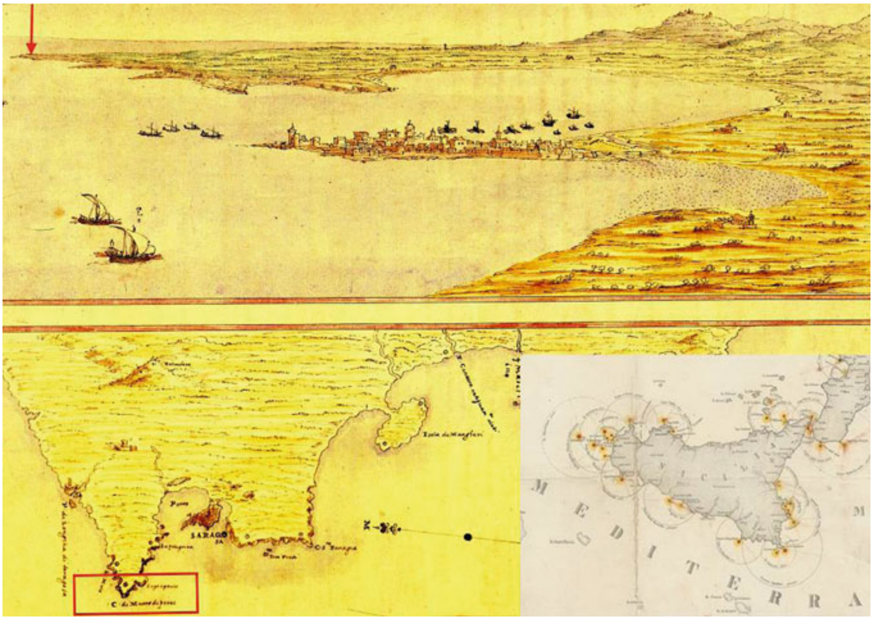

**Fig. 1** Captain Spannochi's view of Syracuse gulf—1578: in red box and red arrow the Murro di Porco Cape. On the right, a map of the Sicilian lighthouses—1889

**Fig. 2** Some views of the lighthouse and its environment

The lighthouse project dates back to 15 September 1857 and was signed by the engineer Nicolò Diliberto D'Anna [8]. The construction of the lighthouse was part of a wider project to improve the safety of the Sicilian coastline, commissioned by the Bourbon government, which between 1857 and 1859 provided for the construction and/or adaptation of 27 lighthouses, all designed by engineer Diliberto D'Anna and therefore characterised by the same typological and constructional features (see Fig. 1). The building has undergone many interventions over the years that have changed the layout of the original 1857 project [9]. In 1932, the tower was connected to the accommodation building by the creation of a covered corridor and therefore two openings were made in the perimeter wall for access to the corridor; the entrance was moved to the North-West elevation and two windows were opened on the same elevation.

The pitched roofs were demolished and replaced with flat roofs on hollow core slabs. The introduction of the incandescent oil vapour lamp and the subsequent construction of the adjacent fuel storehouse and technical room also date back to those years. In 1943, the lookout tower in front of the lighthouse was built, but today it has been completely razed to the ground by sea storms. In 1945, the old lantern was replaced with the current one, as evidenced by the inscription on one of the steps of the access staircase. A few years later, in 1957, the Navy began a series of works: the replacement of the external walls, the thickening of the tower walls and the final demolition of the corner blocks. The building was also entirely plastered. Around the 1970s, the internal layout of the flats was modified and toilets were added as an external superfetation to the main block (see Fig. 3). The electrification and later the complete automation of the lighthouse dates back to the last thirty years, so that the

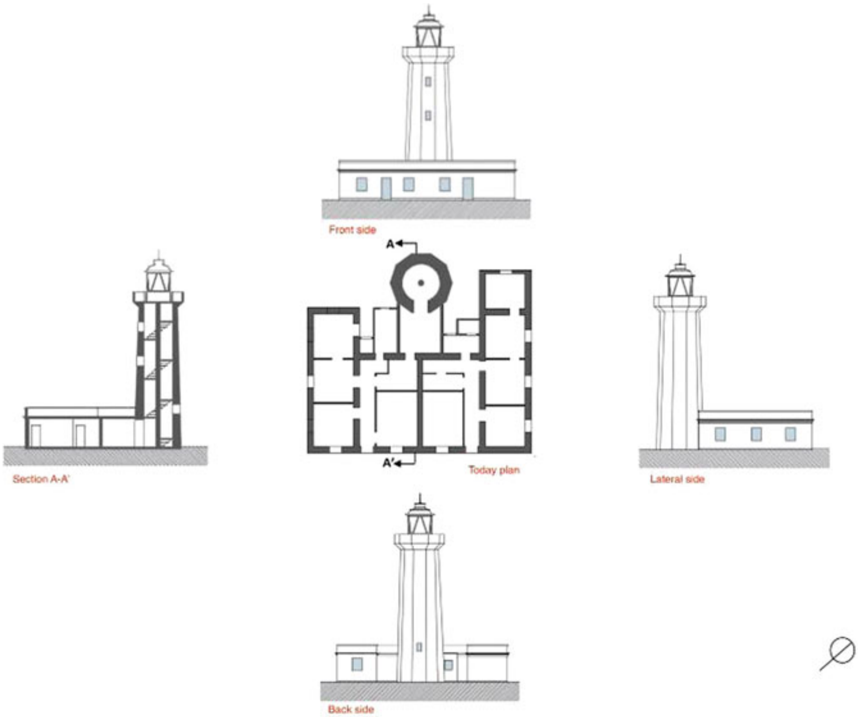


**Fig. 3** Geometrical survey of the Capo Murro di Porco Lighthouse

constant presence of the lighthouse keeper was no longer necessary. This explains the lighthouse's sad state of neglect, a fate similar to many other Sicilian lighthouses. In the 1950s there were three lighthouse keepers: two lived in the block and a third in the adjacent building [8, 10].

### 4.1 Construction Technology and Conservation

The present case study belongs to block lighthouse, as we said in Sect. 3. The external walls of the lighthouse are made of load-bearing masonry: limestone blocks with lime mortar. Some walls were replaced in the 1930s with brickwork. The tower is 20 m high and has a ten-sided polygonal base and is tapered at the top. The most ancient part of the tower core is in stone masonry, which was lined with bricks. The higher part of the tower is characterized by simple mouldings. Next to the tower, there is a single-storey building that housed the keeper's quarters. The roof of this building is a cement slab floor and is accessible directly from the tower. Before the lighthouse was connected to the water distribution system, the terraces served the function of collecting rainwater which was conveyed into a cistern located at the entrance and already visible in the original project. The frames around the windows are lime stone simple blocks.

The lighthouse and the surrounding buildings have been in a state of complete abandonment for years (see Fig. 2). Although a fence protects the lighthouse, the building has been vandalised several times: some of the windows are missing, the floors are unsafe, because the irons in the beams are badly oxidised. The exposure of the buildings to the action of the sea has accelerated the deterioration phenomena.

Although the lighthouse is not in good condition, the environmental value of the site is high. In 2015, the State Agency and the Ministry of Defence, with the proclaimed aim of redeveloping State property, launched a recovery and redevelopment operation involving dozens of Italian lighthouses. This operation has been one of the most contested and opposed by environmental associations in recent years, for some "too much creative" solutions that have been proposed.

The past few years have therefore seen a renewed interest in lighthouses. The project proposal presented here is part of this trend.

### 4.2 Daylighting Model

During the survey, it became clear that one of the most critical aspects was the interior lighting. In the redevelopment proposal, we placed particular emphasis on the role of daylighting, which was assessed using simulations with DIVA software. The role of light has become one of the cornerstones of the redevelopment proposal. In Fig. 4 is reported the 3D model built with the interface DIVA-for-Rhino (see Fig. 4). The

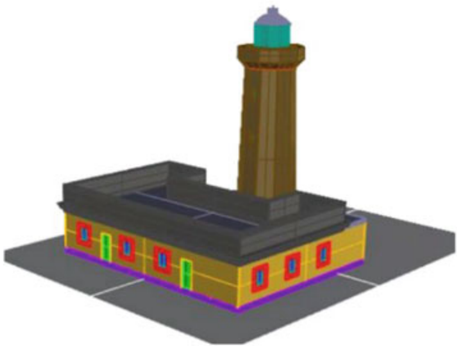

**Fig. 4** 3D model built with the interface DIVA-for-Rhino

3D model library was carried out taking into account all geometric and architectural characteristics of the building, rooms, furnishing, texture [6].

Different daylighting strategies were modelled and analysed using Grasshopper and DIVA [7]. In particular, it was created a number of design variants that differed from a base case by a single parameter, i.e. size of the skylight, optical proprieties of materials, inclination of reflective slatted panels, etc. Each case was analysed quickly for its light performance and the simulation results were analysed with the aim of deducing guidelines for daylight design [11–14].

## 5 The Refurbishment Intervention

The hypothesis of recovery included the demolition of some internal walls, in order to rationalise the original volumes. The planned function is that of a restaurant space with the necessary annexed services. The main room becomes the new restaurant, obtained by demolishing the back wall and joining the adjacent rooms. This solution was also suggested by the static condition of the floors, which required a revision of the horizontal closures, which will become the main feature of the new project (see Fig. 5).

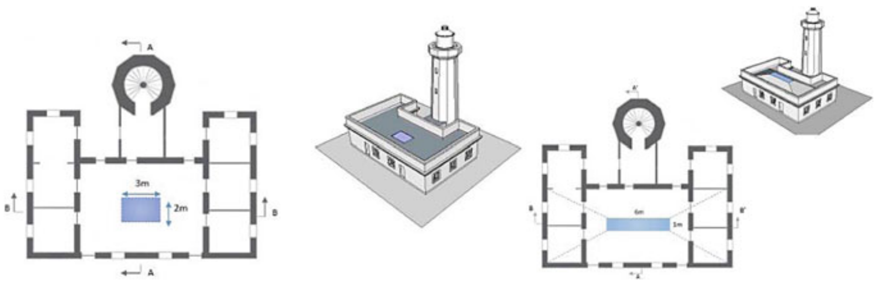


**Fig. 5** The new skylight: on the left the simple one; on the right the pavilion skylight

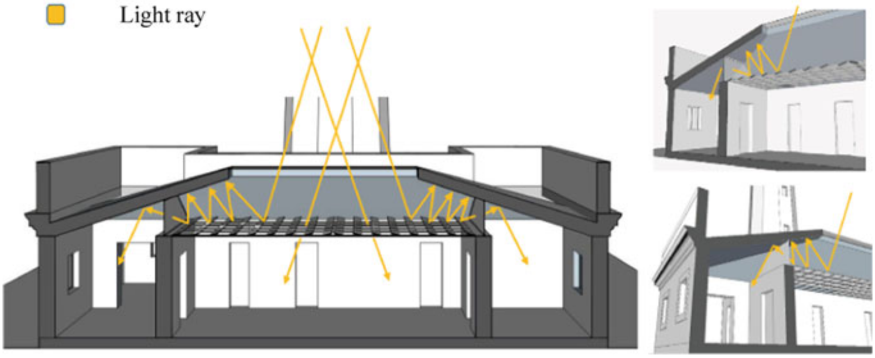


Fig. 6 The light ray simulation inside the restaurant atrium and adjacent rooms

A simple skylight ($3.00 \times 2.00$ m$^2$) doesn't allow a proper diffusion of the light in the atrium and even less in the adjacent rooms (see Fig. 5). So, the roofs of the central building will be replaced by a $6.00 \times 1.00$ m$^2$ skylight, placed in the centre of a pavilion extending across the whole building (see Fig. 6).

Consequently, underneath the skylight, in order to better diffuse natural light, a false ceiling made up of reflective slatted panels organised according to $0.50 \times 0.50$ m$^2$ meshes has been installed (see Fig. 6).

The light rays are carried to the adjacent rooms thanks to the inclinations of reflective slatted panels. The ceiling and walls were covered by particular reflective and diffusive material to redirect light coming from the reflective slatted panels and spreading it down through the atrium and adjacent rooms (see Fig. 6). The optimal inclination and the most favourable reflective values of elements materials to avoid annoying dazzling phenomena were calculated using Rhino-Grasshopper plugin [6, 14, 15].

The lighting analyses with the effective design solution of a skylight with reflective slatted panels (RSP) (see Fig. 7) highlight the improvement of all daylight parameters

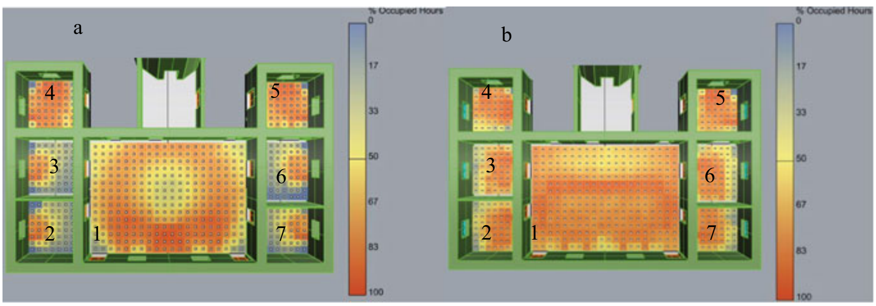


**Fig. 7** UDI maps with **a** with simple skylight (SS) and **b** with reflective slatted panels (RSP)

**Table 1** Comparison between the results with simple skylight (SS) and reflective slatted panels (RSP)

| | DF | | UDI | | PL (21 June) | |
|---|---|---|---|---|---|---|
| Rooms | SS (%) | RSP (%) | SS (%) | RSP (%) | SS (lux) | RSP (lux) |
| 1 | 6.46 | 4.68 | 62.62 | 74.6 | 5534.6 | 4035.06 |
| 2 | 1.31 | 2.61 | 35.55 | 64.25 | 241.11 | 402.93 |
| 3 | 1.32 | 2.55 | 37.14 | 64.25 | 241.85 | 393.53 |
| 4 | 2.86 | 2.81 | 72.73 | 70.14 | 477.41 | 490.44 |
| 5 | 2.88 | 2.95 | 71.47 | 70.57 | 481.61 | 488.42 |
| 6 | 1.25 | 2.54 | 34.29 | 63.6 | 246.67 | 400.41 |
| 7 | 1.49 | 2.57 | 40.59 | 63.88 | 268.69 | 413.73 |

(DF, UDI, PL), distribution in all adjacent rooms and comply with actual regulation (EN 17037) (see Table 1).

## 6 Conclusions

This paper presents a daylighting design approach that can be useful for studying a new lighting system that complying the architectural constraints and preserve the cultural value of Capo Murro di Porco lighthouse. The Maddalena peninsula, also, has great environmental value. The analysed territory has always been inhabited and its high cliffs have made it a privileged place for coastal control. The lighthouse, now abandoned, is in a deplorable state of decay. A call for tenders in 2015 suggested a more contemporary use for this building and its surroundings. Its use as a restaurant suggested that the restoration strategy should be geared towards greater attention to lighting aspects.

Simulations using DIVA software showed dark and uncomfortable rooms, leading us to choose a new top lighting system. The design concept stems from the idea of not modifying the external envelope, also in order to satisfy the existing constraints, by inserting a new box that regulates the solar inputs (see Fig. 8). The skylight is not perceptible from the outside because its height is contained in the original parapet. The insertion of the new skylight also suggested the demolition and replacement of the existing floors, which were also seriously damaged. The new pavilion roof will be supported on glulam beams anchored to the existing masonry. The reflective surfaces of the skylight will allow light to be diffused into adjacent rooms. The data obtained from the simulation showed a significant improvement in the conditions of visual comfort and therefore an improvement in the enjoyment of the new use inside the lighthouse. The daylighting proposed system guarantees the required illuminance levels and luminance uniformity for a great range of solar angles during winter and summer with significantly improved user visual comfort not only in the atrium but into adjacent rooms. Finally, the proposed method could be a guideline and inspiration

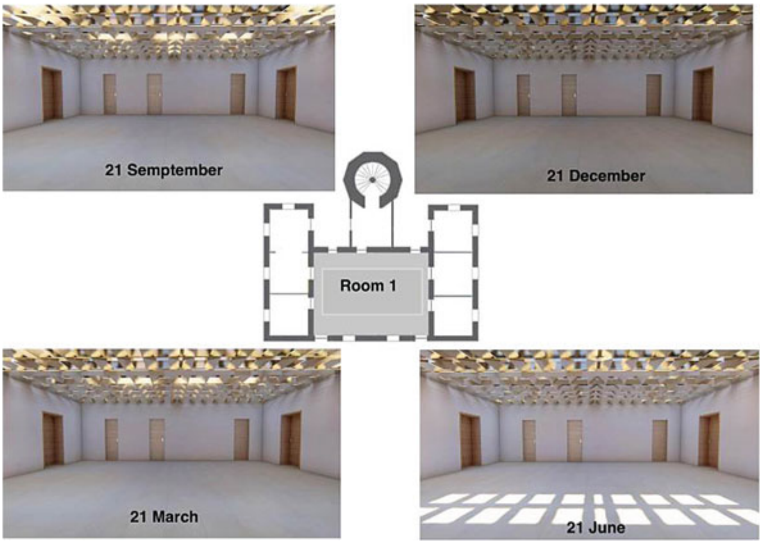


**Fig. 8** Daylight simulations in different period of the year

for building designers in which it is fundamental to both preserve cultural value of the architectural good and a guarantee visual comfort for the occupants.

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## References

1. Lo Faro, A., Evola, G., Salemi, A., Costanzo, V.: Ponti termici nell'edilizia storica in ambiente mediterraneo: valutazioni e proposte di intervento. In: Cascone, S., Margani, G., Sapienza, V. (eds.) Colloqui.AT.e 2020, pp. 471–487. Edicom editore, Gorizia (2020)
2. Nocera, F., Lo Faro, A., Costanzo, V., Raciti, C.: Daylight performance of classrooms in a Mediterranean school heritage building. Sustainability **10**, 3705 (2018)
3. Buda, A., de Place Hansen, E.J., Rieser, A., Giancola, E., Pracchi, V.N., Mauri, S., Marincioni, V., Gori, V., Fouseki, K., Polo López, C.S., et al.: Conservation-compatible retrofit solutions in historic buildings: an integrated approach. Sustainability **13**, 2927 (2021)
4. Marzouk, M., Eissa, A., El Sharkawy, M.: Influence of light redirecting control element on daylight performance: a case of Egyptian heritage palace skylight. J. Build. Eng. **31**, 101309 (2020)
5. Boubekri, M.: Daylighting, Architecture and Health. Architectural Press, Oxford (2008)
6. Rhinoceros (Version 5): https://www.rhino3d.com/features. Last accessed 2021/05/16
7. Diva Features: http://solemma.net/Diva.html. Last accessed 2021/05/16
8. Bartolonei, C., Amoruso, G.: Architecture of the Italian Lighthouse. Alinea Editore, Firenze (2009)
9. Ufficio Idrografico della Marina: Elenco dei fari e fanali sulle coste del Mar Mediterraneo, Mar Nero, Mare D'Azof e Mar Rosso. Hoepli, Napoli-Milano (1889)

10. Fatta, F.: Luci del Mediterraneo. I fari di Calabria e Sicilia. Disegni, rilievi e carte storiche. Rubbettino editori, Cosenza (2002)
11. Reinhart, C.F., Mardaljevic, J., Rogers, Z.: Dynamic daylight performance metrics for sustainable building design. Leukos **3**(1), 7–31 (2006)
12. Nabil, A., Mardaljevic, J.: Useful daylight illuminances: a replacement for daylight factors. Energy Build. **38**(7), 905–991 (2006)
13. Mardaljevic, J.: Climate-based daylighting metrics. In: LEEDv4, A Fragile Progress. Light. Res. Technol. **47**(4), 388 (2015)
14. Mardaljevic, J., Bermbilla E., Drosou N.: Real-world validation of climate-based daylight metrics: mission impossible? In: CIBSE Technical Symposium, Edinburgh, UK, 14–15 April, pp. 1–12 (2016)
15. Leung, T.C.Y., Rajagopalan, P., Fuller, R.: Performance of a daylight guiding system in an office building. Solar Energy **94**, 253–265 (2013)

# Urban Floods Management: The Integrated Approach of the City of Rome (Italy)

**Fabiana Cambiaso and Alessandra Valentinelli**

**Abstract** Urban flash floods represent one of the most challenging issue for city councils among climate risks: as they are expected to become more and more frequent in the changing climate local scenarios, flash floods are one of the most alarming issue for urban citizens and the quality of their lifestyles; moreover, as urban runoff is closely linked to urban land uses and related soil sealing levels, urban flash floods prevention policies deeply concern the local capacity to tackle with environmental integrated strategies, addressing the institutional capability to put them actually into practice. In this framework the integrated approach developed by the City of Rome, in Italy, shows a positive case of those tools whose horizontal replicability, environmentally oriented and scientifically sounded basis are needed both to face specific floods risks and to deal with the territorial dimension of climate adaptation's strategies.

## 1 Introduction

According to the *Atlas of the Human Planet 2017: Global Exposure to Natural Hazards* by the Joint Research Centre [1], the global exposure to natural disaster risks doubled between 1975 and 2015, mainly due to the urbanisation process and the growth of the urban population, representing the main risk exposure factors. The European Commission adopted in 2013 the *EU Climate Change Adaptation Strategy COM 2013/216*, in order to help countries planning their activities with due regard to resilience, to allocate specific funds and to foster all Member States national plans approval. Today seventeen European countries have adopted an Adaptation Plan, except for Italy where these tools and strategies are limited to the single and most virtuous municipalities.

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In 2015 the European Commission published the final report *Towards an EU Research and Innovation policy agenda for Nature-Based Solutions and Re-Naturing Cities* [2]; in the same year the EEA Report *Exploring Nature Based Solutions* [3] was released, then updated in 2021 by the new Report *Nature based solutions in Europe* [4]. These documents summarise the various study and innovation opportunities related to new design, construction and management practices using the natural component as a tool to support urban redevelopment processes. Therefore many cities are applying them in the context of local "Climate Plans", the framework programs with which they manage, contrast and adapt to the climate risks.

The NBS approach is connected to ideas such as Natural Systems Agriculture, Natural Solutions, Ecosystem-Based Approaches, Green/Blue Infrastructures (GBI) and Ecological Engineering [5]. In particular, GBIs are an evolved application of NBS, which transcends the only focus on mitigation to propose a theoretical and applied reflection on how to proactively obtain ecosystem services by enhancing the shared benefits deriving from positive socio-ecological interactions. In Italy, the sectors where green and blue infrastructures have had some success are those of waste water and flood management (i.e. phytoremediation, sustainable urban drainage, hydraulic interventions). The GBIs are associated with the sewage system to create filter ecosystems; namely adding surface flow wetlands that improve the quality of wastewater by interposing an additional safety system overcoming plant malfunctions and improving their environmental suitability [6, 7].

The purpose of this work is to demonstrate how the Administration of Roma Capitale is implementing this new approach in its urban planning, through a pilot application example. The paper is structured in subsections aimed at framing the "state of the art" (paragraph 2 and paragraph 3) in which the work is contextualised; two presentation subsections of the "Methodology and Case Study" adopted and proposed (paragraph 4 and paragraph 5); a section illustrating the "Results" achieved (paragraph 6) together with the "Conclusions".

## 2 State of Art

### *2.1 The Territorial Dimension of Environmental Management*

Urban flash floods prevention should be considered a core indicator of institutional capacity to integrate urban management with environmental concerns [8]: a "proxy" measuring flooded areas, in order to assess the effectiveness of strategies and actions aiming at reduce the urban vulnerability to climate risks.

The hydrologic behaviour of urban areas depends more on impervious surfaces extent than on seasonal rainfall quantities [9]. An urban area exceeding critical sealed levels generates itself the amount of flooding runoff: where soil is 100% paved, there, the 100% of the rainfall is expected to heighten the score of the flooding surface runoff. To act on the water balance where the pick intensity for most climate induced rainfall events appears to heavy for the drainage urban network, pervious soils and trees canopy are needed.

Portland [10], the pioneer city experimenting WSUDs, was induced to fund new "green" runoff management solutions by the huge costs estimated to upgrade the local "grey" drainage system. As citizens decided rather to invest in better qualified living conditions, Portland has since then grown up an increasing capacity of environmental integrated management, linking the tiles of its green network mosaic to urban planning. By now, many best cases suggest the broader opportunities to enhance, in the wider framework of urban local plans, ecological networks enlargement and rural landscape's valuable topics safeguard, together with traffic calming strategies, urban heat islands and greenhouse gasses mitigation, in the framework of what we call here "the territorial dimension of environmental integrated management".

Still the so called "Climate Plans" are most voluntary strategical assets, lacking of any compulsory mandate to be implemented, integrated planning is both a necessity and an opportunity. To apply this task, cities are asked to better coordinate sectoral plans each others and in a new multidisciplinary approach, aiming at consistent strategies among environmental goals and sectoral solutions, urban functions and land use. Cities have thus to reinforce technical knowledges and capacities in order to project reversible solutions with low, or better zero, environmental impacts, and to practice the monitoring tools needed to improve their own actions. Finally, to strengthen this path, teaming skills are required aiming at consolidate interdisciplinary working staffs able to tune integrated approaches, to cooperate among institutional bodies and to provide strategical planning.

## 2.2 *The Wider Challenge of Urban Climate Adaptation*

Beside managing runoff in impervious urban areas, there is the wider challenge of climate changing risks adaptation cities are called to face with. Recent data and future trends show an increasing complexity in weather local events related with changing climate global conditions: rainfalls more and more often associated with downburst and hail storms, thunderstorms of high intensity alternated with longer drought periods, critical heat conditions affecting wind turbulences and regimes or stressing vegetative cycles and the related ecosystems services performances; all these events are expected to survive longer to mitigation policies outcomes, since carbon neutrality won't fix the end of changing climate effects [11].

Such scenario of climate complexity shall be tackled in the framework of urban multidimensional and multifunctional adaptation strategies; as the topic of urban runoff prevention has shown, no cutting runoff goals can be reached without decreasing or converting paved areas to pervious functions. The basic argument to get over sectoral solutions in order to gather nature based solutions together with urban land use management is based on the dynamic assets and balance ecosystems services are able to provide, counteracting climate changing risk events by supporting the broader resilience of urban areas. Ecological networks are thus essential to supply full ecosystems services in urban contexts: to face both flash floods and heat island which alternately hit urban cores, as well as providing day by day services like groundwater filtering, evapotranspiration moderating temperatures picks, wind circulation, atmospheric pollution abatement, greenhouse gases control. The richer are biodiversity levels, density and extent, the greater ecosystems services are supplied. Managing urban land use to adapt, adaptive cities shall be greener places to live [12].

Since the European Commission adopted in 2013 the *Strategy on adaptation to climate change* (COM 2013/216), many European cities have managed their own plans aiming at integrate climate adaptation with land use planning, in a long terms perspective: the *Climate Adaptation Plan of Copenhagen* [13], the *Rotterdam Climate Proof* [14], the *Waterproof of 34 Amsterdam* [15], the London *Managing risks* [16], Barcelona [17, 18] or Paris [19] are only the front line of a widespread local engagement against climate change.

## 3 Methodology and Case Study

### *3.1 A New Hybrid Topography of Water Public Spaces*

All these plans transform the challenge of climate risk into an opportunity, engaging activities, architectures and landscapes to promote new urban transformations: by combining protection and adaptation, they provide a huge variety of local solutions forming new urban green networks: small basins which reuse dismissed stations or underground parking lots to prevent the water from being conveyed directly into the sewer, new water squares, rain gardens and stormwater parks serving as additional basins, water reserves or treatment plants, coastal fringes and riverside managed as widespread buffer-spaces for the floods control and the reconstitution of wet riparian environments [20].

At the micro scale, the process of hybridisation, producing new adaptive infrastructures, shapes new topographies, whose convexities and concavities regulate water flows and offer renewed spatial organisation transforming contemporary landscapes. Based on accurate three-dimensional, parametric, topological models, scrupulous hydraulic and hydrodynamic simulation models, these smart micro-topographies all convey, slow down and disperse flows so that landscapes can self-regulate. The soil design integrates the infrastructure into the city landscape through incisions, cuts and cracks in the ground, overlapping and layering, compressions, extrusions and lifting, grafting, morphing, bending and ripples according to a multipurpose infrastructural model.

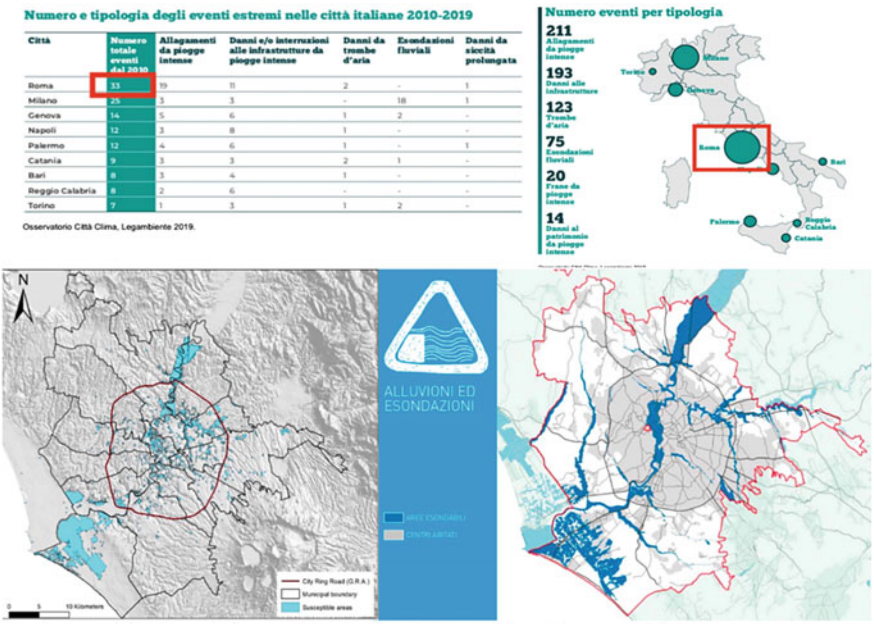
As promenades, urban parks and new public spaces, these hybrid hydraulic infrastructures that draw strength from the presence of water, rather than oppose to it, catch the opportunity of an alternative urban model in order to revitalise the existing city, by promoting scenarios in which waters and inhabited areas coexist peacefully.

### 3.2 *The Case of Rome: Monitoring Phenomena, Tuning Strategies*

Italy lays at the core of an "hot spot" of climate change, in one of the most sensitive areas where climate scientists have long warned about the increase in unprecedented cyclones (the so-called "medicane", mediterranean tropical-like cyclone), along with the increase in temperature and their relationships with sea temperature, winds and precipitation regimes [21]. Data collected by the *Milano Duomo* Meteorological Observatory Foundation show an already significant and alarming difference in average temperatures between 2001–2018 and 1971–2000 (Fig. 1). The example of Rome is resounding; from 2010 to October 2019, 33 events occurred, of which over half, namely 19, were floods following intense rainstorms [22].

In Rome, three different flooding processes are observed. River floods of the natural hydrographic basin, catching the main Tiber and Aniene, their tributaries and minor courses, affect mainly the floodplains both in the urban and in the rural contexts; at the basin scale, the main cause is to be seen in the increasing meteoric inflows drained by the network, but locally flooding effects can be fostered by the rising levels of the aquifer.

Secondly, floods of the rural reclamation canals network affect the alluvial areas at the mouth of the Tiber in the Municipality 10 of Rome. Here the raising water



Numero e tipologia degli eventi estremi nelle città italiane 2010-2019

| Città | Numero totale eventi dal 2010 | Allagamenti da piogge intense | Danni e/o interruzioni alle infrastrutture da piogge intense | Danni da trombe d'aria | Esondazioni fluviali | Danni da siccità prolungata |
|---|---|---|---|---|---|---|
| Roma | 33 | 19 | 11 | 2 | - | 1 |
| Milano | 25 | 3 | 3 | - | 18 | 1 |
| Genova | 14 | 5 | 6 | 1 | 2 | - |
| Napoli | 12 | 3 | 8 | 1 | - | - |
| Palermo | 12 | 4 | 6 | 1 | - | 1 |
| Catania | 9 | 3 | 3 | 2 | 1 | - |
| Bari | 8 | 3 | 4 | 1 | - | - |
| Reggio Calabria | 8 | 2 | 6 | - | - | - |
| Torino | 7 | 1 | 3 | 1 | 2 | - |

Osservatorio Città Clima, Legambiente 2019.



**Fig. 1** Meteorological events in Italian cities 2010–2019 and in Rome; (from the left) flash floods, public services crisis, thunderstorms, floods, droughts inflows are linked to the increasing extent of impervious urban surfaces which, in the last 30 years, have largely affected some sub-basins (Acque Alte, Medio and Basse) located both on the left (Infernetto, Stagno di Levante, Bagnoletto) and on the right bank of the Tiber (Piana del Sole); still the local vulnerability is fostered by predisposing factors to ground water flooding, such as the presence of sub-outcropping aquifers and the morphologies proximal to the zero altitude above sea level, characteristic of lagoon and delta areas.

Finally, the pluvial flooding caused by the inadequacy and undersizing of the sewage systems are increasingly associated with the changing rainfall regimes that not only convey higher flows than those of the project, but above all reduce corrivation times, causing more frequent crises of the water pumping systems expected to drain local former lowlands and swamps now urbanised (Fosso di Pratolungo, Corcolle, Prima Porta). To tune the appropriate strategies, the City of Rome has catalogued all the data processed within the urban planning sectoral tools, such as rainfall, observed floods, groundwater subsidence, land use, hydrographic, main collectors, drains and road network. The implementable dataset so obtained, has then been shared in technical working groups with the various Departments of the City (Urban Planning, Development and Infrastructure, Environment, Civil Protection), the Tiber Basin Authority and the Italian Environment Agency, which now allows to manage the most vulnerable areas of the Roman territory, divided into Municipalities (Fig. 2) [23].


**Fig. 2** Gis system. Emergency mapping of Rome's Administration (©Roma Capitale, Development and Infrastructure Department)

## 4 Results and Discussion: Rome's Green Factors of a Different Urban Metabolism

Roma Capitale joined the Covenant of Mayors in November 2017 and completed the drafting of its Action Plan for Sustainable Energy and Climate (SECAP / PAESC) by March 2021. Rome's PAESC sets among the adaptation priorities, the transition from a "grey" to a "green/blue" infrastructural system and the integration of water with the natural components of the urban metabolism aiming at gain more pervious soils (Fig. 3). The adopted approach foresees that in an area subject to flooding, before proceeding with a sewage disposal work, all the possibilities for absorbing water naturally into the ground have to be evaluated. Expected benefits are countless: from greater environmental sustainability to water conservation for compatible agricultural and green uses, from the rediscovery of water as an opportunity for recreation, up to lower construction and maintenance costs [24, 25].

How to achieve the transition from grey to green/blue, and get a climateproof urban planning, integrating mitigation and adaptation within planning tools and public works manuals, was one of the main questions of the working groups. The answer came from the *Green factors* of Berlin [26]: the application to new built or redevelopment areas of urban planning coefficients which guarantee the finding and the most effective distribution of a given quantity of surfaces improving the urban quality living conditions, the microclimate, the healthiness of the air, the vital spaces for urban fauna and flora, the environmental functions of the soils and the sustainable management of water cycles.

On the basis of the in-depth analyses of international examples, "Type Sheets" of infrastructural strategies have been developed in order to support the pilot actions, with the technical data and the costs to be incurred (Fig. 4); the "Summary Table" has therefore identified their replicability and the degree of applicability into the different Municipalities of Rome. Finally, by assessing the most vulnerable areas, the Municipality 10 has been identified for the first pilot project aiming at monitor and test the efficacy of natural lamination ponds (Fig. 5).

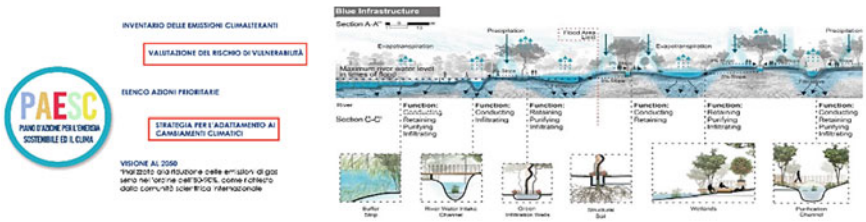



**Fig. 3** The PAESC/SECAP of Rome and main adaptation actions to mitigate the increased flood vulnerability by green/blue infrastructure (©Roma Capitale)


**Fig. 4** "Type sheets" of green/blue infrastructures describing technologies, design and construction aspects (flooring, thicknesses, materials …); costs, maintenance, regulations and replicability in different urban contexts, integration with other SUDS; design references (©Roma Capitale, Infrastructure Department)

## 5 Conclusions

The systemic adoption of NBS can make it possible to integrate the transformation and management project of the environmental, landscape and socio-economic components within an organic vision aiming at increasing the urban resilience. The experiments on the architectural scale, with regard to both the built and the open spaces, show how the green and blue components can really allow to reach new levels of performance that are difficult to achieve with traditional solutions and techniques. Their use can be declined in many contexts, and most in those requiring the activation of regeneration processes. In addition to the so-called brown fields, they can be applied to qualify public spaces, residual areas in densely urbanised contexts, the blind fronts of buildings, unfinished and/or abandoned building and infrastructural works, up to naturally improving the performance of the existing heritage. The results of this work have been applied to mitigate the increased flood vulnerability, promoting a framework where the specific solutions can be replicated in similar cases as reported in the Summary Table (Fig. 6). Currently the pilot project is the basis for the preparation of the "Permeability Plan" the Municipality of Rome is establishing within the European Life project Soil4life [27].

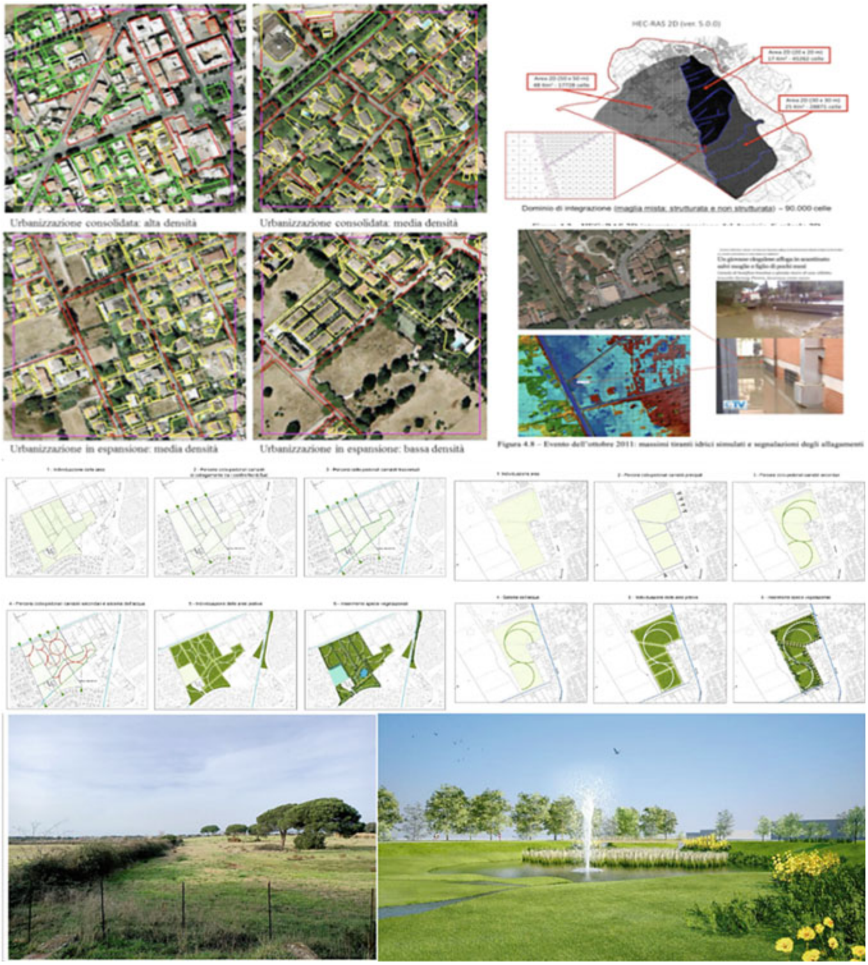



**Fig. 5** Pilot project for Rome's Municipality 10: assessment of urbanised levels, geological and hydraulic characteristics, identifying flood prone areas by their return times and simulating dynamically meteoric events and urban flooding phenomena; details of the natural flood basin's project (©Roma Capitale, Development and Infrastructure Department)

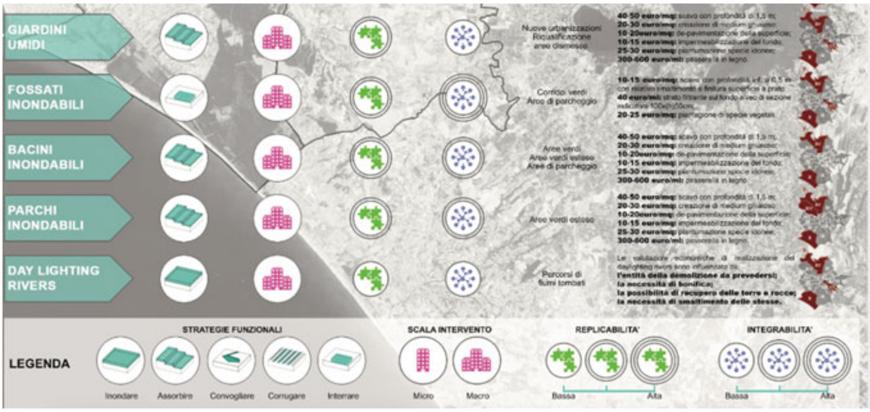



**Fig. 6** "Summary table" for Rome's Municipalities replicability. The table shows (from the left to the right): the identification of infrastructures like "wet gardens", "flood ditches", "flood basins", "floodable parks", "day lighting rivers"; the water functions the infrastructure can offer, like controlled "flood", "absorb", "convey", "corrugate", "bury"; the urban scale of the intervention "micro scale", "macro scale"; the degree of replicability "low", "medium", "high"; the degree of integration with other infrastructures "low", "medium" and "high"; the main costs. On the right, the hypothesis of application in the different Municipalities of Rome (©Roma Capitale, Development and Infrastructure Department)

## References

1. Joint Research Centre: Atlas of the Human Planet (2017)
2. European Commission: Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-naturing Cities. EU Publications Office (2015)
3. EEA: Exploring Nature-Based Solutions, The Role of Green Infrastructure in Mitigating the Impacts of Weather and Climate Change Related Natural Hazards. EU Publications Office (2015)
4. EEA: Nature-Based Solutions, Policy, Knowledge and Practice for Climate Change Adaptation. Report n.1 (2021)
5. Eggermont, H., et al.: Nature-Based Solutions, New Influence for Environmental Management and Research in Europe, GAIA 24/4, pp. 243–248 (2015)
6. ISPRA: Focus Acque e Ambiente urbano, IX Rapporto Ambiente Urbano (2013)
7. ISPRA: Focus Cambiamenti climatici, Ambiente, Città circolari, XV Rapporto (2020)
8. Berchum, E.C., Mobley, W., Jonkman, S.N., Timmermans, J.S., Kwakkel, J.H., Brody, S.D.: Evaluation of flood risk reduction strategies through combinations of interventions. J. Flood Risk Manag. **12**(S2), 1–17 (2019). https://doi.org/10.1111/jfr3.12506
9. Mignot, E., Li, X., Dewals, B.: Experimental modelling of urban flooding: a review. J. Hydrol. **568**, 334–342 (2018). http://doi.org/10.1016/j.jhydrol.2018.11.001
10. The City of Portland-Oregon: Stormwater Solutions Handbook (2013)
11. EEA: Climate Change Adaptation and Risk Reduction. Report n.15 (2017)
12. EEA: State of the Nature in the EU. Report n.10 (2020)
13. City of Copenhagen: Climate Adaptation Plan (2011)
14. City of Rotterdam: Climate Change Adaptation Strategy "Rotterdam Climate Proof" (2013)
15. Municipality of Amsterdam: Waterproof of 34 Amsterdam, De Urbanisten (2011)
16. Greater London Authority: Managing Risks and Increasing Resilience, the Climate Change Adaptation Strategy (2011)

17. Ayuntament de Barcelona: Plan Clima 2018–2030 (2018)
18. Ayuntament de Barcelona: Plan del Verde y de la Biodiversidad (2020)
19. Ville de Paris: Plan Climat 2030–2050 (2017)
20. EEA: Urban Adaptation to Climate Change in Europe. Report n.12 (2020)
21. EEA: The European Environment State and Outlook. SOER (2020)
22. Legambiente - Osservatorio CittàClima: Rapporto 2019: Il clima e già cambiato [pdf]. https://www.legambiente.it/wp-content/uploads/2019/11/Il-Clima-è-già-cambiato-2019.pdf. Last accessed 2021/05/10
23. Roma Capitale: Strategia di Resilienza di Roma Capitale, Deliberazione di Giunta Capitolina n. 116, 23 ottobre 2018
24. Roma Capitale: Definizione di un Piano di Sviluppo resiliente e sostenibile per Roma Capitale, Memoria di Giunta Capitolina n. 48, 28 agosto 2020
25. Roma Capitale: Ricognizione e prime linee di indirizzo in materia di gestione geologico-idraulica del territorio e di mitigazione del rischio di dissesto idrogeologico, Delibera di Giunta Capitolina n. 160, 7–8 agosto 2020
26. ADAPT-The European Climate Adaptation Platform Climate: Green and Blue Space Adaptation for Urban Areas and Eco Towns, GRaBS and Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin (2016)
27. Roma Capitale-Dipartimento di Protezione Civile: Piano di Protezione Civile - Edizione 2021, Deliberazione di Giunta Capitolina n. 1/2021, 8 gennaio 2021

# A Proposed Method to Pre-qualify a Wireless Monitoring and Control System for Outdoor Lighting to Reduce Energy Use, Light Pollution, and Carbon Emissions

**U. Thurairajah, J. R. Littlewood, and G. Karani**

**Abstract** STUDENT PAPER. This paper discusses a novel method to Pre-qualify a Wireless Monitoring and Control System (WMACS) for Outdoor Lighting to Save Energy, Reduce Light pollution, Carbon Emissions, and Global Warming in the Built Environment. The WMACS can be used for various outdoor lighting applications. The first author is undertaking the proposed work as part of his Ph.D. at Cardiff Metropolitan University, UK. The proposed method is to pre-qualify a wireless network control system for the light-emitting diode (LED) lighting system to save energy, reduce light pollution and promote safety, health, wellbeing, and quality of life in the built environment. There is currently (2021) no standard method to pre-qualify a wireless control system for various applications in an outdoor built environment. This novel method is not replicated but original and can be considered an innovative method to pre-qualify a wireless control system for outdoor LED lighting systems. The paper discusses the selection method of a wireless control system for LED lighting in consideration of energy and cost savings, reduce carbon emission and global warming, sustainability, and the residents' quality of life, and mitigating outdoor light pollution, including trespass lighting. This paper will be helpful for academics, researchers, scientists, engineers, consultants, architects, lighting designers, contractors, developers, financial institutions, and government offices funding and managing upgrades to outdoor lighting applications in the urban environment.

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## 1 Introduction

Outdoor lighting provides the safety for nighttime operations of vehicular and pedestrian traffic on pathways, roadways, parking, and other infrastructure in rural and urban conurbations. Street lighting consumes approximately 40% of the total energy in cities [1]. The High-Intensity Discharge (HID) luminaires are the most dominant technologies used for outdoor lighting applications [1]. The LED is emerging as the most energy-efficient technology with various color temperatures available for outdoor lighting applications. Compared to its HID counterpart, LED can be dimmed and controlled without impacting its lifespan [2].

A lighting system can be made more efficient using the current state-of-the-art technologies, including centrally controlled and monitored energy-efficient and demand-sensitive lighting systems. A careful selection of lighting control systems is necessary to implement this technology fully and efficiently. This paper aims to select appropriate WMACS to save energy and reduce carbon emissions in the outdoor built environment. National Electrical Manufacturers Association (NEMA)—7 Pin twist-lock photo-controls mounted on top of the luminaire can communicate with a wireless system [3]. The scope of this paper is to focus on the current (2021) and future LED wireless control technology used in the outdoor built environment, with a particular focus on Canada, which is the location of the first author's professional and academic practice as an Electrical and Lighting Engineer for WSP [4]. To evaluate the wireless control system's pre-qualification for LED luminaires, six wireless manufacturers based in Canada participated in a study documented in this paper. The wireless evaluation criteria, potential outputs, and the next steps in the evaluation process will be discussed.

## 2 Background and Literature Review

Electricity production is needed to power artificial lighting systems, which, when none renewable energy is used, can add significant carbon dioxide ($CO_2$) emissions to the environment [5]. The costs of electrical power and the environmental factors encourage government municipalities to implement solutions to reduce energy use and maintenance costs, $CO_2$ emissions, and light pollution [5, 6]. Energy efficiency can be addressed by integrating LED luminaires with a Smart Server for lighting control and traffic sensors for sensing traffic movements and adjusting lighting levels accordingly. Each LED luminaire must have a built-in controller that allows the fixture to transmit its status information to the Smart Server [4]. The advantages of LED technologies include their low energy consumption, longer lifetime, good quality and control, wider input voltage range, dimming control, safety, instantaneous response time, easy installation, directionality, and reduction in waste disposal [7].

The newly installed LED outdoor lighting system received a high user satisfaction level at various locations throughout Canada. Many existing LED outdoor lighting installations are now observing 50% or more in energy savings, with failure rates below 1% adding to the significant maintenance savings [8]. The existing street lighting units can be made more efficient using current state-of-the-art technologies and careful engineering in the lighting control systems' design and operation. The LED retrofit projects, including the control system, are expected to lead to high cost and energy savings and reduce $CO_2$ emissions [9].

### *2.1 Lighting Technologies*

Since the 1960s, the common NEMA twist-lock photo control had 3-pin to turn a luminaire ON and OFF, typically in sync with dusk-to-dawn sunlight phases [10, 11]. This style was the de-facto standard in North America and several countries around the world [10]. ANSI C136.41 specifies the dimming 7-pin receptacle is becoming standard for all fixtures with a photocell [12]. It provides electrical and mechanical interconnection between a photocell and luminaire and the wireless node installed in each luminaire [13]. If the photocell has 7-pin, it can talk to the luminaire's driver through either an analog (0–10 V) or digital (DALI) signal [14]. A New 7-Pin Photocell Design Provides Smart Control and ready for customers with maximum flexibility for outdoor lighting [11].

The LED driver which has a self-contained power supply can control the current and voltage supplied to an LED luminaire, and responds to changing needs to provide a constant quantity of power to the LEDs as their electrical properties change with temperature [15]. The driver power outputs are matched to the electrical characteristics of the LED(s). LED drivers can offer pulse width modulation (PWM) dimming circuits or may have more than one channel for separate control of different LEDs [16]. The LEDs are maintained by a constant power provided by the LED driver. The electrical properties change as the LED's temperature changes. The LED luminaire temperature may increase and unstable without the proper driver, causing poor performance or failure [17].

The WMACS is an intelligent network, and it incorporates communication between various system inputs and outputs with the use of central computing devices [18]. WMACS delivers the required light level as per the standard to a location where and when it is most needed. It maximizes the lighting system's energy savings by automatically adjusting the light intensity of luminaries while maintaining user satisfaction [19]. The outdoor lighting control systems are referenced in the Canadian industry as Smart Controls [20]. This technology may include high-efficiency luminaires and automated controls that adjust based on outdoor occupancy and the outdoor daylight availability conditions.

The principal advantage of a lighting control system versus stand-alone lighting controls or manual switching is the ability to control a separate light source or groups of lights from an individual user interface device [20]. The wireless control system's goal is to limit and save energy [20]. Some field studies from others indicate that the new energy-efficient LEDs can more than 40% power [21]. The combination of new, efficient LED luminaires and dimming controls can yield from 31 to 60% savings in energy use, carbon and cost saving [22]. The extended luminaire life can be achieved through dimming and switching off lights when not required [23]. The wireless control networks provide essential maintenance and repair cost savings and improved energy and environmental efficiency. The ideal condition for a wireless control system is when retrofitting existing luminaires to LED's or installing new LED luminaires, which combined with a WMACS, delivers the greatest return on investment (ROI) [19, 20].

A control device has the ability to control multiple light sources allows complex lighting scenes and provide the required lighting to satisfy human needs. The LED technology and WMACS provide effective lighting to suppress melatonin and avoid sky glow, glare, and trespass lighting. It keeps the drivers and pedestrian active during the night time and sleep well when they get home safely.

## 3 Methodology

Many criteria should be considered when determining the lighting control systems for urban conurbations. Therefore, questionnaires were developed in 2015 to choose the appropriate manufacturers from the essential function of WMACS and the selection of product(s) through the decision-making process. The essential functions questionnaires were sent by email to the various manufacturers to select appropriate manufacturers for their review and response. Initially, six manufacturers participated in the process, and later two manufacturers did not respond to the questionnaire. Therefore, four manufacturers were selected in the process in consultation with the client. The selection of appropriate WMACS was challenging. Thus, the selection process was simplified by breaking it down into smaller categories. First, the essential function is to select suitable manufactures. Second, the decision-making process is to choose the right product(s)—finally, the rolling out of the WMACS. The following Table 1 indicates that the decision-making processes.

**Table 1** The decision making process

| No | Items | Description |
|---|---|---|
| i | Essential functions | The essential functions of the WMACS |
| ii | Decision making | The selection process of WMACS |
| iii | Rolling out | The crucial steps in rolling out a WMACS |

### 3.1 Essential Functions

The WMACS needs to support each luminaire to deliver the required control functionality successfully. Therefore, before the evaluation of each WMACS, the compulsory performance requirements need to be satisfied. The following Table 2 highlights the essential functions required of the WMACS.

### 3.2 Decision Making

The author went through the decision-making process to select the appropriate WMACS and discovered that each product provides similar operating platforms. Many WMACS have specific capabilities that are not the best option for this project's requirements. The following Table 3 highlight and address the necessary selection process of WMACS.

### 3.3 Rolling Out

The development of an installation or project rollout plan is necessary for a successful WMACS. The following Table 4 provides the crucial steps for the official rollout of a WMACS.

These are general guidelines that, when followed, can help to assure success in planning and installing a wireless control system. There is a variety of available options and considerations for any wireless control system project. It is important to have a plan in place to guide the team as well as during and after the system installation. An efficient WMACS will provide important energy and maintenance savings when properly installed and maintained.

## 4 Process and Results

Four manufacturers participated in the selection process of Supply and Installation of WMACS for 10,000 Decorative LED luminaires in the Canadian cities of Kitchener, Waterloo, and Cambridge between the years 2015 and 2016. All the manufacturers provided their responses to the questionnaire and eagerly participated in the evaluation process. As part of the evaluation, the author requested the cost estimates for the WMACS from each manufacture. Names of the manufacturers and the corresponding results are not included. Table 5 gives a summary of all the evaluation criteria and the relative weightings below.

**Table 2** The essential functions required of the WMACS

| No | Requirement | Description |
|---|---|---|
| a | Monitor and control | Do WMACS remotely monitor and control any luminaire with seven (7) pin photocell to ensure proper functioning and also to measure the energy usage of each luminaire? |
| b | Capacity | How many luminaires can you control? How do you configure, monitor and manage the luminaires remotely from a central web-based management application? |
| c | Data privacy | Does your system include encryption capabilities for data privacy and network protection? |
| d | Wireless communication | Does your system has the capacity of self-healing (If one of the luminaires is not functioning, the signal will spontaneously route through another functioning appliance)? |
| e | Ability to work with any luminaire | Does your system controller work with any luminaire or manufacturer (The controllers automatically integrate into the network and are easier to install)? |
| f | Advanced scheduling | Does your system can specify multiple (ON/OFF/Dimming) schedule controls, individual plans and grouping options for higher energy savings? |
| g | Fault-tolerant operation | Can the luminaire obey to their schedules even if communications are interrupted (The wireless controls must always turn the luminaires on even when the network is not communicating)? |
| h | Failure of a component | Does the system has a backup component or procedure to avoid direct loss of service if a component fails (The fault tolerance may be given with software, or already embedded in hardware or some combination)? |
| i | Luminaire health monitoring | Does the luminaire health monitoring and fault notification capabilities includes the automatic detection and reporting of fault conditions, or malfunctioning equipment (Luminaire burnouts, over/under voltage, driver failure, irregular power consumption, low power factor, communication failures, other issues)? |
| j | Utility grade metering | Does the utility grade metering provide analysis and reports of energy usage by luminaire or group of luminaires? Do the nodes have the capability of energy monitoring? |

(continued)

**Table 2** (continued)

| No | Requirement | Description |
|---|---|---|
| k | Asset reporting | Does your system be able to maintain an electronic file of lighting equipment and pinpoint the status of the luminaires for "one-trip repair" and similar report requirements on all the lighting equipment within the system? |
| l | The range of RF signal | What is the range of RF signal for your wireless system? What is the required frequency used to communicate between nodes? |
| m | Standard for LC communication | What is the standard for lighting control (LC) communication or diagnostics for your wireless system? |
| n | WMACS and RL | Does your WMACS support any roadway lighting (RL) luminaire? |
| o | Ability to control by smartphones | Can your system talk to smartphones through the web or mobile access? |
| p | GPS location | Can your system provide GPS location of each luminaire? |

**Table 3** The necessary selection process of WMACS

| No | Items | Description |
|---|---|---|
| a | Topology | What wireless topology does the system use (mesh, star, point to point)? |
| b | Dimming | Does it support dimming (0–10 V, PWM, DALI)? |
| c | Controller location | Does your system include encryption capabilities for data privacy and network protection? |
| d | Gateway | Is there a gateway device and how does it function/connect? |
| e | Power metering | How accurate is the power metering and has it been certified? |
| f | Software | Is management software provided? Is there a software support plan, including updates? |
| g | Internet | Is it web-based; are there any other critical capabilities? |
| h | Hosting party | How is it hosted (by customer or vendor)? |
| i | Installation tools | Are any special installation tools required (for the commission, GPS)? |
| j | Training and support | What are training and support services the potential vendor provides? |
| k | Trial | Can you conduct a limited test of the system for a period? |
| l | Largest installation | What is the largest installation the products are used in (to qualify capabilities)? |
| m | ROI | Can the return on investment (ROI) for the solution be calculated? |
| n | Warranty | How many years you can provide a warranty for your wireless system? |
| o | References | Installation and operation of system and references |

**Table 4** The crucial steps in rolling out a WMACS

| No | Items | Description |
|---|---|---|
| i | Outline plan | Outline all assumptions; schedules, installation, resource allocations, and others |
| ii | Meetings and evaluations | Conduct regular project status meetings. Evaluate and consider the best format for a particular project needs |
| iii | Documents | Note action items which will provide historical documentation of the discussions, assumptions, and commitments |
| iv | Utilize software | Utilize a project management software tool when there is collaboration from multiple resources |

**Table 5** The evaluation criteria and relative weightings

| No | Evaluation criteria of WMACS | Yes/No | Weight | Cost |
|---|---|---|---|---|
| 1 | Control node (7 pin) for 10,000 luminaires | Y/N | Required | N/A |
| 2 | Warrantee period = 10 years | Y/N | Required | N/A |
| 3 | Training staff (Both field and office) | Y/N | Required | N/A |
| 4 | Gateway | Y/N | 25%/0 | $ |
| 5a | Handheld equipment (Crews are required to enter GPS coordinates)[a] | Y/N | 25%/0 | $ |
| 5b | On-board GPS chips (Crews are not required)[a] | Y/N | 20%/0 | $ |
| 6a | Manufacturer managed central management system[b] (Access fee/yr.) | Y/N | 20%/0 | $ |
| 6b | Customer-owned central management system[b] (No fee/yr.) | Y/N | 25%/0 | $ |
| 7a | Data charge per gateway[c] (Cellular/yr.) | Y/N | 20%/0 | $ |
| 7b | Data charge per gateway[c] (Ethernet) | Y/N | 25%/0 | $ |
| 8 | Motion sensor-informed dimming (Bonus) | Y/N | 10%/0 | $ |
| 9 | Utility grade metering (Bonus) | Y/N | 10%/0 | $ |
| | Total | | 100% | $ |

*Note* $ = Canadian Dollar. One option will be selected[a,b,c]

The author recommends a non-GPS version of photocells with nodes and attributes located with the handheld device during installation. It takes less than one minute per node to assign a GPS location per luminaire, and there is no added labor cost to this method. A City-owned enterprise system eliminates fees and gives the city complete control over outdoor lighting operational data and integrated into the city servers. A standard warranty (typically shown that 10-year warranty costs are to the customers' disadvantage). Gateways are located with Ethernet connections where possible to eliminate cell carrier costs. This would ensure the most cost-effective version of a system.

## 5 Discussion

The luminaire and WMACS manufacturer(s) must work together with the Cities to develop the perfect, functional luminaire with an excellent light output. WMACS provide additional benefits and savings. The existing flat-rate tariff cost varies for street lighting usage in most cities in Canada. The local utilities will not provide actual power consumption since the monthly rate per light based on the wattage of the street light, and actual power consumption through dimming will not be used. Therefore, the Cites can achieve cost savings by moving at a metered rate using the WMACS.

Most of the WMACS technology specification indicates that it will provide accurate energy metering per light. The specific usage information allows municipalities to pay for what it uses. The methodology allows us to find the pros and cons of WMACS in the market.

It is possible to further evaluate the strengths and weaknesses of the WMACS products if a pilot is installed. From this experience, the Cities can make the future procurement decision for a city-wide installation of LED luminaires and WMACS. The pilot installation should provide the required technical feasibility for larger-scale implementation in the Cities. The pilot will aim to check the overall operation of WMACS and ascertain from the participants and their views on commands to individual luminaires or groups of luminaires and set up and execute schedules and functions. The pilot will also evaluate how well the WMACS diagnoses asset errors and failures, which can be highly beneficial to maintenance staff. In addition to that, learning WMACS requires training from the manufacturer, and it can take at least three (3) months of experience before a new user is comfortable with some of the deeper functions and operations. Each WMACS has a distinctly different Control system, and the implementation, usefulness, and effectiveness of each system's diagnostic procedures and maintenance dashboards may be different and take time to understand.

## 6 Conclusions

There are two different approaches to adaptive lighting: preset dimming schedules and motion sensor-informed dimming. Preset dimming schedules were simple to apply and resulted in verifiable energy savings. The light levels should be raised or lowered, proven to be technically feasible using motion sensors. Still, there are possible difficulties in demonstrating this functionality, combined with the limited added benefit beyond scheduled dimming. The research does not support relying on motion sensor adaptive dimming since it is not yet ready for full-scale deployment.

The ability to use WMACS to dim the lights offers a significant benefit, particularly to residential neighborhoods that appreciate maintaining the required light levels based on standard roadway classification. Furthermore, the general acceptance of scheduled dimming may be an efficient and well-received method for capturing energy savings. An efficient WMACS will enhance lighting service while reducing operational costs. The system can control remotely and monitor assets and strengthen system maintenance practices. The adaptive lighting through scheduled dimming proved to be a promising energy-saving opportunity. Cities are looking to invest in advanced controls infrastructure with many products to choose from in a still-maturing marketplace. Care must be taken based on experience and performance, system design, and WMACS functionality, to ensure that the installed system will provide the full range of benefits that have proven to be achievable.

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## References

1. Mohamed, S.: Smart street lighting control and monitoring system for electrical power saving by using VANET. Int. J. Commun. Netw. Syst. Sci. **06**, 351–360 (2013). http://doi.org/10.4236/ijcns.2013.68038. Cited at: https://www.scirp.org/journal/PaperInformation.aspx?PaperID=35223. Accessed 24th Mar 2021 (available)
2. Brock, K., et al.: Light the way for smart cities: lessons from Philips lighting (2019). Cited at: https://www.sciencedirect.com/science/article/pii/S0040162517317043. Accessed 24th Mar 2021 (available)
3. Schreder Expert in Lightability: Wireless outdoor luminaire controller (2019). Cited at: https://www.schreder.com/sites/default/files/2021-02/LUCO_P7_CM_Datasheet_EN.pdf. Accessed 24th Mar 2021 (available)
4. Thurairajah, U.: LED Street Lighting Luminaire Wireless Control System Prequalification of Approved Equipment. The Cites of Kitchener, Waterloo and Cambridge, Ontario. Unpublished Project, WSP Canada Group (2016)
5. Cho, S.K., et al.: Street lighting control based on LonWorks power line communication. In: 2008 I.E. International Symposium on Power Line Communications and Its Applications. (2008). Cited at: https://ieeexplore.ieee.org/document/4510461. Accessed 24th Mar 2021 (available)
6. Li-jun, Q., et al.: Intelligent streetlight energy-saving system based on LonWorks power line communication technology. In: 2011 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT) (2011). Cited at: https://ieeexplore.ieee.org/document/5993976. Accessed 24th Mar 2021 (available)
7. Slocum, A.: A technology assessment of light emitting diode (LED) solid-state lighting for general illumination (2005). Cited at: https://www.epa.gov/sites/production/files/2014-12/documents/technology_assessment_of_light_emitting_diode.pdf. Accessed 24th Mar 2021 (available)
8. Light servers Canada: The realized results of LED streetlights: seizing the opportunity (2017). Cited at: https://saveonenergy.ca/-/media/Files/SaveOnEnergy/Industry/LightSaversLEDResults2017.ashx. Accessed 24th Mar 2021 (available)
9. University of Toronto: Low carbon action plan 2019–2024 (2019). Cited at: https://www.toronto.ca/legdocs/mmis/2020/ec/bgrd/backgroundfile-141837.pdf. Accessed 24th Mar 2021 (available)
10. Poplawski, M.: Emerging technology primer: networked outdoor lighting control systems (2014). Cited at: https://www.energy.gov/sites/prod/files/2015/09/f26/ssl_outdoor-lighting-control-tech-primer_0.pdf. Accessed 24th Mar 2021 (available)

11. LED Lighting Expert: 3 Pin vs 5 Pin vs 7 pin photocell receptacles—NEMA street light photocell standards (2021). Cited at: https://www.ledlightexpert.com/3-pin-vs-5-pin-vs-7-pin-photocell-receptacles--NEMA-street-light-photocell-standards_b_123.html. Accessed 24th Mar 2021 (available)
12. Palmer, M., et al.: Smart lighting for smart cities (2021). Cited at: https://www.sciencedirect.com/science/article/pii/B9780128168165000231?via%3Dihub. Accessed 24th Mar 2021 (available)
13. Bellido-Outeiriño, F., et al.: Streetlight control system based on wireless communication over DALI protocol. Cited at: https://www.mdpi.com/1424-8220/16/5/597. Accessed 24th Mar 2021 (available)
14. Denver Public Works: Street lighting design guidelines and details (2019). Cited at: https://www.denvergov.org/files/assets/public/doti/documents/standards/pwes-012.2-street_lighting_design_guidelines.pdf. Accessed 24th Mar 2021 (available).
15. Lighting Manufacturer: LED driver (LED power supply): What is it and how it works? (2021). Cited at: https://www.manufacturer.lighting/info/208/. Accessed 24th Mar 2021 (available)
16. Attial, H., et al.: Pulse width modulation based decentralized street LED light dimming system (2017). Cited at: https://core.ac.uk/reader/192463230. Accessed 24th Mar 2021 (available)
17. Farahat, A., et al.: Energy efficiency considerations for LED-based lighting of multipurpose outdoor environments (2014). Cited at: https://ieeexplore.ieee.org/document/7151785. Accessed 24th Mar 2021 (available)
18. Pilar Elejoste, P., et al.: An easy to deploy street light control system based on wireless communication and LED technology (2013). Cited at: https://www.mdpi.com/1424-8220/13/5/6492. Accessed 24th Mar 2021 (available)
19. Michele Magno, M., et al.: A low cost, highly scalable wireless sensor network solution to achieve smart LED light control for green buildings (2015). Cited at: https://ieeexplore.ieee.org/document/6994782. Accessed 24th Mar 2021 (available)
20. Canadian Urban Institute: Adaptive control for roadway and parking lighting (2015). Cited at: https://canurb.org/publications/adaptive-controls-for-roadway-and-parking-lighting/. Accessed 24th Mar 2021 (available)
21. Djuretic, A., et al.: Actual energy savings when replacing high-pressure sodium with LED luminaires in street lighting (2018). Cited at: https://www.sciencedirect.com/science/article/pii/S0360544218310235. Accessed 24th Mar 2021 (available)
22. Yoomak, S., et al.: Comparative study of lighting quality and power quality for LED and HPS luminaires in a roadway lighting system (2018). Cited at: https://www.sciencedirect.com/science/article/pii/S0378778817303717. Accessed 24th Mar 2021 (available)
23. Lau, S., et al.: A traffic-aware street lighting scheme for smart cities using autonomous networked sensors (2014). Cited at: https://www.sciencedirect.com/science/article/abs/pii/S0045790615002153?via%3Dihub. Accessed 24th Mar 2021 (available)

# Open-Source Integrated Mapping of Urban Form and Solar Radiation for Environmental Design

**Michele Morganti, Matteo Clementi, and Alessandro Rogora**

**Abstract** This paper investigates the possibility of using open-source data and GIS tool for the integrated mapping of urban form indicators and solar radiation in different urban textures. Two typical urban textures within the Metropolitan city of Milan have been selected as a case study in order to develop and test the novel method. The main goal is to associate significant data on buildings geometry and solar radiation to control environmental performance and renewable potential of urban areas and to promote evidence-based urban regeneration initiatives or self-sufficiency scenarios. The integration of open data in GIS platform, on the one side, allows to provide an easy-to-use tool for investigating urban solar performance (intended for specialists and public companies), on the other side offers a visual tool (intended for a wider audience of architects and planners).

## 1 Introduction

Solar availability is a key variable for the sustainability of the urban environment. On one hand, building's solar gains account for a significant part of the energy balance during both winter and summer and, in light of climate change, affect urban climate performances and comfort, such as urban heat islands. On the other hand, the potential for harvesting solar energy in the urban context is directly connected to the potential for renewable energy systems to enhance energy efficiency at urban scale. The effect of urban form on solar performance has been widely investigated with different approaches and purpose: urban archetypes vs real urban forms [1–3].

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Some of them are based on open-source GIS software [4, 5]. However, these studies require specialist knowledge to be applied by practitioners and public institutions.

This paper investigates the possibility of using open maps database and open GIS for integrated mapping of urban geometry solar radiation in different urban textures. The main goal is to associate significant data on urban geometry—using widespread urban metrics (UM) and associated indicators (UI)—and solar radiation with the census block (the smallest geographic unit containing public domain data at the highest resolution in most countries). In this way, it would be possible to define regulations, incentives and evidence-based design scenarios by identifying portions of the urban fabric characterized by similar factors.

Constraint for such elaborations is to use free data and to produce easy-to-use browsable thematic maps, in such a way as to be easily transferable to public administrations and designers (without the need of a specialist knowledge in the field of solar analysis) and to facilitate the transition from design scenarios to real urban renovation policies and actions. The identification of different factors through GIS would make it possible to apply appropriate design solutions to portions of the urban fabric with similar characteristics.

## 2 Method and Tools

The workflow of the study has been shown in Fig. 1. According to available geo-referred data, physical models of the urban textures have been developed with a level of detail LoD 1 [6]. Based on the GIS modelling environment, we make use of data at different scale and resolution levels, related to the urban and building components and to population, land use and economic activities, as provided by the Italian statistical dataset (associated to census blocks and buildings) [7]. Using this dataset, on the one side the urban form has been characterized through spatial metrics and seven associated indicators (Fig. 2); on the other side, solar irradiation has been analyzed using open spaces and roofs parameters. It has been widely demonstrated that urban form can be represented by urban metrics [8, 9].

Among the existing urban metrics, here we investigate the reliability in terms of solar availability of the most diffused urban form indicators in planning practice and regulations. Metrics and indicators definitions are shown in Fig. 2. Solar mapping techniques using GIS require the elaboration of digital elevation models (DEM) [5]. In this study DEM has been developed from open data in shapefile format available to public authorities in the Metropolitan City of Milan, using software QGIS 3.4.8.[1] The model has been processed at a resolution of 1 pixel on 0.5 m. Afterwards, the solar radiation mapping is carried using the open-source software GRASS GIS 7.0.2,[2] in order to calculate yearly and monthly clear day average (June and December) of direct and diffuse irradiation on an horizontal plane. The numerical values adopted

[1] https://qgis.org/.

[2] https://grass.osgeo.org/.

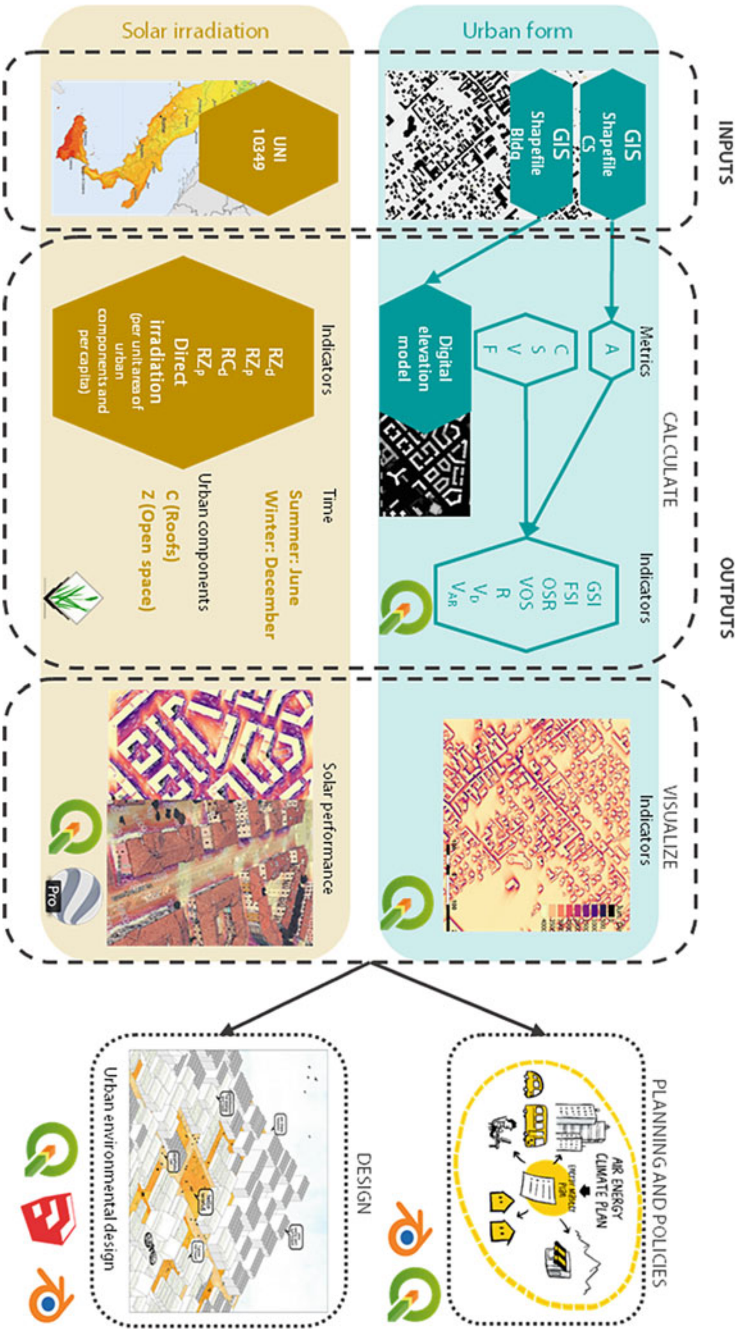


**Fig. 1** Research workflow

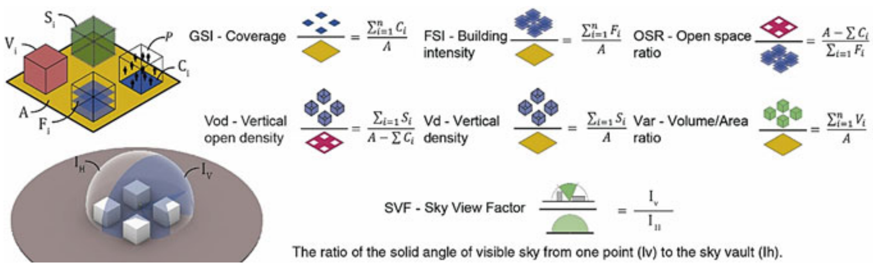


**Fig. 2** Definitions of urban form indicators and associated metrics, based on urban geometry characteristics: A, land area; Ci, footprint; Fi, floor area; Si, Building façade surface; Vi, Building volume; P, population; Iv, solid angle of visible sky from one point; Ih, solid angle of sky vault

to create representative maps of the average monthly solar irradiation refer to UNI 10349, which publishes average climatic conditions in the Italian context [10].

This work takes the European compact city of the XX Century as reference. Two urban textures of the Metropolitan city of Milan (Italy) have been selected as a case study: a portion of the Municipality of Rescaldina and the Corvetto neighbourhood in the southern periphery of Milan—lat. 45° 27′ (Fig. 3). The cases represent two widespread urban layouts and an effective testbed for the novel design research method. Rescaldina is an example of suburban historical town, developed mainly

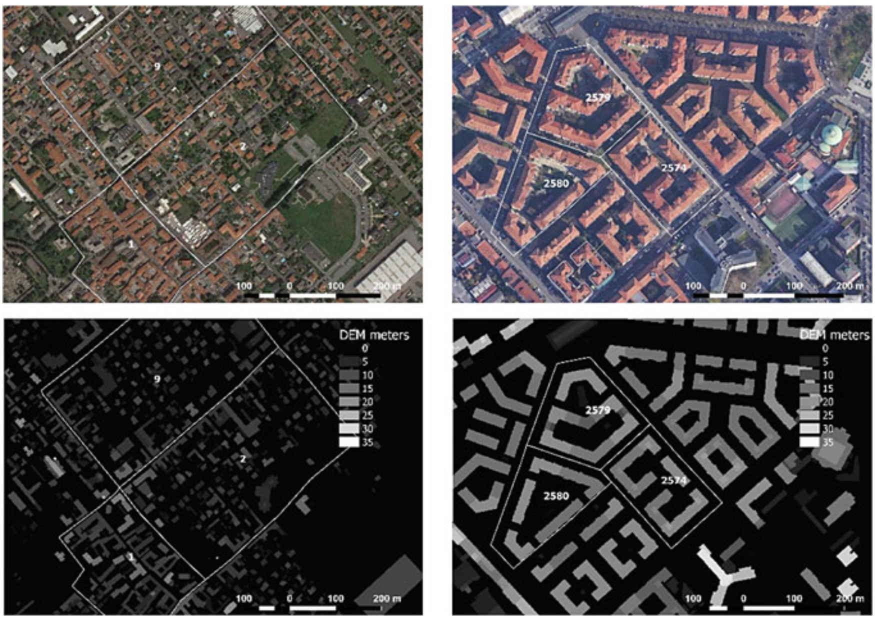


**Fig. 3** Aerial views and digital elevation model of case study urban areas: Rescaldina—left (R-n); Corvetto—right (C-n)

during XVI and XVII centuries, nowadays at the edge of the Metropolitan city of Milan. The urban texture is characterized by low-rise and low compactness with high availability of open spaces. Corvetto is a typical example of 1920s public housing intervention, based on low-mid compactness and mid-rise courtyard blocks. Results have been translated into maps based on GIS and implemented in Google Earth® in order to offer policymakers and practitioners an easy-to-use visualization tool for planning and policies based on environmental design (Fig. 6).

## 3 Results and Discussion

The purpose of this section is twofold. On the one side, to analyze and discuss the proposed method; on the other side, to investigate reliability in integrating urban form analysis and solar performance through practical application on case studies. By using GIS platform, data implementation concerning urban form and solar access can be easily integrated with all other geographical datasets. For this reason, control and analysis of built environment characteristics correlated with census blocks is useful and reliable in the case of evidence-based design, regulations, and policies. In Table 1 and Fig. 4 metrics and indicators selected to describe urban form are calculated on different census blocks. Qualitative characteristics of urban geometries are translated into quantitative values in order to highlight differences among cases. This process, permit investigating urban geometries at island and neighbourhood scale: differences and similarities emerge between Rescaldina and Corvetto (by considering the three

**Table 1** Metrics and indicators of urban form in selected census blocks (R-n = Rescaldina; C-n = Corvetto). See also Fig. 2

| Census blocks | Code | R-1 | R-2 | R-9 | C-2574 | C-2579 | C-2580 |
|---|---|---|---|---|---|---|---|
| | P (inhab) | 746 | 603 | 328 | 364 | 324 | 220 |
| Urban metrics | A ($m^2$) | 55′178 | 123′761 | 122′911 | 8′494 | 9′799 | 8′708 |
| | C ($m^2$) | 21′030 | 28′855 | 29′944 | 3′107 | 3′623 | 2′807 |
| | F ($m^2$) | 57′949 | 62′616 | 61′677 | 17′900 | 20′959 | 16′278 |
| | S ($m^2$) | 41′674 | 52′745 | 49′047 | 11′697 | 12′534 | 11′044 |
| | V ($m^3$) | 171′556 | 186′942 | 179′078 | 53′686 | 62′864 | 48′824 |
| | Z (m) | 34′152 | 94′906 | 94′608 | 5′391 | 6′175 | 5′900 |
| Urban form indicators | GSI | 0.38 | 0.23 | 0.24 | 0.37 | 0.37 | 0.32 |
| | FSI | 1.05 | 0.51 | 0.50 | 2.11 | 2.14 | 1.87 |
| | OSR | 0.59 | 1.52 | 1.51 | 0.30 | 0.29 | 0.36 |
| | VOd | 1.22 | 0.56 | 0.53 | 2.17 | 2.03 | 1.87 |
| | Vd | 0.76 | 0.43 | 0.40 | 1.38 | 1.28 | 1.27 |
| | VAR (m) | 3.11 | 1.51 | 1.46 | 6.32 | 6.42 | 5.61 |
| | SVF | 0.465 | 0.659 | 0.652 | 0.322 | 0.324 | 0.363 |

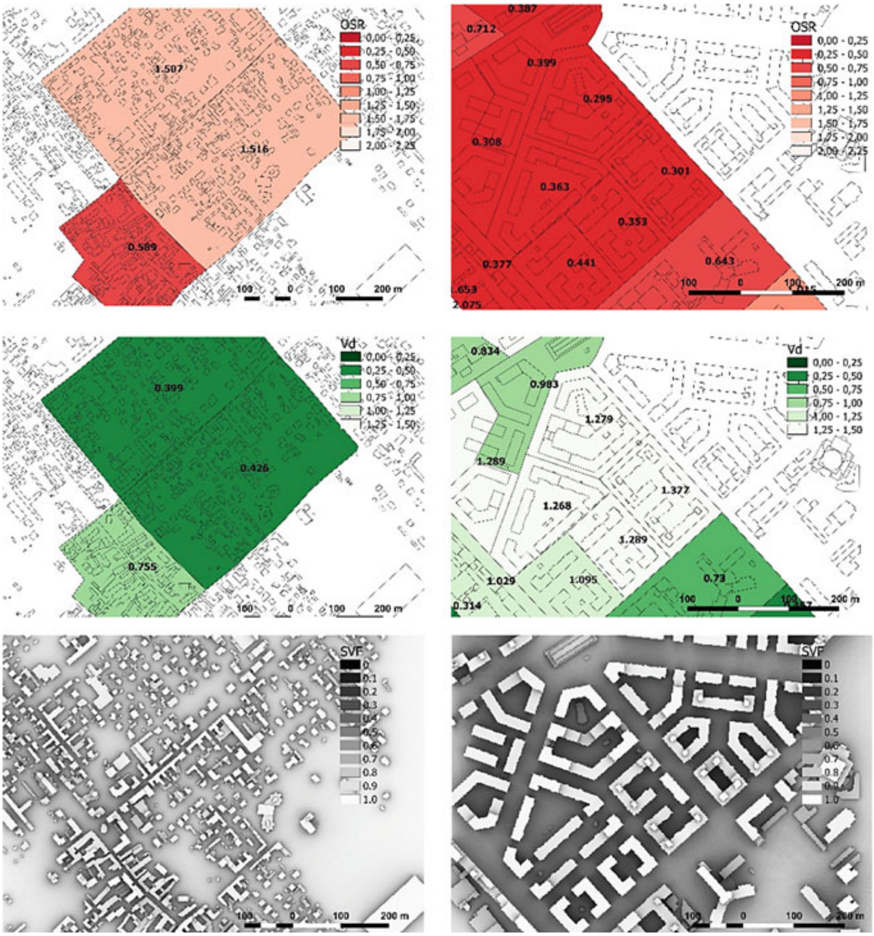


**Fig. 4** Urban form indicators for Rescaldina (left) and Corvetto (right): top, open space ratio—OSR; center, vertical density—Vd; bottom, sky view factor—SVF

census blocks) and among census blocks within the neighbourhoods: cases R2 and R9 have very similar geometries, compared to R1, as well as cases C-2574 and C-2579 compared to C-2580. Level of compactness and density for case studies, as well as insights on qualitative characteristics of the fabrics can be red via urban form indicators, especially if used in a multi-parametric approach, as in this work. In addition, data processing based on *volume units*[3] and *census blocks* with shapefile maps permits to develop extensive studies, even to the entire city boundaries, and to easily control the amount of data with a visual tool. An example of this for case studies can be seen in Fig. 3.

[3] With this definition here we refer to the "Unità Volumetrica" that is the primary shape of a building. This indicates an approximation of building massing delimited by plan surfaces (façades and roof).

**Table 2** Monthly means of direct solar irradiation in selected census blocks normalized by roofs, open spaces and inhabitants

| Census block | Metrics | | R-1 | R-2 | R-9 | C-2574 | C-2579 | C-2580 |
|---|---|---|---|---|---|---|---|---|
| | P | Inhab | 746 | 603 | 328 | 364 | 324 | 220 |
| June | Z | $RZ_d$[a] | 2′653 | 3′249 | 3′253 | 2′003 | 2′118 | 2′266 |
| | | $RZ_P$[b] | 121′454 | 511′360 | 938′295 | 29′664 | 40′369 | 60′774 |
| | C | $RC_d$[a] | 3′710 | 3′757 | 3′765 | 3′683 | 3′682 | 3′812 |
| | | $RC_P$[b] | 104′585 | 179′772 | 343′707 | 31′416 | 41′165 | 48′870 |
| December | Z | $RZ_d$[a] | 86 | 203 | 185 | 48 | 22 | 42 |
| | | $RZ_P$[b] | 3′937 | 31′950 | 53′361 | 711 | 419 | 1′126 |
| | C | $RC_d$[a] | 302 | 321 | 322 | 310 | 335 | 354 |
| | | $RC_P$[b] | 8′513 | 15′360 | 9′395 | 2′644 | 3′745 | 4′538 |

[a] Direct irradiation (Wh day$^{-1}$ m$^{-2}$); [b] Per capita irradiation (Wh day$^{-1}$ pers$^{-1}$)

Regarding solar irradiation analysis, the digital environment selected for the study allows for reducing process timing. By means of DEM mapping it is possible to investigate and control interactions between solar access in urban spaces and UI.

Results for solar irradiation is shown in Table 2 and Fig. 5. Units selected for describing the results are associated to open spaces (Z), roofs ($C_i$) and inhabitants ($P_i$) of the census blocks. This, firstly, make possible investigating—respectively—outdoor comfort, climate change adaptation strategies; secondly, allows to assess buildings solar energy potential, based on available surface and residing population within the neighborhood; thirdly, by use of per capita solar irradiation make possible to estimate available open areas (especially outskirt of cities and suburbs) and associated local distribution of renewable potential and self-sufficiency scenarios. The mapping of solar radiation per capita over open spaces gives the possibility of verifying the availability of renewable energy to power charging stations for electric mobility, or other service activities for the community aimed at achieving energy self-sufficiency. Moreover, it is possible to take planning and environmental design decisions with an evidence-based approach. As case studies are limited in number, some general considerations on expected tendencies for similar urban textures can be drawn. Considering building roofs, the proposed method provides a fast and reliable tool for estimating solar availability in urban areas and associated solar potential. Due to similar characteristics of the cases, urban form does not affect solar potential of roofs, both in December and June. Contrarywise, the effect is clearly described considering open spaces: the more the urban density, the less the solar irradiation received. Concerning diffuse solar irradiation, sky view factor of open spaces has been used as indicator to investigate solar irradiation variation among cases: the indicator can be effectively applied in a multi-parametric description of solar performance in the case of open spaces (Z).

Outputs of the modelling have been processed to provide two open access visualization tools, useful for several design and urban policy purposes. Urban form and solar irradiation analyses are translated into falsecolor maps implemented in

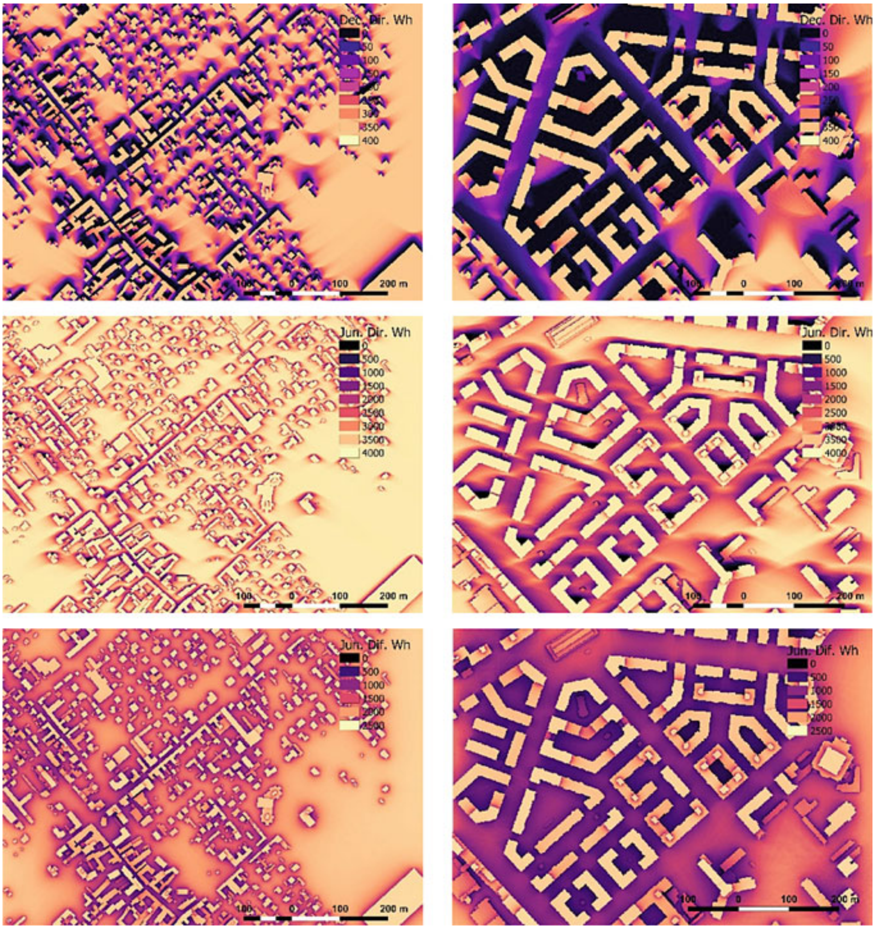


**Fig. 5** Solar maps for Rescaldina (left) and Corvetto (right): top, mean direct irradiation—December; center, mean direct irradiation—June; bottom, mean diffuse irradiation—June

GIS platforms (Fig. 5) and superimposed in Google Earth® (Fig. 6). The former is for development purposes and require technical skills to implement urban design scenarios, regulations and policies; the latter turns to a wider public and is for consultations of analyses and environmental regulations by architects and planners. The use of a widespread mapping tool allows for opens to a non specialistic public, enhancing environmental awareness of urban transformation in design actors and engaging communities and citizens.


**Fig. 6** Browsing the map using Google Earth®

## 4 Conclusions

This study aims at correlating urban and building geometry with solar availability in existing urban textures by means of open-source integrated mapping. Two urban fabrics located in the Metropolitan area of Milan have been selected as testbed for the proposed method. The results suggest that similar approaches, can be applied to control environmental performance and renewable potential of urban areas and promote evidence-based urban regeneration initiatives and self-sufficiency scenarios. Moreover, this may lead to develop urban regulations and policies, to support environmental design and to enhance environmental awareness in architects, urban planners, practitioners and communities.

In order to conduct comparative solar analyses of roofs to apply the proposed method to wider portion of urban texture it is advisable; otherwise, open space solar performance and urban comfort analyses can be conducted on every scale. In future development, to analyse larger urban areas with the support of open-source data and GIS platform, to compare the estimated solar availability with LIDAR satellite data would be helpful for evaluate the analyses' reliability, taking into account also the effect of vegetation and trees. Finally, to control the effect of design choices and evaluate the solar performance of different regeneration scenarios, the method can be easily integrated within open-source parametric digital tools.

## References

1. Li, D., Liu, G., Liao, S.: Solar potential in urban residential buildings. Sol. Energy **111**, 225–235 (2015). https://doi.org/10.1016/j.solener.2014.10.045
2. Mohajeri, N., Upadhyay, G., Gudmundsson, A., et al.: Effects of urban compactness on solar energy potential. Renew. Energy **93**, 469–482 (2016). https://doi.org/10.1016/j.renene.2016.02.053
3. Chatzipoulka, C., Compagnon, R., Nikolopoulou, M.: Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study. Sol. Energy **138**, 53–66 (2016). https://doi.org/10.1016/j.solener.2016.09.005
4. Hofierka, J., Zlocha, M.: A new 3-D solar radiation model for 3-D city models. Trans. GIS **16**, 681–690 (2012). https://doi.org/10.1111/j.1467-9671.2012.01337.x
5. Hofierka, J., Suri, M.: The solar radiation model for open-source GIS: implementation and applications. In: Ciolli, M., Zatelli, P. (eds.) Proceedings of the Open-source GIS-GRASS Users Conference. University of Trento, Trento, Italy (2002)
6. Consortium OG: OGC City Geography Markup Language (CityGML) Encoding Standard (2012)
7. ISTAT: Basi territoriali e variabili censuarie, censimento della popolazione e delle abitazioni 2011 (2012). https://www.istat.it/it/archivio/104317. Accessed 23 Apr 2021
8. Sanaieian, H.: Review of the impact of urban block form on thermal performance, solar access and ventilation. Renew. Sustain. Energy Rev. **38**, 551–560 (2014). https://doi.org/10.1016/j.rser.2014.06.007
9. Morganti, M., Salvati, A., Coch, H., Cecere, C.: Urban morphology indicators for solar energy analysis. In: 9th International Conference on Sustainability in Energy and Buildings, SEB-17, 5–7 July 2017, Elsevier Ltd, Chania, Greece, pp. 1–8 (2017)
10. UNI: UNI 10349-1:2016. Riscaldamento e raffrescamento degli edifici. Italy (2016)

# A Multi-functional Design Approach to Deal with New Urban Challenges

**M. Pereira Guimarães and V. Dessì**

**Abstract** The document addresses the urban regeneration of an area starting from multi-step interventions in a small square. These interventions consider a multi-faceted point of view which respects local ecological processes while ensuring that transit and other economic and social functions take place. This approach encompasses solutions that respond to city scale needs in terms of stormwater management and the local conditions of thermal comfort and livability at the neighborhood scale. The benefits of urban liveability are now well recognized internationally, and among them increased city attractiveness to avoid abandonment is at the table of several local governments. Municipalities worldwide have pushed for the development of new pedestrian spaces or the regeneration of existing ones to foster liveability through a strategy known as Tactical Urbanism. The paper focuses on the first square in the south of Milan-Italy to receive such intervention. Beyond Tactical Urbanism, but starting from it, this proposal is a preliminary assessment that aims to evaluate permanent and structural interventions in a square that can also contribute to the environmental resilience of the city. Two different software were used to estimate the environmental benefits of the proposal. The software SWMM (US-EPA) was used to evaluate strategies that guarantee the hydraulic invariance of the intervention area. Second, RayMan Pro enabled evaluate the proposed solutions contribution to the microclimate by comparing scenarios in terms of the UTCI index, taking as input local climatic data and data present in the literature.

## 1 Introduction

As we enter the post pandemic period, climate change impacts such as extreme urban heat was already starting to be felt in urban areas. Cities were at the forefront of the Covid-19 crisis and experienced the worst effects concerning the health of citizens, that led to reductions in urban liveability levels [1]. Many local administrators

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have since then embraced the goal to "build back better" by redefining the role and quality of urban spaces as well as encouraging forms of coexistence that reinforce the environmental and social resilience of the city [2].

The management of material (such as is water) and immaterial flows (such as is energy) within the city, constitutes only part of the solution for the urban complexity equation [3]. Urban flows also vary periodically: episodic intense events require corrective and sometimes extraordinary actions. Among the material flows we have, for example, transportation of goods and people, and regular or excessive stormwater runoff. Intangible flows, such as solar radiation that generates shaded and sunny areas or air temperature, usually receive less attention from city officials.

Nevertheless, some of these flows often intercept the daily life of city inhabitants, and can imprint, consciously or not, a sense of belonging or discomfort towards the spaces they frequent. One of the most successful strategies to improve the urban livability is to modify the setting of the open spaces by increasing pedestrian areas to the detriment of roads and car parking lots often by visual low-cost interventions.

On the other hand, individual municipalities have already identified more concrete and long-term actions to adapt the urban environment that must be implemented now to cope with the negative impacts of climate change in a timely manner. Whether it is about reducing the summer heat island or managing excess rainwater, the post-pandemic planning scenario offers an opportunity to rethink city spaces. The regenerative design approach offers possible solutions for both the mitigation and adaptation to the effects of climate change. Particularly in the short-term planning spectrum, such approach can enhance the capacity of local urban areas to buffer seasonal flooding and extreme heat events [4].

Inspired by the many opportunities to recover and rebuilt greener and livable cities, this paper focuses on an Italian case study in Lombardy Region (Milan City). The Lombardy Region Administration counts on policy instruments to impose limits of rainwater discharge to the sewer system that define specific percentage of permeability to lots that undergo new interventions, using the principles of hydraulic and hydrological invariance. These limits have a legal binding and mitigate the phenomena of flooding caused by the increase of impervious surfaces, and contribute to ensuring high levels of aquifer recharge and environmental protection. The reduction of soil permeability is calculated in relation to the original natural permeability of the site, before urbanization, and not the urban condition prior to the intervention. Although restrictive, the concept of hydraulic and hydrological invariance is usually not sufficient to address situations in which the risk is posed by rivers in densely built and impervious river plain areas. In these cases, a threshold can be used when defining and dimensioning a series of interventions [5]. Thus, the impositions of this law direct new interventions to apply sustainable water solutions to the site.

Sustainable urban drainage solutions (SUDs) have several co-benefits [6]. Therefore, we observe that in trying to integrate design processes through different approaches—always respecting the local environmental resources—some of the strategies used for sustainable rainwater management can be reinterpreted to respond to extreme heat and reduce air and surface temperatures in summertime. Such measures are especially important in the onset of more intense, frequent, and prolonged heat waves. Rain gardens with shading trees, located near rest areas along urban equipment that favor seated activities, or cisterns for collecting rainwater that can be stored and purified to be reused as a water-based cooling strategy in squares, are just some of the possibilities.

The approach proposed feeds from different design perspectives and is not often reflected in the existing strategic tools. For example, in Milan, the Territorial Government Plan (PGT), through the "Neighborhood Plan", guides interventions targeted at the redevelopment of public spaces, while strategies for climate adaptation are advised in other plans (such as the ARERA's "Resiliency of the Energy Networks") [7] and seem to respond with specific requirements for particular issues. The Milan Metropolitan Area's Resilient Territories sector present strategies that try to combine social and ecological aspects, but without defining a clear methodological structure.

## 2 Tactical Urbanism

In the last ten years, the international movement called Tactical Urbanism has become an easy low-cost and temporary scheme for redesigning public spaces. It usually also includes community engagement and participation in the project and implementation of new uses in urban spaces [8]. Since 2018, numerous small projects were implemented in Milan based on the tactical urbanism strategies adopted previously by other cities around the world, such as New York and Dallas in the United States. These projects aimed at "testing" alternatives of public space reconfiguration selected by the public administration and, so far, amount to around thirty initiatives throughout the city [9].

The main goal was to reverse the current cycling-pedestrian-private car use trends in the street space and, ultimately, trigger mechanisms that attract people to urban spaces (using, for example, ping pong tables, as seen in Fig. 1). The Municipality of Milan started the program "Open Squares", (Piazze Aperte—Comune di Milano) with five strategic goals:

- To strengthen local identities of de-characterized neighborhoods.

**Fig. 1** Aerial view of Angilberto II Square in Milan, before and after the tactical urbanism intervention (left and central pictures) and an element that invite people to visit and spend time in the renewed square (picture on the right)

- To foster pedestrian walkability and slow traffic.
- To increase city attractiveness, beauty, and livability.
- To encourage local economy and tourism.
- To promote safety, social cohesion, and inclusion.

Recent surveys observed that the behavior of users has changed positively, and the population has been given the opportunity to make suggestions to improve the proposal. The Angilberto II Square in Milan is the first experience of the kind carried out in city and was very well received by the population.

The tactical urbanism interventions through the city accelerated in the lockdown months during the Covid-19 pandemic, in Spring 2020. By taking advantage of the limited number of cars and moving people, many kilometers of cycle paths were traced on the streets; and some interventions were expanded to incorporate whole squares and part of streets. Most important to note, with the need to activate social distancing, the public space was also substantially occupied by bars and restaurants. The goal of the current public administration is to intervene permanently in these spaces once its uses have been consolidated, considering that some minor changes are still taking place (e.g., realocation of benches or the redesign of pedestrian walkways). Among the most common elements used in these interventions there are pavement painting, trees, shading systems, and benches. Overall, a positive impact in the city that could benefit with more design.

## 3 Management of Excess Stormwater in a Regenerative Design Approach

Taking as a starting point the tactical urbanism experience carried out in Piazza Angilberto II in Milan, a regenerative design approach for stormwater management is proposed for the area. Located in a densely built and waterproofed neighborhood, the current tactical intervention did not contribute to change the permeability of the existing impervious surfaces.

The proposal's step two goal is to intercept excessive rainwater (for design storms of 10-years and 100-years intensity, respectively, see hyetographs in Fig. 2), store and infiltrate part of it, and possibly send the remaining (or at least part) water volumes to the sewer system once the worst of the storm event has passed. It initially involved only the public space, concerning interventions in the pavement of the square.

The square and adjacent sidewalks were considered a separate stormwater catchment area: runoff water that flows into the driveway would go directly to the sewer, while the runoff water from the square surface would be collected in an alternative system that can at the same time improve square appearance and attractiveness [10, 11].

Therefore, the new design alternative considers a rain garden with trees, permeable pavements in the area occupied by restaurants, and a water collection system consisting of a small water-square (a paved retention basin) adapted with water

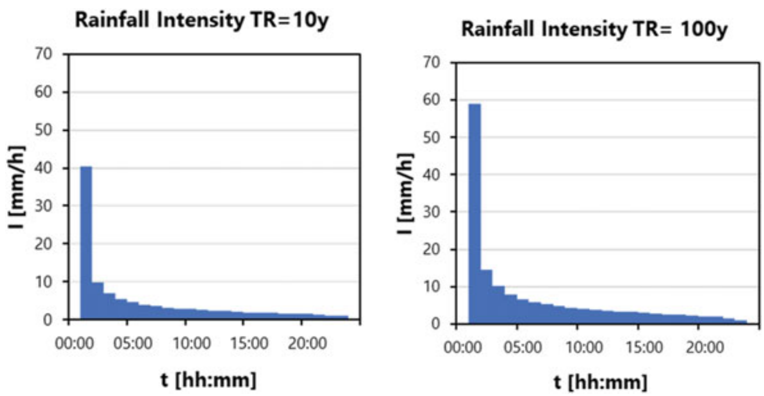


**Fig. 2** Design storm intensities for TR = 10 years and TR = 100 years using data provided by ARPA-Lombardia

splashes or a water misting system fed by the rainwater that is collected is this portion of the square—a system designed to store, clean, and reuse water. The preliminary hydrological and hydraulic modelling and assessments were produced using the Storm Water Management Model (SWMM), developed by the US Environmental Protection Agency (USEPA) [12]. The SWMM software has an in-built stormwater management catalogue of solutions that can be applied to a catchment area. In SWMM they are defined as Low Impact Development (LID) control practices designed to capture surface runoff and provide some combination of detention, infiltration, and evapotranspiration.

Three from the eight possible simulation strategies were chosen to carry-out the analysis: bioretention cells (vegetated rain gardens), pervious pavement, and rain barrel or cisterns (for the water-square). SWMM "LID Controls" are considered as properties of a given sub-catchment. Bioretention cells and permeable pavement systems can contain optional drain systems in their gravel storage beds to convey excess captured runoff off the site and prevent the unit from flooding. Rain Barrels are containers that collect roof runoff during storm events and can either release or re-use the rainwater during dry periods.

In the case study, the adopted bioretention used mostly SWMM default values with exception of the cell berm value of 200 mm, surface roughness of 0.2 (Manning n), suction head of 50, storage thickness of 45 mm and drain offset of 6 mm. Permeable pavement had a berm height of 50 mm, surface roughness of 0.1, pavement thickness of 100 mm and storage thickness of 300 mm.

For the rain barrel, the adopted barrel height was 3 m. This first analysis allows to evaluate the run-off amortization of the proposed solutions in terms of their areas within the main catchment and compare the proposed systems for TR = 10 and TR = 100 years. The catchment areas were estimated using Google Earth pro measurement tool.

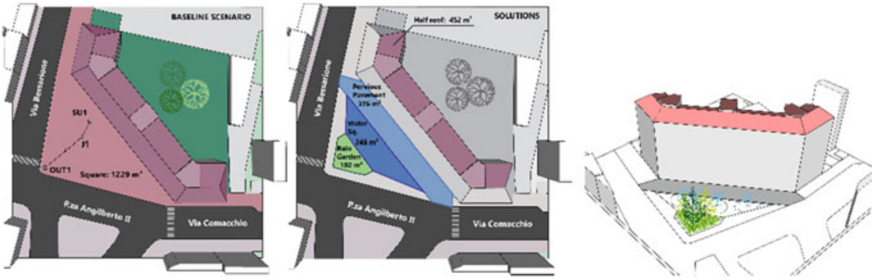


**Fig. 3** The existing drainage condition (left image) compared to the LID (Low Impact Development) strategies implemented in the Angilberto II Square (central and right images)

The Baseline Scenario (a 100% impervious square catchment with an area of 1229 m$^2$) is seen in Fig. 3 and the proposed solutions have the following dimensions: rain garden (102 m$^2$ equal to 8.3% of sub-catchment), water square (248 m$^2$ equal to 20.2%) and pervious pavement (376 m$^2$ equal to 30.6%).

Because the solutions applied to the square would not meet the hydrologic and hydraulic invariance law, it was proposed to capture the rainwater of 452 m$^2$ of roof in the adjacent building, what accounts for roughly half of the roof area (second image in Fig. 3). The amortization capacity of each solution can be seen in Fig. 4. Their combination was then analyzed for the two design storms (TR = 10 and 100).

First, from Fig. 5, in the left, it is possible to observe that the proposed LIDs are not enough to capture and amortize the runoff from the horizontal surfaces (in the public space). And even more, these solutions are not sufficient to manage the volume of water that also comes from the existing (private) buildings. Generally, the stormwater from the roofs is collected and directed to the sewer system.

It is therefore also necessary to involve the surrounding buildings in the alternative drainage system to avoid extra criticalities in the collection system (Fig. 5, right, shows the solutions applied to the square in combination with rainwater collected from half of the building roof). Only by involving the adjacent building it is possible

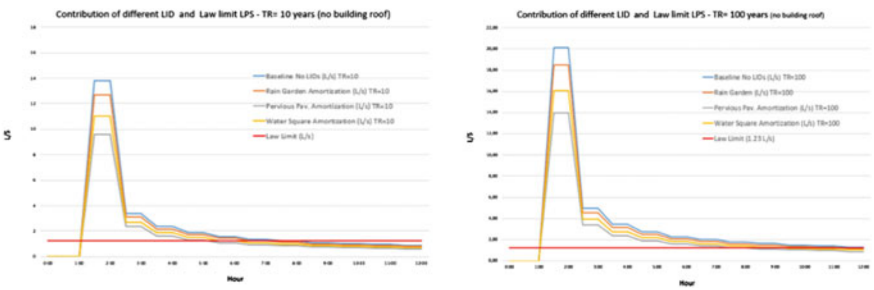


**Fig. 4** The comparison of the contribution from different strategies implemented in the public area, considering a return time storm of a 10 (left) and 100 (right) years

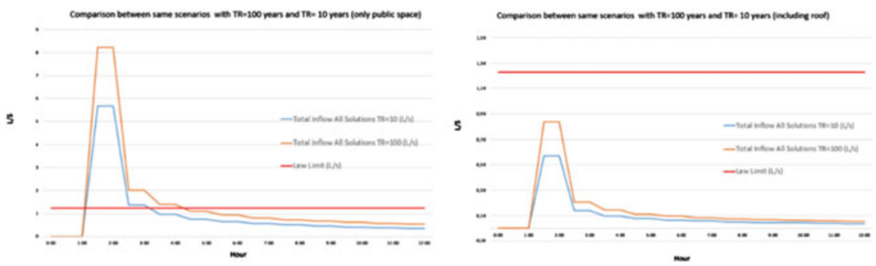


**Fig. 5** Comparison of the scenario that combine all the strategies implemented in the public area in the left versus all strategies implemented combined with stormwater captured from the facing building' roof (right), considering a return time of 10 and 100 years

to meet the restricted limit imposed by the hydrologic and hydraulic invariance law for Milan, i.e., 1.23 L per second.

## 4 Thermal Comfort in an Environmental Design Approach

If the configuration of a square is transformed as so to function as both an attractive public space (with the intervention of tactical urbanism) and as a key site to manage excess rainwater (according to a regenerative design approach), it is also true that the environmental thermal quality of the space must also be acceptable. Therefore, the thermal comfort must be appropriate for the rest of the year in which people use an urban space to carry out social, recreational, leisure and sport activities [13, 14]. The strategies identified for the management of excess water are in fact compatible with strategies that contribute for improving thermal comfort due to reduction of air and surface temperature. Notably, two elements can work to satisfy both requirements: rain gardens that have soil and plants to drain rainwater can host trees capable of providing shade; while harvesting stormwater (with a cistern) in a water square can supply recycled water to fountains and nebulized water systems during the summer for part of the square space. Simulations of energy performance of the urban space coupled with models in dynamic regime allow to evaluate thermal comfort improvement given by the proposed solutions. The software Envi-met 4 [15] can be used to support such evaluation of comparative scenarios and is intended to be used in a later stage of the research project. However, since there is an exhaustive literature that highlights the contribution of both vegetation and water on the amelioration of uncomfortable microclimate, this second method was used instead of a simulation tool, as a preliminary study in this paper (Fig. 6).

According to [16, 17] and to several of field surveys carried out during the research or didactic activities at the School of Architecture of the Politecnico di Milano [18], we can consider a reduction of air temperature and solar radiation due to the presence of trees of about 0.5–1 °C and an increase of relative humidity of about 1–3%.

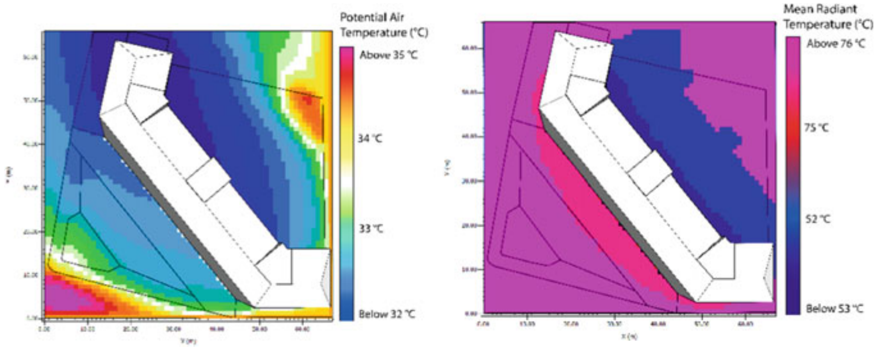


**Fig. 6** Potential air temperature (left) and mean radiant temperature (right) of the Angilberto II Sq., in Milan, for July 12th, 2019, at 16.00 for the baseline scenario, generated using Envi-met 4

It is well known that the most important effect on thermal comfort is due to the decrease of solar radiation in the central and hottest hours of the day—that means less incident solar radiation on the person and on the building facades and pavement surfaces shaded by the trees (about the 90% of direct solar radiation decrease), with an important decrease also in terms of Mean Radiant Temperature.

In this paper, two conditions have been considered. The first one, using data for a very hot day in the middle of an intense heat wave that overlap with the existing urban heat island of Milan (June 27th of 2019) and a warm day of the same year (July 12th of 2019). By observing the results of the comfort condition for these two days without and with vegetation and the water-based solutions to cool the environment it is possible to devise some considerations regarding the applicability of the proposed design alternatives to alleviate extreme heat.

The indicator used is the UTCI, an internationally recognized index of thermal comfort, result of the EU COST 7302 research [19]. By using the UTCI, the comfort condition ranges between 9 and 26 °C and it is calculated in this study through the software Rayman Pro.

The existing condition at 3 p.m. of June 27th, 2019, is very unpleasant, reaching values of UTCI of 43 °C (Table 1), i.e., 17 °C over the comfort limit. Considering a decreasing of 1 °C in temperature and the 90% of solar radiation, the situation would pass from UTCI 43 °C to around 36 °C, only considering the trees' shade. It represents a dramatic improvement, but still not sufficient to reach a comfort condition in the hottest day of the year during an intense heat wave.

Considering the water-based solutions (fountains and nebulizers), air temperature and relative humidity would change, and probably also solar radiation being partly reflected by the water droplets. According to [20–23], air temperature can decrease of 7.5–10 °C as the relative humidity can increase up to 20–30%. During the heat wave on June 27th in Milan, if we consider a misting water system in the water square with air temperature of 28 °C (10 °C less) and relative humidity of 56% (20% more), we can approach a comfort condition, but we cannot reach it (29.7 °C), despite an improvement of about 13 °C.

**Table 1** Data form ARPA, the Protection Agency of Lombardy Region, during one the hottest summer day in Milan, June 27th, 2019 (during the heat wave) and a warm day, July 12th (no heat wave), at 3 p.m., and for both days two different proposals to cool the environments, shadows provided by the trees and misting water

| Date/Condition | Air temperature (°C) | Relative humidity (%) | Global solar radiation (w/sqm) | Wind velocity (m/s) | UTCI (°C) |
|---|---|---|---|---|---|
| **June 27th (heat wave)** | **37.8** | **36.3** | **806** | **2.9** | **42.8** |
| Under a tree (Hypothesis) | 36.8 | 38.0 | 80 | 2.9 | 36.2 |
| Under jets/mists (Hypothesis) | 28.0 | 56.0 | 750 | 2.9 | 29.7 |
| **July 12th (no heat wave)** | **30.0** | **35.6** | **827** | **3.2** | **33.0** |
| Under a tree (Hypothesis) | 29.0 | 37.0 | 82 | 3.2 | 25.2 |
| Under jets/mists (Hypothesis) | 23.0 | 60.0 | 770 | 3.2 | 25.9 |

During a warm summer day, 12th July 2019, in the afternoon after a heat wave period, the UTCI is about 33 °C, i.e., out of the range of the comfort condition. A comfort condition is reached (respectively 25.2 °C and 25.9 °C) when considering the alleviation given by the vegetation or the water-based solution to cool the area of the square.

## 5 Conclusions

Three different ways to design urban spaces have been considered in the study: tactical urbanism, regenerative design, and environmental performance. These approaches involve the quality of public space from different points of view. At first sight, these three approaches are not compatible with each other. They are in fact, complementary, and when taken into consideration at the same time, can contribute to further enhancing the urban space and reinforcing the environmental and social resilience of the urban area.

There are two considerations to highlight. The first concerns the participation of citizens, evident in the tactical planning process, which requires a different strategy when it comes to managing excess rainwater and extreme heat.

Citizen participation in this case refers to the role of private building owners in creating more sustainable and livable cities. Without making available the surfaces and areas pertaining to private residences (for example, the roofs), for the collection and possibly also for the storage—even if temporary—of rainwater, as highlighted by the results of simulations with SWMM, the values imposed by law are not satisfied.

It is necessary to involve the facades of the buildings as well as roofs also for the construction of green and/or blue infrastructure (green facades and green roofs) that guarantee acceptable comfort conditions to people who walk or spend time in an urban space. It was verified using RayMan Pro using data from the literature for the proposed vegetation and water-based solutions applied to square. If implemented widely in the city, these solutions also contribute to reduce the urban heat island (UHI).

The second consideration concerns the climate adaptation strategies considered in the study: stormwater management and passive outdoor cooling. These solutions are certainly effective and manageable for harsh but not extreme conditions (heavy storms and intense heatwaves). This meaning that these adaptation measures can contribute to the enhancement of urban space from the point of view of aesthetics and psychological aspects (for example, by increasing biophilia and safety), but they have a limit beyond which they are no longer sufficient to improve the overall outdoor environment.

In other words, the ability to adapt the urban environment is not infinite and it is essential that these actions are always accompanied by mitigation measures that limit the causes of climate change in the city-region and in the global scale.

Note: this research experience is part of the Ph.D. program of the first author included in the SOLOCLIM (Solutions for outdoor climate adaptation) research, a European Industrial Doctorate project funded by the European Commission within the MSCA-Horizon 2020 program.

## References


1. The Economist Intelligence Unit: The global liveability index 202: how the covid-19 pandemic affected livability worldwide (2021)
2. UN-Habitat: Cities and pandemics: towards a more just, green and healthy future (2021)
3. Timmeren, A.V.: The Concept of the Urban Metabolism (UM). SUET, pp. 1–18 (2014)
4. Zari, M.: Regenerative Urban Design and Ecosystem Biomimicry. Routledge, London, UK (2018)
5. De Certeau, M.: The Practice of Everyday Life. University of California Press, Reprint edition (2011)
6. Alves, A., et al.: Assessing the co-benefits of green-blue-grey infrastructure for sustainable urban flood risk management. J. Environ. Manag. **239** (2019)
7. Pereira Guimaraes, M., et al.: A simplified procedure to improve usability of hydrodynamic modelling software in regenerative urban design. In: Proceedings of CISBAT 2021—Carbon Neutral Cities—Energy Efficiency & Renewables in the Digital Era. Lausanne, Switzerland (2021)
8. Autorità di Regolazione per Energia Reti e Ambiente. Resilienza delle reti di distribuzione dell'energia elettrica. Incentivazione Degli Interventi Finalizzati All'incremento Della Tenuta Alle Sollecitazioni. Report (2018)
9. Programa Piazze Aperte – Comune di Milano. Presentation (2018)
10. Huber, J.: Low Impact Development. A Design Manual for Urban Areas. UACDC. Fayetteville, AK, USA (2010)
11. Masseroni, D., et al.: Manuale sulle buone pratiche di utilizzo dei sistemi di drenaggio urbano sostenibile (2018)

12. EPA: Storm Water Management Model (SWMM) version 5.1 User's Manual. EPA, USA (2015)
13. Nikolopoulou, M., Lykoudis, S.: Use of outdoor spaces and microclimate in a mediterranean urban area. Build. Environ. **42** (2007)
14. Nikolopoulou, M., Baker, N., Steemers, K.: Thermal comfort in outdoor urban spaces: understanding the human parameter. Sol. Energy **70** (2001)
15. Bruse, M.: ENVI-met website retrieved on June 14, 2021, from: http://www.envi-met.com/
16. Boukhabla, M., Alkama, D.: Impact of vegetation on thermal conditions outside. Thermal modeling of urban microclimate. Case study: the street of the republic, Biskra. Energy Procedia **18** (2012)
17. Davtalab, J., et al.: The impact of green space structure on physiological equivalent temperature index in open space. Urban Clim. **31** (2020)
18. Dessi, V.: Use of simplified tools to evaluate thermal comfort in urban spaces in the teaching experience. In: Proceedings of PLEA—Toward Zero Energy Buildings. University College Dublin (2008)
19. Höppe, P.: The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. Int. J. Biometeorol. **43** (1999)
20. Ulpiani, G., et al.: Thermal comfort improvement in urban spaces with water spray systems: field measurements and survey. Build. Environ. **156**, 46–61(2019)
21. Ulpiani, G., et al.: Water nebulization to counteract urban overheating: development and experimental test of a smart logic to maximize energy efficiency and outdoor environmental quality. Appl. Energy **239**, 1091–1113 (2019)
22. Nishimura, N., et al.: Novel water facilities for creation of comfortable urban micrometeorology. Sol. Energy **64** (1998)
23. Xue, F., et al.: Modeling the influence of fountain on urban microclimate. In: Building Simulation. Springer, Berlin (2014)

# A Preliminary Analysis of the Characterizations of Positive Energy Districts

**Xingxing Zhang, Santhan Reddy Penaka, Samhita Giriraj, Maria Nuria Sanchez, and Paolo Civiero**

**Abstract** Positive Energy District (PED) is recently proposed to be an integral part of a district/urban energy system with a corresponding positive influence. Thus, PED concept could become the key solution to energy system transition towards carbon neutrality. This paper intends to report and visualize the initial analytical results of existing 60 PED projects about their main characteristics, including geographical information, spatial-temporal scale, energy concepts, building archetypes, key words, finance model and challenges/barriers. As a result, a dedicated date base is developed. It is found that Norway and Italy have most PED projects so far. Many PED projects state 'yearly' time scale while nearly 1/3 projects have less than 0.2 $km^2$ area in terms of spatial scale. A mixture of residential, commercial and office/social buildings are found. The most common renewable energy systems include solar energy, district heating/cooling, wind and geothermal energy. Challenges and barriers for PED related projects varies from planning stage to implementation stage. These preliminary results are expected to give useful guidance for future PED definition and proposal of 'reference PED'.

## 1 Introduction

The Positive Energy District (PED) concept has been discussed substantially as it could become the key solution to energy system in transition towards carbon neutrality. According to European Strategic Energy Technology (SET) Plan Action 3.2 [1], PED could be defined as an energy-efficient and energy-flexible urban area

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with surplus renewable energy production and net-zero greenhouse gas emission in a certain time frame. Some PEDs initiatives aim to create a knowledge base and a roadmap to achieve the energy transition of cities according to established time horizons [2].

Most of the studies and practical experiences about PEDs are based on newly built districts or planning of future district. A series of technical solutions, such as the integration of batteries, electric vehicles (EV), and the grid-responsive control, were discussed to promote the development of PEDs [3]. From economical and technical points of view, Laitinen et al. [4] concluded that it is more feasible to achieve PED or net-zero energy district, rather than full energy self-sufficiency after they studied a series of technologies using Helsinki as a case study. However, Gouveia et al. [5] argued that the transformation of the existing districts is essential, including historic districts, which present common challenges across EU cities.

Through extensive literature studies, a research gap is observed that there are many studies starting to address technical, economic, social aspects of PED, but very limited study is found in characterizing PED. The Joint Programme Initiative Urban Europe (JPI UE) [6] plays an important role in coordinating PED projects across Europe. To accomplish its objectives, only Bossi et al. [7] summarized part of PED's characteristics in aspects of geographic distribution, implementation status, building structure, land use, energy typology, success factors/challenges, and barriers. While Brozovsky et al. [8] identified different terminologies of PED, and related focused aspects (i.e. energy, social, climate). It needs more comprehensive scientific advice on the knowledge and methods for guiding the design, monitoring the operation and evaluating the performance of PED projects. Therefore, many other PED's characteristics needs to be abstracted and categorized for further development of PED, such as district size, energy concepts, building archetypes, and spatial/temporal scale.

In the framework of both IEA EBC Annex 83 [9] and EU Cost action CA19126 [10], the working groups are now collecting data of PEDs and characterizing them for potential proposal of reference and replication of PEDs in different contexts. This paper therefore reviews existing 60 projects from the JPI Urban Europe PED booklet, establishes the database, and further analyze/visualizes them for the main characteristics. The result will be used for the iterative definition of PED in these two initiatives.

## 2 Data Source and Research Methods

### *2.1 Data Source*

The data of PED related projects is collected from the PED booklet [11] by JPI UE updated latest on 2019. The databank of 60 projects data that has similar goals of PED projects in Europe. These projects have been identified and updated by the

**Table 1** Table parameters for data collection

| Key parameters | Type of data |
|---|---|
| Project characteristics | Location, initiated year, development stage, project area, finance model etc |
| Type of buildings involved | Residential, commercial, social, industry etc |
| Energy technologies | Solar thermal, geothermal, PV, heat pumps etc |
| Key energy concepts | Energy combinations and strategies to meet the goals |
| Keywords | Positive energy district, smart city etc |
| EV/E-mobility | Included/excluded in energy strategies |
| Temporal scale | Hourly/monthly/yearly etc |
| Driving stakeholders | Municipality, citizens, real estate developer etc |
| Others | Supporting regulations, barriers, key success factors etc |

participated cities of workshops conducted by JPI Urban Europe. The database is divided into several key parameters shown in Table 1.

## 2.2 Research Methods

### 2.2.1 Development of Database

The essential data of literature was broken down into thematic categories as shown in Table 1. The important characteristics for PED were either discussed by experts in IEA EBC Annex 83 and EU Cost action CA19126, or extracted from the literature. All the information was observed, recorded and summarized, which forms up the basic data base for this review.

### 2.2.2 Data Visualization

Given that the dataset contains several projects across different cities in Europe, a spatial visualization of the location of these projects was deemed vital. QGIS software [12] is a Geographic Information System (GIS) based open source software used here to display the cities on a map. Each project is appended with the latitude and longitude of the city it lies in, are wrapped over a European base map.


**Fig. 1** Location of 60 PED related projects

# 3 Results

## *3.1 Characteristics of Existing PED Projects*

### 3.1.1 Geographic Location of PED Projects

This location of the identified 60 PED related projects is displayed in Fig. 1. Most number of projects are located in Norway i.e., 9 projects, followed by 8 projects, 7 projects, 6 projects, 5 projects in Italy, Finland, Sweden and Netherlands respectively. Each of 4 projects in Spain, Germany and Austria countries, 2 projects in both France and Denmark. And one project in remaining countries Portugal, Turkey, Ireland, Belgium, Hungary, Switzerland, Greece, Estonia and Romania.

### 3.1.2 Status of the Identified Projects

This section reports the current development stage of 60 PED projects divided into categories mentioned in development of data base. From Fig. 2, the results clearly indicates that majority of the projects are under implementation stage i.e., 26 projects. There are 11 projects under planning stage, and 6 projects under both planning and implementation stage. Totally 16 PED related projects are already implemented or in operation, among which 5 projects have completed implementation but yet to

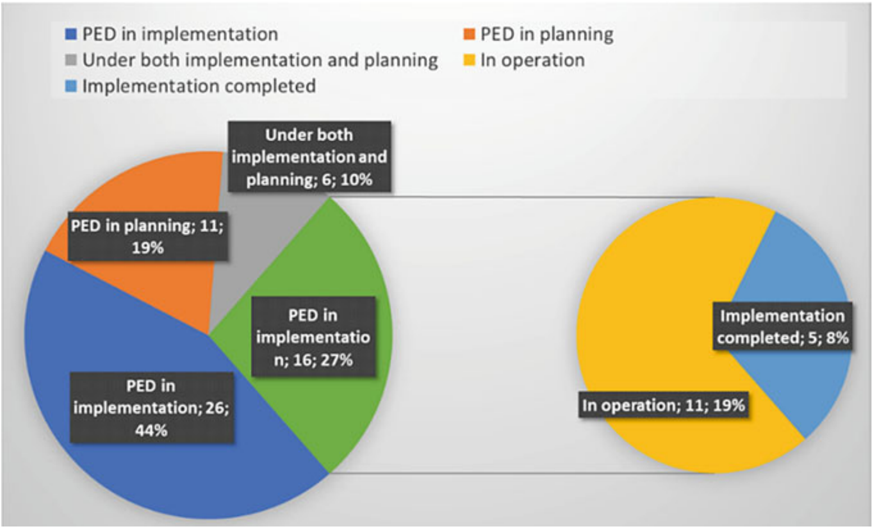


**Fig. 2** Development stage of collected 60 PED related projects

integrate the energy systems into the existing local energy networks, while 11 projects are finally in operation stage. Information is not available for one project.

### 3.1.3 Project Area (Spatial Scale)

The amount of project area (spatial scale) is counted by considering the installation of the planned energy systems in their locality. These energy systems might be installed on the residential, commercial or industrial roofs, or flat ground-mounted in open fields, or even through virtual presence of energy system. From Fig. 3, most of the projects i.e., 19 projects are claimed to be using less than 0.2 km$^2$ area, 7 projects between 0.21 and 0.4 km$^2$ area, 8 projects consuming area between 0.81 and 3.0 km$^2$, and there is one project claim to be consuming more than 25 km$^2$ area.

### 3.1.4 Type of Buildings Involved

This section presents the commonly involved building types for installation of energy systems to supply local energy demand and to produce excess energy to increase energy flexibility according to the specific project goals. Figure 4 illustrates that the residential sector appears to be predominantly used in majority of the projects to install energy systems on available roof areas as it is being the primary focus for 39 projects. Office and social buildings are identified to be main focus in around 24 projects, and also followed by commercial buildings spaces for more than 20

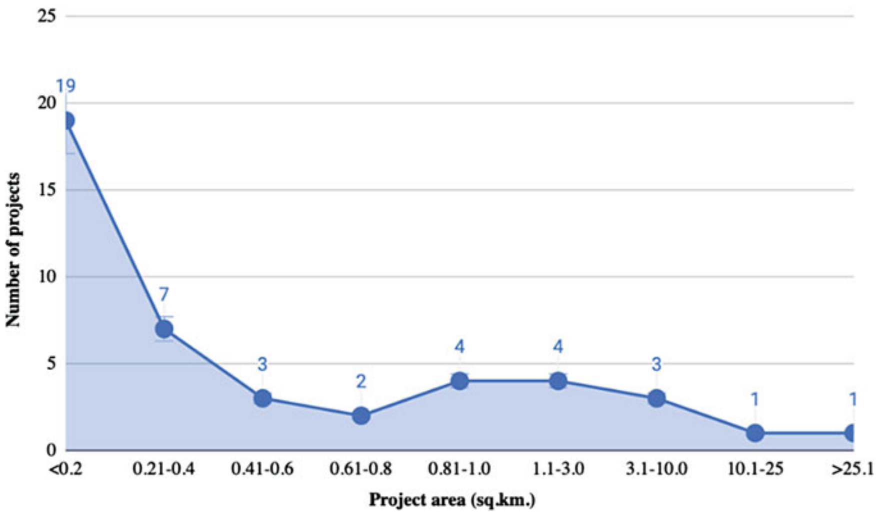


**Fig. 3** Project area of the 60 PED related projects

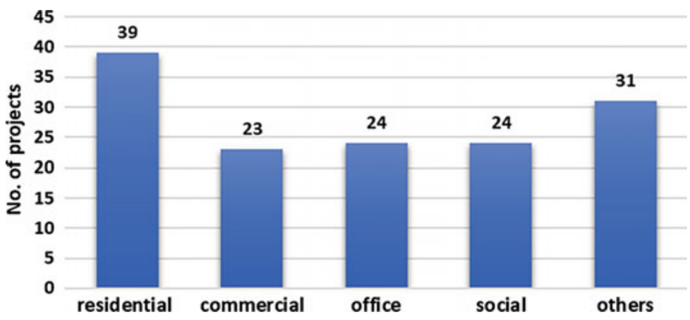


**Fig. 4** Type of buildings involved for space utilized by energy systems

projects. Other type of buildings such as institutional, cultural etc., are used utilized as secondary spaces for implementing the energy systems.

It is also observed that almost all the projects have considered a mixture of different building types, depending on the major type of buildings existing in locality. However, the overall trend focuses on involving the citizens as key drivers with right motivating strategies which eventually address the spatial challenges to install energy systems required for local energy demand.

### 3.1.5 Major Energy Technologies

The popular energy technologies are divided into categories as solar, district heating/cooling, heat pumps, geothermal energy, combined heat and power (CHP), energy storage, wind, e-mobility and the others. Solar energy technology is identified to be the primary source of energy supply in almost all projects, specifically photovoltaics (PV) and thermal are the main contributors for producing electricity and heating applications respectively. There are 5 situations where projects claimed to use solar technology but has not been specific type in solar energy. Others new/innovative forms of solar such as hybrid photovoltaic/thermal (PVT), building integrated photovoltaics (BIPV), floating solar and solar roads technologies are also have been considered in few projects.

District heating/cooling has been founded in 45 projects, in which heating is used in 43 projects and cooling in 2 projects. Heat pumps, geothermal energy and CHP plant used in 37 projects, 27 projects and 21 projects respectively. Electro-chemical energy battery technology storage for electricity application and seasonal thermal energy storage technology for heating/cooling application are explored as under energy storage category. Wind energy and E-mobility technologies are identified using in 6 projects and 8 projects respectively. And other technologies, such as bioenergy, green hydrogen, hydro power and natural/mechanical ventilation etc., have also been integrated partly in few PED related projects in Europe.

### 3.1.6 Challenges Under Different Implementation Stage

The data collection focuses on challenges/barriers that are categorized into 'under planning', 'under implementation stage' and 'implemented/in operation' stages shown in Table 2. The gathered information on challenges/barrier reveals the following main topics: Administrative and policy (A&P), Legal and Regulatory (L&R), Technical. Environmental, Social and Cultural, Information and Awareness, Economical and Financial, and Stakeholders interest perspective [13].

Challenges associated to stakeholders' involvement, administrative, and technical issues had a great relevance in all PED stages. The economic and finance feasibility was crucial in both planning and implementation stages as well as supporting studies or knowledge. However, legal and regulatory barriers were important in implementation and operation stages. Finally, only in operation stage environmental and social and cultural aspects were considered as possible barriers.

## 4 Discussion

In this study, the projects have been taken from the PED book by JPI Urban Europe, which invited voluntary input data over the project experience and knowledge. It should also be noted that this is not an overview of the PEDs in Europe, as countries have contributed unequally to the development of the book. Since most of the projects are still under planning and implementation stages, it has been challenging to understand the updated information/data of many projects. In addition, due to the

**Table 2** Challenges and barriers according to the main topics

| Topic | PED in planning | PED in implementation | PED implemented/in operation |
|---|---|---|---|
| Administrative and policy | Conflicts between different authorities involved in project | Political management | Approvals and permits from municipality and other entities might lead to project timeline extension |
| Legal and regulatory | | Regulatory framework which governs involved actors throughout Europe | Regulatory barriers for piloting/testing |
| Technical | System boundary conditions defined | Identification and deployment of local feasible clean energy systems | Analysis required for hybrid energy system operations |
| | Coping up with rapid growth of new technologies | | Analysis required for underground seasonal energy storage |
| | | | Energy generation systems is far away from the consumers |
| | | | Thermal mining challenges in the urban areas to reduce the distance from energy generation system far away |
| | | | The electricity supply examined properly above 90 degrees |
| Environmental | | | Disallowing inefficient and high polluting energy generation systems |
| Social and cultural | | | Cultural differences between different cities involved in the partnership |
| Information and awareness | | Local citizen acceptance towards new things in rural areas | |
| Economical and financial | Economic feasibility | Finance dependence on private investors | |
| | Finance availing according to the project timeline | Local finance | |

(continued)

**Table 2** (continued)

| Topic | PED in planning | PED in implementation | PED implemented/in operation |
|---|---|---|---|
| | Overlapping implementation with local ongoing constructions | | |
| Stakeholders interest | Encouragement of project drivers like real estate developers | Stakeholders and involved actor's commitment towards project goals | Conflicts due to lack of common interest between different landowners |
| | Uncertainty in stakeholder's commitment | Creating interest in project drivers like building owners and landlords | Strong collaborations needed between energy companies and real estate developers for fast implementation |
| Others | Active consideration of local knowledge | Lack of supporting studies/knowledge for implementation | |
| | Lack of supporting studies/knowledge for planning | | |

insufficient information, there are few data, such as energy technologies for PED, is unclear during data collection. These bring certain uncertainty of the analysis result.

However, it is interesting to examine the main characteristics of the collected 60 PED related projects, and the results shall have certain guidance for final PED definition and the proposal of 'reference PED'. The non-existence of a standard and consolidated definition of the PED concept is in fact one of the main limitations to its development and deployment in European cities, so as to boost the energy transition within a common reference framework [14] for sustainable urban development. So, different approaches and aspects related to the realization of PEDs will be aligned taking account European cities diversity. According to results, the identified 60 projects are constituted in Europe with large number of projects in Norway (9 projects) and Italy (8 projects) respectively. Although the first project took place in 1970, but the momentum for such climate neutral goals has started from 2014.

According to the data base, most of PED related projects choose 'yearly' as the time scale. However, it is not possible to identify the temporal scale for many projects since they are still under planning stage. Regarding the project area (spatial scale), the general trend is to include residential, commercial and industrial buildings for installation of renewable energy systems in a city or district, which is to avoid the deployment of large energy systems in open fields. The analysis observes that public, private with regional/national grants is commonly used financial model which reflects active involvement from private sector. In addition, there are some projects that don't have much local renewable energy source, but they purchase energy from outside of the district boundary (so-called ‘virtual PED’).

Based on the results, residential, commercial and office/social buildings are highly involved for installation of energy systems, which depends on citizens commitment towards project goals (but the goals might deviate from the designed timeframe of the project). Meanwhile the stakeholders, such as municipality, would need to address overcoming the policy restrictions to further ease the process of adapting the energy system, and also need to conduct necessary activities to bring awareness in consumers and motivate for participation.

The energy mix for projects goals include solar energy, district heating/cooling, wind and geothermal energy are primary technologies, where solar technologies show dominance because of its potential. However, due to unavailability of solar energy during most half of the day and during winter seasons, exploration towards other forms of renewable energy sources, such as geothermal energy, wind etc., yet these may not totally reliably options during peak demands. In this context, energy storage might be the alternative way. Energy storage has not been part of the major energy strategies, which might be due to unavailability of enough planning, economic feasibility, high maintenance etc. This also might be part of the reason for PED related projects choosing yearly temporal scale rather than daily/monthly or seasonally.

The lessons learned from the preliminary analysis of these PED projects provide a starting point for achieving the objective of reducing the existing research gap in the characterization of PEDs. A key aspect is facing the complexity of the urban system and the resulting interrelationships between social inclusion, energy system, infrastructure, circular economy and mobility for sustainable urbanization.

## 5 Conclusions

This paper conducts a preliminary analysis of the main characteristics for 60 identified PED projects in the Europe. A dedicated date base is developed by considering a series of key parameters. It is found that a large number of PED projects locates in Norway and Italy. Although the first PED project took place in 1970, but the momentum for such climate neutral goals has started from 2014. Most of PED related projects choose ‘yearly’ as the time scale. Nearly 1/3 projects have less than 0.2 $km^2$ area as their spatial scale. In this case the definition of the project area and the information regarding to its boundaries calculation are both very relevant to evaluate the PEDs features of the projects and the business model adopted. Residential, commercial and office/social buildings are mostly involved for installation of renewable energy systems, which includes solar energy, district heating/cooling, wind and geothermal energy are primary technologies, where solar technologies show dominance. Substantial challenges and barriers for PED related projects varies from planning stage to implementation stage.

The non-technological PEDs solutions (e.g. solution for Governance, Economic, Social, Environmental, Spatial, Legal/Regulatory) are not clearly considered in the

Booklet analysis. This why the next interactive PEDs mapping tools will take into account those aspects that could help to share information and boost the PEDs replication within the main target groups, and according to a local broader perspective.

Although there is uncertainty due to limited data at the initial stage, the results are expected to give useful guidance for final PED definition and proposal of 'reference PED'. It is confident that the alignment among ongoing initiatives will represent the best way and very practical solution to step forward and facilitate the PEDs implementation in the next years, with more useful guidance and tools.

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## References

1. 'setplan_smartcities_implementationplan.pdf'. Accessed: Apr 26, 2021. [Online]. Available: https://setis.ec.europa.eu/system/files/setplan_smartcities_implementationplan.pdf
2. Civiero, P., Sanmartí, M., García, R., Gabaldón, A., Chicote, M.A., Ferrer, J.A., Ricart, J.E., Franca, P., Escobar, G.J.: PTE-ee ITP—Iniciativa Tecnológica Prioritaria (2019). Positive Energy Districts (PEDs). Accessed: May 21, 2021. [Online]. Available: https://static.pte-ee.org/media/files/documentacion/itp-01-2019-distritos-de-energia-positiva-peds-tZU.pdf
3. Zhou, Y., Cao, S., Hensen, J.L.M.: An energy paradigm transition framework from negative towards positive district energy sharing networks—battery cycling aging, advanced battery management strategies, flexible vehicles-to-buildings interactions, uncertainty and sensitivity analysis. Appl. Energy **288**, 116606 (2021). http://doi.org/10.1016/j.apenergy.2021.116606
4. Laitinen, A., Lindholm, O., Hasan, A., Reda, F., Hedman, Å.: A techno-economic analysis of an optimal self-sufficient district. Energy Convers. Manag. **236**, 114041 (2021). http://doi.org/10.1016/j.enconman.2021.114041
5. Gouveia, J.P., Seixas, J., Palma, P., Duarte, H., Luz, H., Cavadini, G.B.: Positive energy district: a model for historic districts to address energy poverty. Front. Sustain. Cities **3** (2021). http://doi.org/10.3389/frsc.2021.648473
6. 'JPI Urban Europe—ERA-LEARN'. https://www.era-learn.eu/network-information/networks/urban-europe. Accessed May 20, 2021
7. Bossi, S., Gollner, C., Theierling, S.: Towards 100 positive energy districts in Europe: preliminary data analysis of 61 European cases. Energies **13**(22), Art. no. 22 (2020). http://doi.org/10.3390/en13226083
8. Brozovsky, J., Gustavsen, A., Gaitani, N.: Zero emission neighbourhoods and positive energy districts—a state-of-the-art review. Sustain. Cities Soc. 103013 (2021). http://doi.org/10.1016/j.scs.2021.103013
9. Hedman, Å., et al.: IEA EBC Annex 83 positive energy districts. Buildings **11**(3), Art. no. 3 (2021). http://doi.org/10.3390/buildings11030130
10. 'Action CA19126'. COST. https://www.cost.eu/actions/CA19126/. Accessed Apr 26, 2021
11. Gollner, C.: Booklet of Positive Energy Districts in Europe, p. 96
12. 'References—Citing QGIS in formal publications?', Geographic Information Systems Stack Exchange. https://gis.stackexchange.com/questions/23622/citing-qgis-in-formal-publications. Accessed May 05, 2021

13. Civiero, P., Sanmartí, M., García, R., Gabaldón, A., Chicote, M.A., Ferrer, J.A., Ricart, J.E., Franca, P., Escobar, G.J.: Distritos de Energía Positiva (PEDs) en España, Una propuesta de Iniciativa Tecnológica Prioritaria de la PTE-EE. VII Congreso Edificios Energía Casi Nula, Madrid. pp. 109–114. Grupo Tecma Red S.L., Madrid (2020)
14. Reference framework for positive energy districts and neighbourhoods key lessons from national consultations. Accessed: May 05, 2021. [Online]. Available: https://jpi-urbaneurope.eu/wp-content/uploads/2020/04/White-Paper-PED-Framework-Definition-2020323-final.pdf

# An Exploration of the Relationships Between Architectural Delight and Human Senses

**P. Grant, J. R. Littlewood, and R. Pepperell**

**Abstract** STUDENT PAPER: Through post occupancy evaluation (POE), the designer can assess how well an initial design objective, agreed at the outset, has succeeded when in use. Current POE procedures have been developed by academics and engineers, often focussing on energy performance and sustainability data. There is no disputing that architects are keen to know how their designs are performing technically, and this is often achieved in collaboration with fellow design engineers on the project. Architects enjoy a sense of achievement when the technical performance of their design shows a marked improvement on previous projects, more so when the data shows their design is better than a building of a similar type. Whilst there is some attempt to gather feedback on the 'aesthetics' it is still scant and tends to focus on the visual appearance and the occupant's initial response, sometimes referred to as the 'wow factor'. POE feedback rarely reflects on the occupant's full experience of designed spaces. Informal consultations with the occupants will often reveal a sense of delight (or deference) when the inhabitants make references to their 'common senses'. This paper argues that experiential feedback from the inhabitants is essential to the initial design concept stage of a project. Architects are encouraged to seek the occupant's sensory feedback from a range of completed projects, as it will inform future design concepts and lead to enhancement of the occupant's feeling of wellbeing and delight in the built environment. The author has significant experience in the design of schools in South Wales, receiving the Eisteddfod Gold Medal Award for Architecture in 2017 on behalf of his employers, Stride Treglown Architects. His research will focus on his many school designs in Wales, recognising that many issues may resonate in other architectural sectors such as hospital design and landscape design.

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## 1 Introduction

Good architecture is *more than just* ***a visually pleasing building***. Consciously or otherwise, it will evoke a multisensory experience prompting occupants to respond with reference to their common senses of sight, sound, smell, touch and taste. Emerging scientific research in neuroscience and psychology offers architects insights into new opportunities in the design of spaces. By recognising how humans respond to designed spaces, architects can access a range of opportunities to make designed spaces a delight to use, subsequently making an influence on the behaviour, health, and well-being of occupants through the reduction of stress, blood pressure, depression, and anxiety [1].

Good architecture can have a positive psychological and restorative impact in its occupants. Psychologists have noted a clear human evolutionary basis for many psychological and physiological responses to design. Nicholson [2] suggests that human beings appear to be hardwired to their survival instincts. They are continuously alert to change, becoming fatigued after constant exposure to the same stimuli. Stangor [3] noted sensory responses adapt to the things that are not changing around them, making it possible to detect changes. Architects can design for this hunger for change by incorporating a variety of experiential changes to alert the senses. Whilst these changes can only be evaluated post completion, they are an essential part of the initial design concept, making post occupancy evaluations (POE) an essential part of the design process.

This paper proposes a change in how POE is gathered, encouraging design architects to allow sufficient time for the initial visceral response to subside, and to have an informal consultation with the occupants once they have settled into their new environment. For this to happen, both the client and the designer must agree on a range of experiential requirements at the concept stage of a design. The design team and the occupants can then have a meaningful set of reference points for discussion and evaluation when the building has been in use for some time.

## 2 POE

In May 2020, the Architects Journal (AJ) reported that only 4% of the top 100 architects in the UK 'always' evaluated their projects post completion. POE was first established in 1965 but as Cooper [4] noted, it evolved during the seventies through academic research, when there was a growing concern for finite natural energy resources. Research tended to gather quantitative data relating to energy use and *Building Performance Evaluation* (BPE), eventually revealing a significant difference between 'designed' energy use and the 'actual' energy used: now commonly known as the 'performance gap'.

The current RIBA Plan of Work was reissued in March 2020, with the aim to evaluate a building's sustainable credentials and to review the ongoing life of *a* *building in use; hence the RIBA's accompanying document* 'Sustainable Outcomes Guide'. These documents provide little attention to architectural delight and there no guidance on how to evaluate it. Even so, *there is a detectable change that has its roots, once again, in scientific research, helping to clarify how we might evaluate 'delight' in architecture.*

All architectural designs commence with defining the client's brief. This usually includes technical requirements of how the fabric should perform by referring to a list of technical documents, British Standards and legislation; all of which provide numerical targets that can be verified and evaluated after the building has been completed. Rarely are there any equivalent design parameters to describe the experiential outcomes for the occupant when the project is completed.

A significant proportion of the building performance is committed during the early stages of the concept design, refinement being resolved and achieved throughout the design process. So, too, are the less tangible features relating to the occupant's experience of spaces. The first author argues that a design brief should also include targets for the occupant's *sensory requirements*. This will allow both the occupants and the architect to review the phenomenological impact when the building is occupied. There is no intention to make a remarkable change in the architect's plan of work; the aim is to formalise 'good practice' that will lead to greater feeling of delight in new buildings.

**IMMERSION IN DESIGN**: An emerging technology that is beginning to play a key role in the future of architectural design is Virtual Reality (VR) and Augmented Reality (AR), both of which are increasing interest in neuroarchitecture. The use of these computer aided technologies provides designers with the opportunity to test new design approaches and to gather objective data on how participants respond to their designs as they emerge. It could become a key activity in determining evidence-based feedback and for developing design briefs that can allow for sensory design strategies. Coburn [5] noted this enabled both the client and the designer to discover a better understanding of how an emerging design might impact on the occupants' health, productivity, creativity, focus and feelings of safety. At Cardiff Metropolitan University there is a Perception Experience Laboratory (PEL) which provides an immersive experience of designs. It includes both sight and sound and could be extended to include smell. This is more inclusive version of VR as it can accommodate a large group of participants immersed within one large enveloping screen. Participants can interact and point to various objects in real time. Immersion allows architects to demonstrate their designs and gain instant feedback well before the more technical layers of a design are committed. Data used to inform future design will no longer need to be obtained retrospectively from mock-ups or post-occupancy surveys, architects could develop an alternative form of POE-based on Pre-Occupancy Evaluation.

## 3 Sensory Responses

**AN OVERVIEW**: Humans are sensory beings. They perceive the world through their senses. Their sensory responses to designed spaces helps them to perceive the physical world around them. The five common senses were first noted by Aristotle. They are: **sight** (vision), **sound** (audition), **taste** (gustation), **smell** (olfaction), and **touch** (haptics). Mammals also respond to heat and cold (thermoception), equilibrium relating to balance and gravity (equilibrioception), pain (nociception), and their own body awareness (proprioception). Architects can allow for each of these senses separately or in any combination to provide sensory signals that can inform an occupant's perception of their new environment.

Aesthetics is a Greek word derived from 'perceiver' or 'sensitive'. It is often used by occupants to describe their cognitive understanding of the way things *look and feel*, but the aesthetics of architecture can be designed for other senses to provide acoustic aesthetics, haptic aesthetics, thermal aesthetics etc. The way a space looks is both important to the designer and to the user but, as Ji Holl [6] points out, *the way it feels*, *the smell and sound of a place* also contributes to a complete experience of a place and to an occupant's feeling of delight and pleasure. Goldhagen [7] suggest that, in most cases, this happens unconsciously. Even so, they are very much a part of the 'aesthetic' design of the architecture.

**SIGHT**: is essentially *one-directional*. Humans can only perceive what they see in front of them, and they can choose whether to see it or not by closing their eyes. Much of the field of view is peripheral vision and not in focus. Loschky et al. [8] determined that focussed vision is within a cone of vision between 3 and 5°. This means that less than 3% of our binocular vision is in focus. The rest is peripheral vision which allows alerts visual changes and the choice to focus on detail. Ulrich et al. [9] noted that good visibility requires good light, adding that good light affects both the psychological and physiological responses of human beings, helping to reduce the risk of depression and fatigue whilst improving alertness and modulating circadian rhythms. Wirz-Justice [10] advised that indoor lighting between 50 and 300 lx is usually satisfactory for the visual system to function, adding that for most occupants this could be well below acceptable for the human circadian system.

**SOUND**: In architectural design, sound tends to be limited to how noise can be controlled or minimised but the aesthetics of sound can add delight and legibility to a designed space. In some buildings, sound is as important to the architectural experience as sight. Whilst sound is invisible it is shaped by the spaces in which it is produced. It is *omnidirectional*. Sound is more often difficult to exclude than sight. It reveals what the eye cannot see, often providing subconscious clues about the identity or proportions of a space.

**SMELL**: Smell is omnidirectional. It is more difficult to avoid than sight, but good spatial design can help to control its movement. Every space has its own characteristic smell which can have a lasting and emotional effect. Mehta [11] noted this could possibly have a stronger and longer lasting influence on the architectural experience than sight. Human capacity to detect by smell cannot be underestimated. MGann [12] confirmed that humans have 400 smelling receptors, fewer than many animals but, because the human brain is far more complex, it helps to make up the difference in detecting changes.

**TASTE**: Forster [13] and Yi Hsuan [14] have shown through research that colours and sound can generate oral sensations related to taste. The sensation of taste is closely related to smell and there is usually a choice to sense tasting. It.is more often experienced when all other senses perceive it is safe to taste. Eberhard [15] found that a restaurant can influence a customer's 'conditioned response' to the taste of the food through lighting, colour and comfort.

**TOUCH**: Touch is the first sense to develop in human beings. Ackerman [16] noted that it influences how humans make decisions through the provision of critical information on the environment and of the physical world. Touch is important to a human's well-being. Mammals perceive touch through physical pressure, temperature, light touch, vibration, pain etc. It is often perceived in combination with another sense, all of which are attributed to different receptors in the skin. Touch can be selectively experienced through the curiosity of another sense, but it is often sensed without choice.

**INTUITION**: has been described as the 'immediate knowing or learning of something without the conscious use of reasoning'. Solovyova [17, 18] noted that intuition is intrinsically part of the designer's experiences, and memories, often being completely unaware of them. Architects can abstract and combine images of past experiences, utilising this knowledge to assist them in the creative design process, adding that an architect's intuition often helps to prioritise and rationalise design solutions; a crucial process in the design of human sensitive environments.

**EQUILIBRIUM**: is an essential response to balance. The vestibular complex within the inner ear is important for balance. It contains receptors that regulate a sense of equilibrium. A sense of balance is retained because the *Eustachian tube* in the middle ear equalizes the air pressure in the middle ear with the air pressure in the atmosphere. The sense of space is known as proprioception. It deals with how the brain learns and comprehends where your body is in space. For example, proprioception enables most occupants to climb steps without looking at each one.

**CROSS MODAL RESPONSES**: Cohen [20] noted the brain exhibits a *cross-modal plasticity* in subjects with blindness from an early age, possibly accounting for the ability to use the reflection of sound to sense *sound shadows* in built spaces. Similarly, Spence [21] notes that the visually impaired often use the sense of touch to determine changes in materials for aiding navigation and to read braille.

Gestalt principles suggest that the sensory input from a designed environment is not simply perceived as the sum of its individual components. The sensory effect of individual environmental characteristics is better known than their combined effects. If a space lacks good lighting, visibility is poor and it can affect the ability to listen. Indoor temperatures can also make occupants so uncomfortable that their ability to listen can be impaired. Schreude [22] noted that occupants who are *touch-sensitive* may be affected by the building's materials and components and some may become distracted by smells within the building. All can disturb an occupant's auditory process. Environmental characteristics such as luminosity of light sources, the nature and level of ambient noise and acoustics, the presence of specific odours, colour hues and shades, and materials and atmospheric factors such as temperature and humidity, all generate sensory input and, when combined, contribute to specific reactions in the observer (ibid).

Loomis [23] says that the environment is sensed through various modes, placing *a spatial image* within the mind. Lewika [24] determined there is an associative memory link between the senses and emotions, known as *place attachment* in psychology, which can be measured quantitatively using Psychometric and Likert scales. The integration (or isolation) of inputs from different sensory modalities not only transforms some of their individual characteristics but it can do so in ways that enhance the quality of life for occupants. There might be design opportunities in isolating spaces that are sensorily distracting to pupils. Smells from the dining hall is one example that could affect the need to listen and learn.

Perhaps the new design aim should be to design for experience rather than just appearance, as it will allow for all relevant sensory responses. When different sensory modalities are integrated, the result differs from a simple accumulation of the effects of each modality separately. Sensory designs can activate all senses to varying degrees of intensity or concentration; both in the delivery and in the reception of a sensory response. In 2014, Spence et al. [25] revealed that the intensity of senses might be better limited to two senses in order not to confuse. This was reported in a study into 'Store Atmospherics' when it was found that there appears to be an optimal level of stimulation leading to a risk of sensory overload. In the design of new schools, the first author now proposes there is an opportunity to play tunes with a range of sensory responses, particularly within long circulation spaces where it is possible to link areas with a range of sensory experiences. Corridors can be designed to modulate the occupant's experiences along the journey, adding interest and awakening the senses. Changes in intensity can be introduced, limiting sensory responses to two being prioritised at any one time. Diurnal changes in daylight might also be incorporated to enhance circadian expectations.

## 4 Methodology

Through their publications of '***The Inhabitant***,' Stride Treglown has created an informal approach to gathering feedback on the '*delight*' of completed projects. Feedback has been more open and engaging, and it provides a more insightful form of information when compared with the more formal and impersonal approach of a questionnaire. Feedback from completed school projects could follow a similar ***informal review model***, possibly involving a walk around the school to prompt responses with the participants. Architects should evolve a new design paradigm that emerges from ***observing and listening*** to the occupants, ultimately allowing the architect to take a ***holistic approach*** to design.

Creswell and Plano Clark [26] noted that mixed methods of research will allow feedback from qualitative research studies can inform data from quantitative research, offering a chance to relate building performance with the experiential responses of the building in use. Currently, there is no POE framework for designers to collect feedback on the occupant's sensory responses to designed spaces. As a result, a significant opportunity is being missed to replicate the more positive outcomes in future projects. The aim will be to link the technical requirements of a building to the innate desire for delight in the spaces designed for good architecture.

The next phase of the first author's research will include qualitative feedback from schools completed by him over the last decade. Participants will include staff and pupils and, hopefully, the community who use the facilities outside normal school hours. All pupils will be in *loco parentis,* making it difficult for non-staff to engage fully with them. There is an opportunity for the pupils to be set a learning task by the teachers who will be able to anonymise all qualitative feedback from pupils so that it can be included in any published evaluations. A Likert scale may be used to simplify these initial responses to the occupant's perception of the spaces. Pupils may also be happier to use a Likert Scale to create some supporting quantitative data.

Face-to-face and Focus Group Meetings will only take place when there has been at least twelve-months after completion. As a precursor, there will be a short series of questions to help to introduce the concepts of the study and to establish the potential interest in participation. Consultations will be developed to allow for free-flowing discussion on how they feel about the designed spaces. Data will be recorded by note-taking and by photography or video of the participants and any pictorial or written work produced. Audio and video recording must have prior permission of all participants attending the session. Preparation is key. An informed consent will be sought for any research work, followed by an initial meeting with the Headteacher to agree on how the data will be used and stored. Any photographs would avoid images of pupils (obscuring any that had unwittingly got in the frame). Output from these consultations will help to inform the proposed changes to improve the POE procedures for architects aiming to enrich the sensory responses of all who use the spaces they design.

## 5 Discussion

The concept of 'sensorially designed spaces' is certainly not new. Even so, there has been little progress in the use of sensory design and researchers are still noting a need for change. Hence this study. The authors query why design teams wait until the end of a project to evaluate a project. Surely it is too late when the client has moved in. Evaluations should become an intrinsic part of the design process. The challenge is in setting the quality design outcomes as a target at the start of a project, making it part of the initial design, and then in programming sufficient time to review these quality targets at each of the design development stages. Design reviews could then involve the client with whom the designer can later evaluate the quality outcomes post occupation.

Feedback on how the fabric is performing provides an essential quarry of information, leading to a degree of replication of successful details. Such evaluations are more accurately called Building Performance Evaluations. There is no disputing that architects are keen to know how their designs are performing technically. Climate change is of great concern to practicing architects but there is still a need to provide some delight in the final project and this delight should be more than just an evaluation of the building's appearance. Feedback requires occupants to be involved and they will naturally evaluate their surroundings with respect to their 'common' sensory responses. Architects rarely seek or record these feelings, but there is a detectable change, and this is being influenced by recent scientific research.

Whilst architectural design has been traditionally linked with the visual arts, more recently it has attracted the attention of psychologists and cognitive neurologists who are keen to understand how the built environment affects the wellbeing of its occupants, both their physically and their mentally. Psychologists recognise that the designed environments affects all building users at a social, emotional, and cognitive level [1]. Cognitive neuroscience [13] has shown that, while insufficient attention is paid to various sensory nuances in design, it cannot be assumed that occupants are unaffected by them: consciously or otherwise. References to associated research in other disciplines, should help to clarify how humans might respond to designed spaces, leading to the opportunity to develop some meaningful vocabulary and facilitating a dialogue between the designer and the client to evolve design parameters suitable for future projects. Feedback from completed projects will inform that dialogue, resulting in a direct link between post occupancy evaluations and the design brief for the next project.

Designed experiential changes can awaken our senses and enhance our enjoyment (delight) of designed spaces. Biederman [27] noted there is an inherent hunger for sensory changes in an architectural design. Merrifield [28] found that even small amounts of boredom can cause stress, recommending a need to produce a design feature or a sensory change along a journey, otherwise there is a risk of users becoming cognitively disengaged. Passini [29] advised that monotonous interior designs can confuse some occupants, whereas designs with frequent visual reference points and exterior views can improve the occupants' wayfinding. Neuroscientist, Ellard [30] concluded that: '*the holy grail*' is to produce frequent changes in the environment to ensure occupants remain cognitively engaged and avoid undesirable psychological disbenefits.

In 2018, Ricci [1] noted there is an intrinsic link between architectural design and human psychology, adding that a successful building design can have a clear psychological and physiological impact on the occupants. Two years later, Spence [21] noted that architecture has a profound influence over the well-being of occupants, positing that a neglect of other senses could have a causal effect on societal problems faced by the occupants. Research sometimes focusses on the negative effects of building design, such as unwanted noise affecting blood pressure and sufficiency of daylight affecting circadian rhythms, whilst Coburn [5] suggests that others provide some positive feedback relating to improved learning, social behaviour, and emotional wellness. Sheehan [31] found that wellbeing in secondary schools influenced how successful students might 'feel' about their work and how they might feel in their peer relationships, indicating there was a psychological dimension in the design of schools.

## 6 Conclusions

A designed environment holds the potential to influence how the occupants feel, and by extension, their behaviour. Architects should familiarise themselves with these psychological impacts, and design accordingly. When evaluating completed buildings, designers should be encouraged to query how the building affects the occupants for whom it was designed. The architectural profession's approach to POE needs to include feedback on how the occupants ***feel*** about the spaces they have designed. The authors suggest that architects will only need ***a nudge*** to make change in their POE procedures, and this can be achieved in how they gather feedback from inhabitants by including some ***qualitative*** as well as ***quantitative*** feedback from completed designs. Architects will then become better informed on what to incorporate in their initial concept designs by using *up-to-date feedback* from their designs 'in use'.

Existing ***quantitative*** feedback is undoubtedly crucial to monitoring and recording of sustainable measures, but there will be greater clarity when the experiential reviews of ***designed spaces*** is included alongside the sustainable and technical performance of the building's materials and components. A much-loved building 'in use' will endure over time, making the use of materials and components far more sustainable.

A more multisensory approach to the built environment, ***designed to be sensitive in the way the senses interact***, should create a more immersive, engaging, and delightful experience that contributes to a better sense of wellbeing for all who use the building. References to a range of associated research disciplines and experiences should, in time, support the designer's own ***intuition and experience***. Spence [21] concludes that it would be unrealistic to assume the dominance of visual aesthetics will change immediately but the design profession should at least try harder to challenge it. Through a change in POE, architects can learn far more from their building designs in use, allowing them to fine-tune the briefing process in their future projects.

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## References


1. Ricci, N.: The psychological impact of architectural design. CMC Senior Theses. 1767 (2018). https://scholarship.claremont.edu/cmc_theses/1767
2. Nicholson, N.: How hardwired is human behavior? Harvard Bus. Rev. (1989) https://www.researchgate.net/.../13115707_How_hardwired_is_human_behavior
3. Stangor, C., Walinga, J.: Introduction to Psychology, Victoria, B.C. (2014)
4. Cooper, I.: Post-occupancy evaluation—where are you? Build. Res. Inf. **29**(2), 158–163 (2001). Special issue: Post-occupancy evaluation
5. Coburn, A., Vartanian, O., Chatterjee, A.: Buildings, beauty, and the brain: a neuroscience of architectural experience. J. Cogn. Neurosci. **29**(9), 1521–1531 (2017). http://doi.org/10.1162/jocn_a_01146
6. Yang, W., Ji Holl, S.: Thin ice. In: Juhani Pallasmaa, The Eyes of the Skin (2005)
7. Goldhagen, S.: How architecture affects your brain: the link between neuroscience and the built environment. ArchDaily. July 25, 2017. https://www.archdaily.com/876465/how-architecture affects-your-brain-the-link-between-neuroscience-and-the-built-environment
8. Loschky, L., et al.: Scene perception from central to peripheral vision. J. Vis. **17**(1), 6, 1–5 (2017). http://doi.org/10.1167/17.1.6
9. Ulrich, R.S., Zimring, C., Joseph, A., Quan, X., Choudhary, R.: The Role of the Physical Environment in the Hospital of the 21st Century: A Once-in-a-Lifetime Opportunity. The Center for Health Design, Concord, CA (2004)
10. Wirz-Justice, et al.: Light, health and wellbeing: implications from chronobiology for architectural design. World Health Design (2010). https://www.researchgate.net/publication/298215187_Light_Health_and_Wellbeing_Implications_from_chronobiology_for_architectural_design
11. Mehta, B.K.: Smell and the Architectural Experience. Assistant Professor of Neurology, Department of Neurology, University of California, Los Angeles (2014)
12. MGann: Poor human olfaction is a 19th-century myth | Science (sciencemag.org) (2017)
13. Forster, F., Spence, C.: What Smell? Temporarily Loading Visual Attention Induces a Prolonged Loss of Olfactory Awareness. PubMed (2018). https://doi.org/10.1177/0956797618781325
14. Yi Hsuan, T., et al.: Environmental sounds influence the multisensory perception of chocolate gelati. Received: 12 March 2019; Accepted: 10 April 2019; Published: 15 April 2019, Foods **8**, 124 (2019). http://doi.org/10.3390/foods8040124
15. Eberhard, J.P.: A place to learn: how architecture affects hearing and learning. The ASHA Leader Feature, 1 Oct 2008. https://doi.org/10.1044/leader.FTR6.13142008.26
16. Ackerman, J., Christopher, I., Nocera, C., Bargh, J.: Incidental Haptic Sensations Influence (2010)
17. Solovyova, I.: The Role of Autobiographical Experiences with Emotional Significance of an Architect in Design Conjecturing. Volgograd State Architectural and Engineering University, Russia (2008)
18. Solovyova, I.: Intuition in interior design. Intuition Regul. Pap. Archnet-IJAR Int. J. Architectural Res. **2**(3), 182 (2008)
19. Cardaioli, M., Scattolin, M., Bisiacchi, P.: Equilibrioception: A Method to Evaluate the Sense of Balance. Department of General Psychology, Padova, Italy (2017)
20. Cohen, L., et al.: Functional relevance of cross-modal plasticity in blind humans. Nature **389**(6647), 180–183 (1997). http://doi.org/10.1038/38278. PMID: 9296495
21. Spence, C.: Cognitive Research: Principles and Implications, vol. 5, p. 46. Springer Publications, Berlin (2020). http://doi.org/10.1186/s41235-020-00243-4
22. Schreude, E., Jan van Erp, J., Toet, A., Kallen, V.L.: Emotional responses to multisensory environmental stimuli: a conceptual framework and literature review. SAGE OPEN, 1–19 (2016). http://doi.org/10.1177/2158244016630591
23. Loomis, J.M., Philbeck, J. W.: Measuring Spatial Perception with Spatial Updating and Action (2008)

24. Lewika: Memory as enabler of place attachment | Request PDF (researchgate.net)
25. Spence, et al.: Store atmospherics: a multisensory perspective. Psychol. Mark. (2014). http://doi.org/10.1002/mar.20709
26. Creswell, J.W., Plano Clark, V.L.: Designing and Conducting Mixed Methods Research. Sage, Thousand Oaks, CA (2007)
27. Biederman, I., Vessel, E.A.: Perceptual pleasure and the brain. Am. Sci. **94** (2006)
28. Merrifield, C.: Characterizing the Psychophysiological Signature of Boredom. University of Waterloo, Waterloo (2010)
29. Passini, R., Pigot, H., Rainville, C., Tétreault, M.H.: Wayfinding in a nursing home for advanced dementia of the Alzheimer's type. First Published Sept 1, 2000. Research Article. http://doi.org/10.1177/00139160021972748
30. Ellard, C., Montgomery, C.: Testing! Testing! A psychological study on city spaces and how they affect our bodies and minds (2011). Retrieved Oct 3, 2017, from http://cdn.bmwguggenheimlab.org/TESTING_TESTING_BMW_GUGGENHEIM_LAB_2013_2.pdf
31. Sheehan, D.: Can secondary school architecture build community, encourage working successfully and enhance well-being? Student and staff evaluations. Exeter University, Child & Community Psychology, May 2015

# A Methodology for Assessing the Impact of Enhanced Energy Performance Standards on the Thermal Performance of Masonry Construction Dwellings, in the United Arab Emirates

**R. A. Hagi, J. R. Littlewood, and F. Sanna**

**Abstract** STUDENT PAPER. The construction sector is responsible for the largest percentage of the total final energy use and carbon emissions worldwide. In the case of the United Arab Emirates (UAE), buildings account for more than 70% of the total electricity used by all sectors, including residential buildings, for cooling to mitigate the high local external temperatures. The UAE residential market sector is mainly in the form of extensive government-sponsored housing programs, and large privately funded rental developments. The dominant construction method for both government and private housing projects is in the form of a concrete post and beam structural system, with insulated concrete blockwork infill. However, in 2020 research indicates that in adequate construction quality is among several causes which lead buildings to perform differently to what was defined in the design stage, commonly referred to as the 'energy performance gap'. Thermography has been used by many experts in the UK and Europe when buildings are in construction and in operation to illustrate qualitatively, defects in the construction fabric including unwanted air leakage or discontinuity of insulation, which can result in heat loss. This research project aims to adapt the methodology for thermography tests to measure unwanted air-conditioned air-cooling loss from residential buildings in the UAE. This paper reports on initial field work using thermography in the summer of 2020 in a residential building, Al Ain City. The outcomes of the research project will be recommendations for improvements to workmanship, and ultimately reduced energy use for cooling and associated carbon emissions in the UAE.

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## 1 Introduction

This paper introduces a Professional Doctorate in Engineering (DEng) research project being undertaken by the first author, which is adopting a multi-methodological approach to assessing the operational energy performance of dwellings in the UAE. Like many countries, in 2021 the impact of climate change is having a detrimental impact on occupant thermal comfort in dwellings, which in the UAE typically rely on air conditioning for eight months per annum (April to November). The performance gap, which has been well documented since 2010 in the UK [1], where design aspirations for dwelling energy use and associated carbon emissions is worse than predicted when in operation, largely due to inadequate construction quality. The focus in the UK for many researchers [2–5] has been to implement enhanced quality control checks during the construction process, to prevent unwanted heat loss, since most UK dwellings require heating for six months of the year (October to March). Conversely in the UAE the focus is to prevent air-conditioned cooled air escaping. In 2017, the UAE Government introduced enhance energy performance targets to achieve Energy Efficiency (EE) standards [6]. This paper introduces the problems which lead to the performance gap in residential buildings in the UAE, and the proposed methodology that will be implemented as part of the DEng research project, to try and resolve the issues.

## 2 Background and Context to the UAE

In the UAE there has been significant built environment growth that coincided with its economic boom since 1980, funded from immense oil revenues [7]. The UAE population increased from one million inhabitants in 1980 to 9.8 million inhabitants in 2020 [8]. Most of the population lives in urban settlements [9]. The UAE's residential sector has grown through extensive programs from the government, mainly detached houses using masonry construction, amounting to about 65% of urban fabric, according to the National Statistics Center [10]. Seventy five percent of electricity is consumed in buildings, with 40% for cooling through active air conditioning [11], and 45.9% of energy consumption is attributable to residential buildings [12] which is recognized as the most demanding building type in terms of cooling demand due to the extremely hot climate [13]. The UAE's hot arid climate, characterized by extreme high summer temperatures, and high humidity on the coastal zones [14]. Al Ain City (location of change project) has a desert climate with year-round sunshine and was classified as bioclimatic region of gravel plains [15]. Temperature, humidity and solar irradiance are the most influential climatic factors in the UAE, where the National Bureau of Statistics recorded the maximum annual temperature average as being some 45 °C in August with a mini-mum of just 13 °C in January [16].

Despite the harshness of climate and its impact on a building's cooling needs and increasing electrical demands, the construction methods and materials used in housing were not controlled until 2010 [17].

## 2.1 Sustainable Initiatives and Measurements

The UAE central government acknowledges the above issues and has introduced several energy conservation measures as an attempt to limit energy consumption (for cooling) and reduce the carbon footprint as listed in Table 1. The Energy Strategy 2050 aims to decrease the energy consumption culture by 40% [6]. Additionally, it targets increased implementation of Energy Efficiency (EE) standards with monitored building performance and audits to achieve greater EE technology adoption and demand site management [18]. This indicates the need for realistic solutions, which forms the basis for the research project and change within the UAE construction industry. The Energy Strategy 2050 will be implemented in phases; one of the phases will focus on research and development in addition to innovation and creativity to achieve EE in the construction field. The need of research and development in construction is cited in many industry reports, such as the Strategy Report [19], which suggested that "*strategy should include a tailored regulatory framework; a communications and information initiative to persuade residents, builders, and other stakeholders to reduce their energy consumption; and a research and development (R&D) component to make sure the UAE is capitalizing on emerging technology to boost efficiency*". The first author will explore ways to work with government authorities to develop more detailed regulations and frameworks that dictate energy efficiency in buildings, particularly during construction.

**Table 1** Energy related targets to be met through the UAE [20]

| Location | Originated | Target action | Target date |
|---|---|---|---|
| Abu Dhabi | 2015 | 15% Waste diversion, 22% Power saving, 32% Water saving, 50% Renewable and clean energy | 2030 |
| Dubai | 2015 | 30% Power saving, 30% Water saving, 25% Renewable energy | 2030 |
| Ras Al Khaimah | 2015 | 30% Power saving, 20% Water saving, 20% Renewable energy | 2040 |
| Sharjah | | 30% Power saving, 30% Water saving | 2040 |
| UAE | 2017 | 40% Increase consumption efficiency of individuals and corporates, 50% Clean Energy, 70% Reduction in carbon footprint | |

### 2.2 Sustainable Assessment Tools

The UAE introduced several control procedures that apply to new construction. In 2010 the Urban Planning Council in the Emirate of Abu Dhabi established Estidama, the local sustainability framework to provide a rating system applicable for the United Arab Emirates climate [21]. Similarly, the Green Building Regulations and Specifications (GRS) [22] in the Emirate of Dubai (2011) was established as a first step toward implementing green building strategies. The approach taken in these assessment tools are similar to both the Leadership in Energy and Environmental Design (LEED) [23] and Building Research Establishment Environmental Assessment Method (BREEAM) [24] in terms of quality assessment system, whereby projects are awarded points for prerequisites and optional credits that are grouped under several categories, but the details of the process and the relative importance of variables/considerations differ [25]. The focus in both resides in the specification of minimum U-values for walls and roofs. For example, in Dubai, Green Building Regulations limit thermal transmittance (U-values) for the roof and walls to a maximum of 0.3 W/m$^2$ K and 0.57 W/m$^2$ K [21], respectively, whereas in Abu Dhabi, the Estidama PEARL code prescribes (at its lowest rating) maxima for roof and wall U-values of 0.14 W/m$^2$ K and 0.32 W/m$^2$ K, respectively [26]. Table 2 shows energy credits considered in LEED, BREEM and Estidama [25].

The aim of the UAE' sustainability assessment tools is to act as pivotal element in the design of sustainable buildings [27], but it is not always clear the how effectiveness of these tools in aiding to create sustainable buildings. In the authors' professional experience these tools used in the design and construction stages are not revisited once a building is complete and in use. The concept of Post Occupancy Evaluation should be combined to these tools, where the analysis of operational energy data can determine whether the design, construction, commissioning, and operation is as anticipated at the design stage. These sustainability tools will be explored further within this research project to gain feedback from construction industry participants on how effective they find these tools, through focus groups and/or questionnaires.

**Table 2** Energy credits comparison of BREEAM, LEED v4 and Estidama

| Credit | BREEAM | LEED v4 | Estidama |
|---|---|---|---|
| Energy efficiency | √ | √ | √ |
| $CO_2$ emissions | √ | √ | √ |
| Sub-metering/measurement | √ | √ | √ |
| Commissioning | √ | √ | √ |
| Lighting | √ | √ | √ |
| Renewable energy | √ | √ | √ |
| Demand response | | √ | |
| Peak load reduction | | | √ |

### 2.3 Current Practice in the UAE Residential Sector

There are different housing programs in UAE, real state housing program where developer build for sell/rent the residential units, and national housing programs, where the government build for the local citizen. Within the national housing program there are two methods of housing provision. First, the government provides residential units within integrated community and delivers thousands of houses for middle income sector which represent almost 40% of all households in UAE [28]. In the residential sector, the selection of the procurement strategy is the key to satisfy construction project's requirements of time, cost and quality. There are two main procurement strategies in residential sector, the traditional lump sum and design and build strategy contracts. In the traditional lump sum, the client's building design consultants completes the design before the building contractor is chosen to guide the client through the selection of the building contractor, based on their tender price and their reputation for the quality of their work [29]. The building contractor commits to a lump sum price and completion date, taking the financial responsibility and program risk of the building works, whilst the client accepts the risk for the quality of the design and the design team's performance. In the design and build procurement strategy, the building contractor undertakes the detailed design and construction for a lump sum price [ibid].

### 2.4 Existing Studies on Sustainable Initiatives

The UAE has achieved some milestones including the development and implementation of building regulation standards related to energy performance [30]. However, there are significant untapped opportunities to enhance energy efficiency level for new and existing residential buildings. Throughout the Middle East and North Africa (MENA) region, limited studies [31] are reported to review the status of implementation of energy efficiency standards for buildings including housing stocks. In 2019, Krati [32] has evaluated energy efficiency policies prevalent in the Arab countries for both residential and commercial buildings, where more than 50% of these countries have adopted energy efficiency codes for new buildings. However, these codes are typically limited to prescriptive requirements for the U values) of exterior walls and roofs, and the use of double glazed glazing for windows [ibid]. The enforcement of these building energy efficiency codes is still a challenge for most Arab countries. A study in 2015, showed that adapting the built environment and energy efficiency building codes to work with the Gulf Region's harsh climate and resulted with up to 60% reduction in energy demand due to retrofit programs to existing buildings, and 70% in new buildings in full as first use [33]. However, the benefits of energy efficiency remain largely untapped in Gulf Cooperation Council (GCC) countries, (the UAE is member of the GCC) due to factors such as bureaucracy and governance challenges, lack of awareness, limited enforcement of existing regulations, and significant energy subsidies in full as first use [34].

Another study about the UAE, suggested that more stringent building energy efficiency code requirements can be developed for all new UAE residential, governmental, and commercial buildings [35]. Based on the results, at least an additional 40% in energy savings from existing building energy efficiency requirements can be achieved cost-effectively [ibid]. A change to the enforcement of building energy efficiency codes, as proposed in this research project, is needed. For achievable change, the authors believe there should be a sensible mechanism to enable this to happen, which could be series of workshops/online sessions for construction field members, and government authority bodies to facilitate the change by introducing specific compliance requirements as part of their energy efficiency code on the new building stock.

## *2.5 Energy Performance Gap in Residential Buildings*

Construction defects in residential buildings, that occurred in the envelope are recognized to contribute to the energy performance gap between the predicted and actual energy performance [36]. Construction defects can be defined as deficit in the construction process, that been caused either from design, materials and system, or workmanship failure. Many researchers have addressed the construction defect type, classification, and source of defects [37], or the relationship between quality defects and thermal performance of buildings [38]. A study carried out in Al Ain (UAE) examined the thermal behavior and construction quality of residential buildings' envelope, through an infrared thermography audit, performed on several existing and under construction residential units [39]. The results highlighted three major areas of defects: lack or discontinuity in the building envelope insulation, thermal bridging, and discrepancies due to non-compliant design changes. Littlewood and Smallwood [40] suggested a mandatory compliance test method during the construction stage to reduce instances of the performance gap and its impacts upon occupant comfort, energy costs and carbon emissions. However, in the UAE context, research investigating housing defects that occur due to inadequate building fabric, or to assess whether buildings codes and standards have met design aspirations in operation for energy use limited. Hence, the main objective of this research project is to propose a new approach for thermal performance assessment of residential buildings in UAE, and quality control of the building fabric in new dwellings as illustrated in Fig. 1.

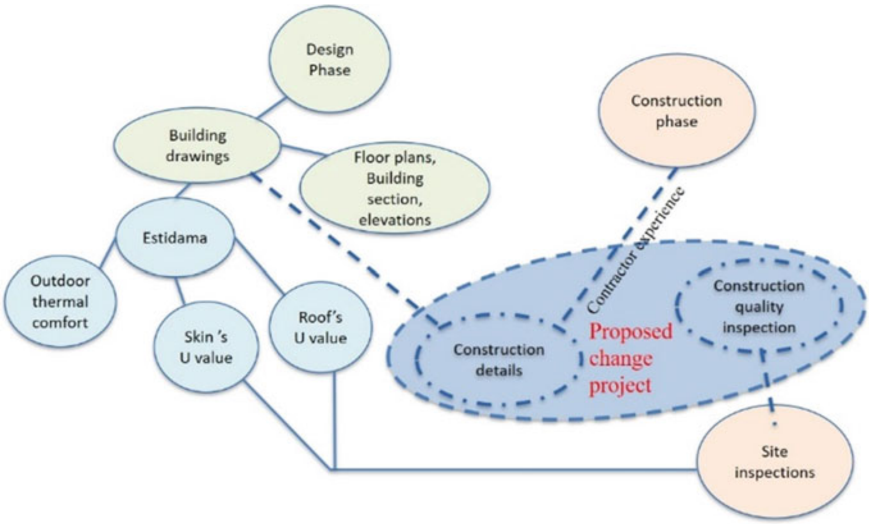


**Fig. 1** Construction quality assurance and its relation to energy impacts

## 3 Methodology

This DEng change project is following a Participatory Action Research (PAR) methodology, which is considered a subset of action research, and it's a "systematic collection and analysis of data for the purpose of taking action and making change" by generating practical knowledge [41]. PAR is a qualitative research methodology that requires a comprehensive understanding and consideration between research and real construction process [ibid]. PAR is distinct from other qualitative methodologies by democratic, equitable, liberating, and life-enhancing qualitative inquiry, that reveal an individual's feelings, views, and patterns without control or manipulation from the researcher [42]. Furthermore, the framework for PAR consists of fact finding, action, reflection, leading to further inquiry and action for change [43]. Within this change project, the first author is exploring the action research principals that have been applied to other aspects of change within the construction industry. De Oliveira et al. [44] adopted a PAR methodology to describe the procedures and decision making during the project procurement, including the evaluation of the tenders, and succeeding competitive negotiation process. The action research method is being used by Grant et al. [45] during the investigation of the sensory experiences of users in schools in Wales UK (between 2019 and 2023), to propose a new approach of sensory Post Occupancy Evaluation (POE). The main objective of this research project is to develop guidelines to enhance the thermal performance of residential building in UAE, to reduce the unnecessary loss of air-conditioned air. The participants of this project are listed in Fig. 2, and the interrelationship between the participants is related to the type of procurement as discussed in Sect. 2.3.

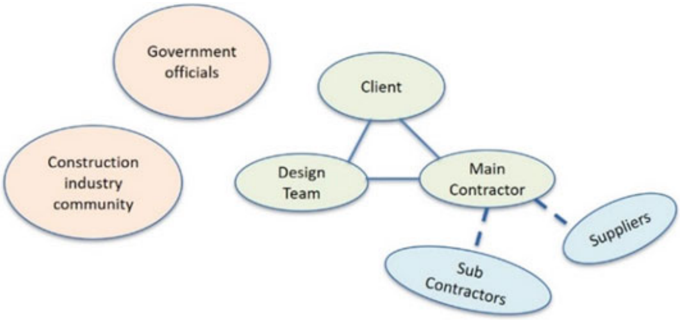


**Fig. 2** Participants of the research project

Various methods for data collection have been used in PAR, that differ for each specific issue or situation, where the researcher and participants collaborate to establish the appropriate methods of data collection [46]. Some of the effective methods of data generation employed in PAR are, focus groups, participant observation and field notes, interviews, diary and personal logs, questionnaires, and surveys [41]. However, it is recommended that at least three selected methods are used to excel the limitations of each individual one and produce more effective outcomes.

## 4 Anticipated Project Outcomes

The UAE Governmental Municipality especially the Abu Dhabi municipality which governs Al Ain city, the location of change project, should benefit as the legislation authority for building regulations, as data collected in this project will be directly disseminated to them. It is hoped this dissemination will lead to updates to the Abu Dhabi International Building Codes (ADIBC) [47] and provide clear direction for engaging with all members in the construction process. The outcomes of the project could also complement the existing sustainable assessment tool such as Estidama Pearl Rating System [21] with building performance evaluation guide that will include construction quality guidelines, standard construction details, and a building quality inspection protocol using thermography. It is hoped that all stakeholders within the UAE construction industry, including architects, building engineers, and contractors will benefit from the suggested building performance guide. House owners as an end user of buildings could also benefit from the proposed guide, if defects are identified and rectified that lead to reduced energy use and costs for cooling. There are some studies which considered the area of building performance evaluation, but most of these studies are carried out in developed countries which have different weather patterns, environmental and social variables as compared to GCC in general. and the UAE specifically. For instance, the outdoor temperature in the UAE in summer reaches 50 °C [14]. A building performance evaluation guide that is developed for residential buildings in mild temperatures would not be effective for residential building in extreme hot and humid climatic conditions. This research project is aimed to reduce energy use and the associated carbon emissions for residential cooling, which is one of the main phases to implement Energy Strategy 2050 adopted by the UAE Government [6]. The main outcomes of the project will be developing a building performance evaluation guide that will provide a guidance for the operatives with the necessary construction details; to meet energy efficiency targets, guidelines on energy efficiency for architects and architectural student to support existing building regulations, and quality inspection protocol during construction to ensure building's thermal performance.

## 5 Conclusions

This paper has discussed a new approach for thermal performance assessment of residential buildings in UAE, that will guide to close the gap between design and as built energy performance. The paper highlighted the challenges, that the UAE government is facing to meet the current (2021) energy efficiency targets in terms of improving the construction industry and meeting carbon targets, without a change to the process of construction and procurement of buildings, reflecting the changes to the be proposed in the DEng project. A lack of construction quality control is recognized as the root cause of the problems with energy performance of residential buildings, which will be addressed through the suggested approach to construction detailing, linked to improved quality control from design through to the construction and commissioning phase. This project is about developing a more holistic approach to thermal performance assessment of residential building where all construction industry members are involved to produce more stringent construction quality control protocol and design guidelines on energy efficiency, which will lead to reduced energy usage for cooling and associated carbon emissions in the UAE.

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## References

1. Bell, M.: Getting real on 'zero'. CIBSE J. **12**(1), 5–5 (2010). ISSN 1759-846X
2. Gupta, R., Gregg, M., Cherian, R.: Tackling the performance gap between design intent and actual outcomes of new low/zero carbon housing. In: ECEEE Summer Study Proceedings, pp. 1315–1328 (2013)
3. Littlewood, J.R.: Assessing and monitoring the thermal performance of dwellings, chap. 4. In: Emmitt, S.W. (ed.) Architectural Technology: Research and Practice (2013)
4. Gorse, C.: Building performance and measurement: its place within a variable climate. Int. J. Build. Pathol. Adapt. **38**(1), 1–2 (2020)

5. Zero Carbon Hub: Closing the gap between design and as built performance, end of term report (2014), [Online]. Available: https://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf. Last accessed 2021/05/30
6. UAE Energy Strategy 2050. https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/federal-governments-strategies-and-plans/uae-energy-strategy-2050. Last accessed 2021/05/30
7. Elessawy, F.: The boom: population and urban growth of Dubai City. Horizons Human. Soc. Sci. J. https://doi.org/10.19089/hhss.v2i2.60 (2017)
8. World Population Review: United Arab Emirates Population (2020). [Online]. Available: https://worldpopulationreview.com/countries/united-arab-emirates-population. Last accessed 2021/05/30
9. CIEC DATA: United Arab Emirates AE: Urban Population: % of Total Population 1960–2017 | YEARLY | % | WORLD BANK. [Online] Available: https://www.ceicdata.com/en/united-arab-emirates/population-and-urbanization-statistics/ae-urban-population--of-total-population. Last accessed 2021/05/30
10. Abu Dhabi Government Statistics Center: Statistical Yearbook Energy and Water. Available Online: https://www.scad.gov.ae/ReleaseDocuments/StatisticalYearbookEnergyandWater_2020_Annual_Yearly_en.pdf. Last accessed 2021/07/15
11. Juaidi, A., Montoya, F., Gazquez, J., Manzano-Agugliaro, F.: An overview of energy balance compared to sustainable energy. Renew. Sustain. Energy Rev. **55**, 1195–1209 (2016)
12. Radhi, H.: Evaluating the potential impact of global warming on the UAE residential building—a contribution to reduce CO2 emissions. Build. Environ. **44**(12), 2451–2462 (2009)
13. Clair, P.: Low-energy design in the United Arab Emirates—building principles. BEDP Environ. Des. Guid. (2009)
14. The World Weather: https://worldweather.wmo.int/en/city.html?cityId=222. Last accessed 2021/05/30
15. Böer, B.: An introduction to the climate of the United Arab Emirates. J. Arid Environ. **35**(1), 3–16 (1997). https://doi.org/10.1006/jare.1996.0162
16. Taleb, M.H.: Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. buildings. Front. Archit. Res. **3**, 154–165 (2014)
17. Friess, W.A., Rakhshan, K., Hendawi, T.A., Tajerzadeh, T.: Wall insulation measures for residential villas in Dubai: a case study in energy efficiency. Energy Build. **44**(1), 2011 (2012). https://doi.org/10.1016/j.enbuild.2011.10.005
18. Efird, B., Griffiths, S., Mollet, P., Al-Mubarak, I., Sgouris, S., Tsai, I.: The political feasibility of policy options for the UAE's energy transition. The King Abdullah Petroleum Studies and Research Center (KAPSARC), Saudi Arabia (2017)
19. Karlsson, P., Decker, C., Moussalli, J.: Energy Efficiency in the UAE Aiming for Sustainability, Strategy and Formerly. Booz & Company (2015) [Online]. https://www.strategyand.pwc.com/m1/en/reports/energy-efficiency-in-the-uae.pdf. Last accessed 2021/05/30
20. UAE Sustainable Initiatives: https://emiratesgbc.org/uae-sustainability-initiatives/. Last accessed 2021/05/30
21. Department of Municipalities and Transport: Pearl Building Rating System. Available Online: https://www.dmt.gov.ae/en/Urban-Planning/Pearl-Building-Rating-System. Last accessed 2021/07/15
22. Dubai Municipality, Green Building Regulation & Specification. Available Online: https://www.dewa.gov.ae/~/media/Files/Consultants%20and%20Contractors/Green%20Building/Greenbuilding_Eng.ashx. Last accessed 2021/07/15
23. The world's foremost environmental assessment method and rating system for buildings, BRE Global. Available Online: https://tools.breeam.com/filelibrary/BREEAM_Brochure.pdf. Last accessed 2021/07/15
24. Why LEED, Available Online: https://www.usgbc.org/leed/why-leed. Last accessed 2021/07/15

25. Small, E.P., Al Mazrooei, M.: Evaluation of construction-specific provisions of sustainable design codes and standards in the United Arab Emirates. Procedia Eng. **145**, 1021–1028 (2016)
26. Department of Urban Planning and Municipalities: Estidama insulation products and systems for PEARL villa rating, 2016, [Online]. Available: https://dmat.abudhabi.ae/en/ADM/ELibrary/Document%20library/Estidama.pdf. Last accessed 2021/05/30
27. Ramani, A., García de Soto, B.: Estidama and the pearl rating system: a comprehensive review and alignment with LCA. Sustainability **13**(9), 5041 (2021). https://doi.org/10.3390/su13095041
28. Elkaftangui, M., Mohamed, B.: Optimizing prefabricated construction techniques in UAE as a solution to shortage of middle-income housing. In: 2018, MATEC Web of Conference 221,01006. ICDME (2018)
29. Middle East Property and Construction Handbook 2018/19: AECOM. Available Online: https://www.aecom.com/ae/wp-content/uploads/2018/10/Construction-Handbook-2018_19.pdf. Last accessed 2021/07/15
30. Emirates Green Building Council. Defining Nearly Zero Energy Buildings in the UAE. Available [Online] Available: http://emiratesgbc.org/wp-content/uploads/2017/03/Defining-nZEBs-in-the-UAE-2017.pdf. Last accessed 2021/05/30
31. Ghabra, N., Rodrigues, L., Oldfield, P.: Improving energy performance in Gulf-region residential high-rises. CTBUH J. (III) (2017)
32. Krarti, M.: Evaluation of energy efficiency potential for the building sector in the Arab region. Energies **12**(22), 4279 (2019)
33. The regional center for renewable energy and energy efficiency (RCREEE), Arab Future Energy Index (AFEX) Energy Deficiency 2015. Cairo RCREEE. [Online]. Available: https://www.rcreee.org/content/AFEXRE2015. Last accessed 2021/05/30
34. UN-ESCWA: Energy vulnerability in the Arab region report 2021, Lebanon. [Online]. Available: https://www.unescwa.org/sites/www.unescwa.org/files/publications/files/energy-vulnerability-arab-region-english_0.pdf. Last accessed 2021/05/30
35. Krarti, M., Dubey, K.: Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock. Renew. Sustain. Energy Rev. **82**, 14–24 (2018)
36. Gupta, R., Kotopouleas, K.: Magnitude and extent of building fabric thermal performance gap in UK low energy housing. Appl. Energy **222** (2018). https://doi.org/10.1016/j.apenergy.2018.03.096
37. Forcada, N., Macarulla, M., Gangolells, M., Casals, M., Fuertes, A., Roca, X.: Post handover housing defects: sources and origins. J. Perform. Constr. Facil. (2013). https://doi.org/10.1061/(asce)cf.1943-5509.0000368
38. Alencastro, J., Fuertes, A., Wilde, P.: The relationship between quality defects and the thermal performance of buildings. Renew. Sustain. Energy Rev. **81** (2018). https://doi.org/10.1016/j.rser.2017.08.029
39. Tabet Aoul, K.A., Hagi, R., Abdelghani, R., Syam, M., Akhozheya, B.: Building envelope thermal defects in existing and under-construction housing in the UAE; infrared thermography diagnosis and qualitative impacts analysis. Sustainability **13**, 2230 (2021). https://doi.org/10.3390/su13042230
40. Littlewood, J.R., Smallwood, I.: Testing building fabric performance and the impacts upon occupant safety, energy use and carbon inefficiencies in dwellings. Energy Procedia **83**, 454–463 (2015). ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2015.12.165
41. Gillis, A., Jackson, W.: Research methods for nurses: methods and interpretation. F.A. Davis Company, Philadelphia (2002)
42. MacDonald, C.: Understanding participatory action research: a qualitative research methodology option. Can J. Action Res. **13**(2), 34–50 (2012). https://doi.org/10.33524/cjar.v13i2.37
43. Morris, M.: Participatory Action Research: A Guide to Becoming a Researcher for Social Change. Canadian Research Institute for the Advancement of Women, Ottawa (2002)
44. de Oliveira, R., Lopes, J., Abreu, M.: Insights from a project procurement strategy through an action research. Procedia Comput. Sci. **181**, 1002–1010 (2021). ISSN 1877-0509, https://doi.org/10.1016/j.procs.2021.01.275

45. Grant, P., Littlewood, J.R., Pepperell, R.: Can architectural delight improve concept design and human sensory response in schools. In: Sustainability in Energy and Buildings 2020. Smart Innovation, Systems and Technologies, vol. 203. Springer, Singapore (2021). https://doi.org/10.1007/978-981-15-8783-2_36
46. Yin, R.K.: Case Study Research: Design and Methods. Sage Publications, Thousand Oaks (2005)
47. Department of Municipal Affairs: The Code Handbook Abu Dhabi International Building Codes. http://docshare01.docshare.tips/files/22456/224563680.pdf. Last accessed 2021/07/13

# Fundamentals of Energy Modelling for Positive Energy Districts

**Luigi Bottecchia, Andrea Gabaldón, Tony Castillo-Calzadilla, Silvia Soutullo, Saeed Ranjbar, and Ursula Eicker**

**Abstract** Positive Energy Districts (PEDs) are one of the concepts developed to reduce the impact of cities and districts on overall carbon emissions. Given the innovation brought by this concept, the implementation of PEDs comes with a series of challenges. These range from the high use of renewable energy sources, through the need of a positive balance at the end of the year. To have a more optimized deployment, it is important to understand what are the must have's that are necessary to consider when modelling PEDs. This paper aims at investigating and presenting these must haves for modelling PEDs and analyzing them in relation with some of the most common definitions of PEDs to understand how this affects the modelling of a PED. The identified must haves, i.e. the loads and the technologies, the spatial and temporal dimension and the objective function, specify how PEDs are modelled when the most strict definition is considered. However, in the case of a virtual PED, which is the less strict definition, the differences of modelling a PED compared to a normal district are almost none.

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## 1 Introduction

Three quarters of the current global emissions come from the energy sector. Several initiatives are currently undergoing that aim at reducing emissions. At European level the European Green Deal provides a roadmap to make Europe the world's first climate-neutral continent by 2050 [1]. At global level, the next UN Climate Change Conference of the Parties (COP26) will likely set ambitious targets to reach net zero emission by 2050 [2]. Following this goals, various ways of reducing the impact of cities and districts on the overall emissions have been considered. Among these, Positive Energy Districts (PEDs) are one of the newest concepts. A PED is seen as "a district with annual net zero energy import and net zero $CO_2$ emissions, working towards an annual local surplus production of renewable energy" [3]. However, multiple definitions of PEDs are currently being used [4, 5]. The Europe's Strategic Energy Technology Plan (SET Plan) on Smart Cities and Communities has set the ambition to reach 100 PEDs by 2025 in Europe [6]. Being able to reach this goal means considering all the elements that contribute to create the PED concept. In fact, the elements (loads, renewable energy technologies, ICT tools, etc.) and assumptions (primary energy factors, efficiencies, etc.) which are considered in the PED concept, will affect its design. The particular characteristics of PEDs and its innovative concept make it necessary to use energy system modelling to better plan, design and implement them.

In this context, energy system modelling is an essential tool given its ability to provide outcomes that can be used by a set of different stakeholders. The use of simulation or optimization tools to model the energy performance of a district can increase operational efficiency, environmental improvements and economic benefits. There are many challenges identified in urban modelling but most of them can be categorized in three sections: technical, methodological and institutional challenges. Technical and methodological challenges are related to the limitations produced in the modelling process such as availability, quality or granularity of data; transparency and reproducibility of models; balancing model resolution, complexity, and computational tractability or the uncertainties produced in the modelling process. Institutional challenges are related to organizational, educational and structural gaps that complicate the use of urban modeling tools for urban energy planning [7–9]. The aim of this paper is to present and clarify what are the must haves that need to be considered when modelling PEDs. Hence, the authors will provide an answer to the following research questions:

1. What are the elements that need to be considered when modelling a PED?
2. How do the adopted definition of PEDs affect these must haves?
3. What are the differences of modelling a PED compared to a normal district?

The paper is structured as follow. Section presents the different definitions of PEDs and identifies the must haves for positive modelling PEDs focusing on: (1) the elements, (2) the spatial dimension, (3) the temporal resolution and (4) the objective function. Section 3 will discuss the findings by analyzing the impact of the different definitions of PEDs. Finally, Sect. 4 will present the conclusion as well as identify future area of work.

## 2 Methodology

The initial framework of PEDs is the above-mentioned definition proposed by JPI Urban Europe [3]. Following it, a PED is considered as a set of energy efficient and flexible buildings that work towards achieving surplus of energy from renewable sources. A PED scheme is shown in Fig. 1, and the different aspects will

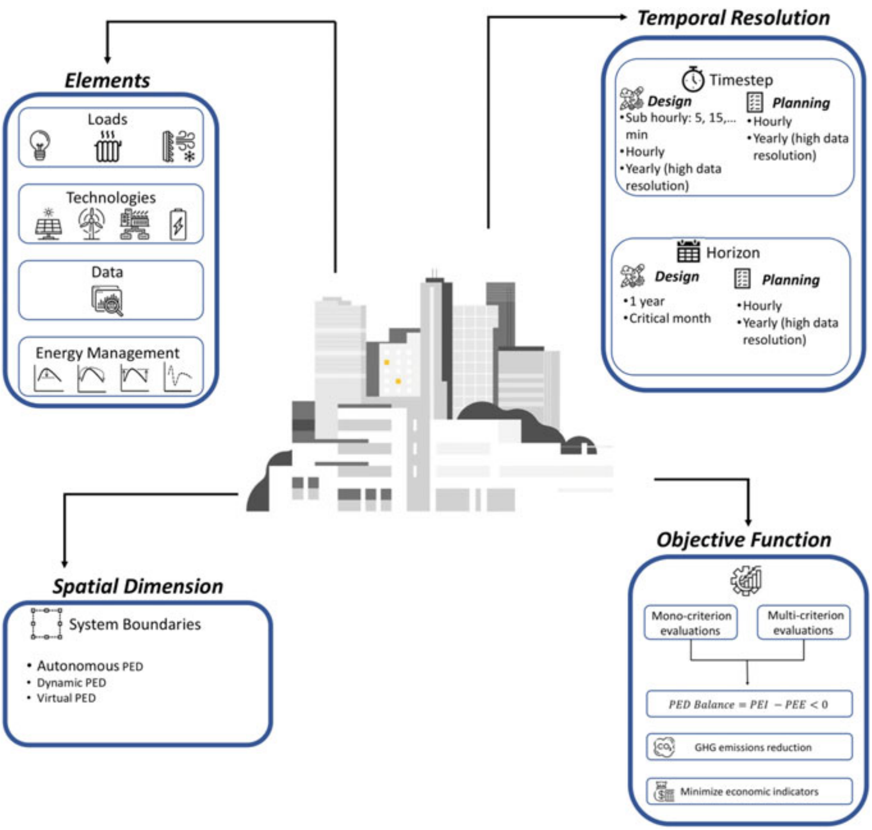


**Fig. 1** Framework of positive energy districts

be discussed in detail. The proposed framework involves a flexible approach with regards to the spatial dimension and the system boundaries. This flexibility is well pictured by the classification proposed by [4]. Following it, PEDs can be classified into autonomous PED, dynamic PED and virtual PED. The former one has geographical boundaries and it must be self-sufficient, i.e., covering all needs by means of on-site self-generation. In this case, only export of energy is allowed. In a dynamic PED, although the boundaries are also geographical, import of energy is allowed as long as the energy produced on-site that is exported is greater than what is imported. In the virtual PED, the energy units can be freely located outside the geographical boundaries of the PED and import of energy is allowed as in the dynamic PED.

The implementation of a PED in an existing community is more challenging than building it from scratch. According to [10] the main city needs and priorities are defined regarding land use context and existing city plans within the policy domain and energy simulations would be very useful for demand side scenarios. Thus, it is clear how the definition of PED that one adopts can influence the modelling of the district.

## *2.1 The Elements: Loads and Technologies*

In the framework of PEDs shown in Fig. 1, the following elements can be found: loads, generation technologies, energy management systems (EMS), and data.

When modelling a PED, it is highly important to be aware of the loads to be included. Loads are very related with citizens comfort since they provide heat, cold, entertainment, mobility and also security [11, 12]. The first two services may be clustered as thermal loads that will provide domestic hot water, heating and cooling needs. Furthermore, electricity loads should also be considered like lighting, home appliances or electric mobility. The loads can be considered at building level (such as a residential load) or at district level, that could also include street lighting, consumption from common district infrastructures, or even, electric bicycles, cars and buses. It is worth mentioning that understanding the size and also the behavior of the loads is crucial for PED. In fact, in a case in Finland presented in [13] different intervention scenarios were assessed at district scale, and the most optimal techno-economic option that allowed to achieve a PED was the case where the demand was reduced.

The next elements to be included in the PED modelling are the supply side models. These technologies based on renewable energy sources (RES) such as solar (PV, thermal and hybrid), wind, geothermal, or biofuels are necessary to achieve the yearly positive balance. The exact elements to be considered will depend on the city and country context, RES local potential, available space, the demands to be satisfied and the stakeholders desires. Furthermore, the associated variability of RES could require the onsite implementation of energy storage systems (ESS) in the model. There are a wide variety of ESS that could be included, such as lithium batteries, super-capacitors-, short- and long-term thermal storage, or even, power-to-hydrogen technologies, if sector coupling is desired. Depending on the objectives of the project owner, an understanding of the grid infrastructure surrounding the PED and services to be provided could be needed. Nevertheless, there are still questions on what is the most optimal operation of a PED that includes ESS. The most common practice is to inject the surpluses of energy into the utility grid and use it as storage, hence using it later when energy demand from the PED cannot be meet by RES. This way of operation is commonly known as virtual storage (VS), but according to the experts in the IEA Annex 83 on PEDs, it does not consider the impact of the power grid and it should be avoided as PEDs should aim to help balancing the wider grids. There are PEDs that implement both strategies ESS and VS for diminishing the renewable intermittency in a way to reduce the investment on ESS. This VS configuration forces the PED to be connected to the grid. In the case off-grid configuration is desired, self-sufficiency is mandatory and EES must be included. Lastly, energy management systems (EMS) are usually required to efficiently operate the multi-vector energy production at district level. EMS can include demand side management (load shifting), demand response, RES prediction, among others. These flexibility options are of particular importance when modelling PEDs particularly when no exchanges with the outside of the boundaries are allowed. In fact, these solutions will help to maximize and optimize the use of the locally generated energy to cover the demand and achieving the positive energy balance. The specific objectives that can be considered when modeling the PED are described in detail in Sect. 2.4.

## *2.2 The Spatial Dimension*

The integration of the spatial dimension within the modelling of energy systems is still a challenge. In 1980 Nijkamp identified a set of issues related to the interaction between the spatial dimension and energy problems [14]. These range from how changes in the energy sector impact the spatial distribution of activities to the analysis of distributional impacts of energy issues. However, according to [15], only few aspects have been investigated. Particularly, the efforts taken focused on the development of optimization tools to find the least-cost technology choices to meet certain goals, on network models for the flow of energy and on regional economy models. However, with the evolution of concepts related to the urban development in lights of the energy transition, the spatial dimension is of a paramount importance [7]. One of the reasons for that is the high granularity of data needed for energy system modeling that are highly dependent on RES [16]. Additionally, the definition of system boundaries is essential for a more detailed analysis not only on possible import/export of the PED with the surrounding context (i.e. other districts or PEDs, national power grid, DH&CN, etc.) but also for understanding possible areas for new installation of generation units. In the context of PEDs, particularly when the autonomous PEDs is considered, having a deep and precise knowledge of the spatial characterization of the district allows to properly analyses the energy flows that must be included in the balance to see whether positivity is achieved. In this sense, this is a peculiarity of autonomous PEDs that clearly distinct them from a more classical concept of district.

## *2.3 The Temporal Resolution*

One of the main challenges in district scale studies is the need of data and monitoring methodologies. This is particularly true when the district investigated is part of a project aiming at achieving the energy transition. In fact, as pointed out also by [7, 9, 16], the increasing deployment of RES coupled with storages options, make it necessary to have precise data even at low temporal resolution. However, the temporal resolution to be chosen depends on the data availability at the district site, whether the district study itself is being done in a new or existing area and, lastly, whether the study is meant for planning or detailed design purposes. The main critical data needed is the district energy demand, which sets the business-as-usual scenario (BAU) and allows to study different energy systems that can meet and go beyond these demands [24]. But a literature review performed in [25] shows that district energy demand simulations are often estimated by breaking down the district into representative buildings or "archetypes" and assign to each of them a building typology demand (for example, from TABULA project). This is mainly due to a lack of input data as well as the lack of an efficient methodology to process different types of data sources. Nevertheless, it is up to the modeler to choose the level of detail that the model should have, which usually depends on the objective of the simulation. For example, if just a high-level energy estimation is desired, a simple yearly energy balance can be performed using a steady state model, which will allow to estimate the energy supplied by each technology to meet the demand and achieve the positivity. If a greater precision is desired to assess capacities of each technology, start-stop operation, storage or optimization of the size, a quasi-dynamic model is needed, and hourly simulations are required. If equipment failure conditions or analysis of ancillary services is needed, a dynamic model is required to prevent risk situations. Most of these options are meant for designing districts or PEDs, and the time resolution is usually one year or one month. For system sizing hourly simulations are necessary, even if it is just for typical days in different seasons. If instead of designing, long-term assessments are required, e.g., how many PEDs should be implemented in a city level to achieve a determined objective, then the simulation should run over multiple years (usually determined by the year in which the objective is fixed, e.g., achieve climate neutrality in 2050). Also in this aspect what makes PEDs unique, compared to a canonical district, is the positive requirement of the energy balance. In fact, to have a better and more detailed overview of the system may require the use of a more detailed temporal resolution to and optimize the use of the available sources and technologies.

### 2.4 The Objective Function

There is no single simulation tool to model the energy performance of urban energy systems [17]. Optimal operations are difficult to predict due to the wide variety of energy consumption profiles, integration of fluctuating RES, characteristics of ESS and fluctuations in the market prices. This great versatility makes it necessary to use optimization models for the management of this urban multi-vector system. Two approaches can be developed to identify good urban solutions: mono and multi-criteria evaluations. Mono-criteria evaluations are based on the district optimization with a single objective function, usually a positive energy balance. Multi-criteria evaluations are based on the district optimization using different weighted objective functions, such as energy balance, reduction of carbon dioxide emissions, cost, improvement of comfort levels or life cycle impact. The criteria to define a PED will depend mainly on the objectives that the developer wants to achieve as well as the business model behind it.

One of the main criteria for PED optimization is that the PED Balance must be positive. The main problem is that there is no common methodology to calculate it. Nevertheless, [18] considered a calculation methodology based on the ISO52000-1 where the PED Balance in non-renewable primary energy terms is calculated as the difference between the primary energy imported (PEI) and primary energy exported (PEE), in non-RES primary energy terms (using non-RES primary energy factors of the delivered energy to and from the PED). The typical delivered energy carriers are electricity (the power grid), fuels (such as natural gas coming from the pipeline), or biomass (coming from forest waste, peat, among others.). The PED achieves positivity when the PED Balance value is negative, i.e., when the PEE is higher than the PEI [18]. Ala-Juusela et al. [13] calculates the energy positivity of a neighborhood through the On-site Energy Ratio (OER). This index represents the relationship between the annual supply of energy from local renewable energy sources (RES) and the annual demand for energy. Ala-Juusela et al. [13] highlights the necessity to assess other indices that consider different types of energy as well as their evolution over time, such as Annual Mismatch Ratio (energy imported in each energy type), Maximum Hourly Surplus (excess of local renewable supply), Maximum Hourly Deficit (excess of demand) and Monthly Ratio of Peak hourly demand to lowest hourly demand (peak power demand). In terms of economic factors, typically total investment cost (CAPEX), operational costs (OPEX) and simple payback period are calculated. Finally, authors consider other social or environmental factors through several KPIs such as level of energy demand, creation of jobs, environmental impact (in terms of GHG emissions reduction or air quality index) or transport distance of biofuels.

## 3 Discussion

The energy model of a PED couples sustainable demands with renewable technologies, low-carbon energy sources and storage systems. An effective integration between supply and demand side is necessary both in geographical and temporal terms, regulated by the boundary conditions of the district. It is then clear that the modeling of a PED considers numerous aspects and factors of various nature. This modeling is strongly influenced by the final objective, both in terms of accuracy due to the way in which the technologies and loads are defined, as well as in terms of the spatial resolution, temporal resolution and the definition of the objective function. Thus, the first step is to understand the final goal of the analysis, and for whom is it targeted. Is it a model for technicians that are approaching the implementation of a PED from a technical perspective or is it a model that decision makers will use to plan and implement a strategy in terms of interventions and policies, for example as done in the City of Bilbao through the Bilbao bold city vision [19]? Consequently, it is essential to understand and define the kind of data that is needed according to the goal of the modelling. Data is the cornerstone to determine consumption profiles, demand habits, or renewable potential in the specific area. Urban microclimate data are needed to provide information on weather patterns considering local phenomena produced by urban structures. As pointed out by [20] the approach could go towards optimization, when there is a need to identify the optimal solution or a simulation approach can be used to evaluate the performance of possible future systems. In case of optimization often there is a need of a detailed modelling of all the technical characteristics of the system in order to make the model as realistic as possible. Thus, all the elements presented in 2.1 should be modelled with the highest possible degree of accuracy. However, this translates in the need of data at a high level of temporal resolution that normally also results in high computational times. In fact, from modelling experiences from the Annex 83 team, if the impacts of the grid and an optimization of the size of the technologies is desired, the best solution is to combine detailed building data with consumption data from bills or monitoring data [20]. In the case of simulation models, not aiming for an optimal solution facilitates the computational time of the model allowing for both, high temporal and spatial resolution as well as for short computational time [21]. Additionally, this approach is also well suited for establish a dialogue with decision makers.

Additionally, the final goal of the modelling approach, also influences the definition of the objective function. If a mono-criterion evaluation is performed, the PED Balance should be prioritized to ensure the definition is achieved. Nevertheless, there is no scientific evidence, that this positivity will provide positive impacts to the district nor to the city where is applied. In fact, depending on the definition of the PED, other objectives could be prioritized. For example, if an autonomous PED is desired, the self-consumption and self-sufficiency should be maximized in order to meet the demand within the district boundaries. If the size is larger than this resulting optimal scenario, the PED will export energy. If the objectives of the PED implementation are others such as improving the air quality of the district, a multi-criteria approach could be followed, minimizing PEI and biomass use, for example.

## 4 Conclusion and Future Works

This paper focuses on analyzing the must haves for modelling a Positive Energy District and aimed at identifying how the definition adopted affects these must haves and the differences of modelling a PED compared to a normal district. In particular, the main aspects to be considered when modelling a PED can be summarized in four categories: the elements such as loads and technologies, the spatial resolution to identify the boundaries of the system and where to place the generation technologies, the temporal resolution and the objective function to be considered.

All these aspects are crucial for allowing an effective and complete modelling of PED. However, it was also seen that another important aspect to be considered is the definition of PED adopted for the analysis. In the stricter case of Autonomous PED, with no exchanges of energy with the outside grids, there is a clear need of high level of detail in order to ensure the positivity of the balance at the end of the year, but also the matching of supply and demand at every time step. This means that all the technologies and solutions that provide flexibility to the district must be accurately modelled as well as the spatial resolution and analysis to understand where generation technologies can/should be placed. Thus, a high resolution of the data is needed. On the contrary, if one considers modelling a Virtual PED, given that there are less constraints, the modelling approach can be different. In fact, the possibility to exchange energy with the outside of the districts as well as the possibility to place generation units outside the districts results in a lower need of flexible solution and in a lower requirement in terms of spatial resolution. Thus, in this case the difference with modelling a normal district only relies on the necessity of achieving a positive balance at the end of the year. The same applies for modelling a Dynamic PED, but without the possibility to place any generation unit outside the district. In this case, the spatial resolution is also a restriction.

Hence, it was seen that it is important to clearly define what is the ultimate goal of modelling a solution as well as be sure of the definition of PED adopted. In fact, there is no common methodology to approach the modeling of a district, and it is a case-by-case scenario. The IEA ANNEX 83 will create an inventory of technologies with techno-economic data and data templates to help modelers in the design and planning phases of PEDs. The data templates will be performed within subtask B, whereas subtask C and D will set guidelines for monitoring and assessment of PEDs.

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## References

1. European Commission: Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions. The European Green Deal (2019)
2. Alyssa Fischer: How Energy Efficiency Will Power Net-Zero Climate Goals—Analysis. https://www.iea.org/commentaries/how-energy-efficiency-will-power-net-zero-climate-goals. Last accessed 2021/05/10
3. JPI Urban Europe: White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods, pp. 1–22 (2020)
4. Wyckmans, A., Karatzoudi, K., Brigg, D., Ahlers, D.: D9.5: Report on Attendance at Events Held by Other SCC-01 Co-ordinators, p. 2 (2019)
5. Lindholm, O., Reda, F.: Positioning positive energy districts in European cities. Buildings **11**, 19 (2021)
6. European Commission: Strategic Energy Technology Plan (2014)
7. Pfenninger, S., Hawkes, A., Keirstead, J.: Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. **33**, 74–86 (2014). https://doi.org/10.1016/j.rser.2014.02.003
8. Yazdanie, M., Orehounig, K.: Advancing urban energy system planning and modeling approaches: gaps and solutions in perspective. Renew. Sustain. Energy Rev. **137**, 110607 (2021). https://doi.org/10.1016/j.rser.2020.110607
9. Chang, M., Thellufsen, J.Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H., Østergaard, P.A.: Trends in tools and approaches for modelling the energy transition. Appl. Energy. **290**, 116731 (2021). https://doi.org/10.1016/j.apenergy.2021.116731
10. Alpagut, B., Akyürek, Ö., Mitre, E.M.: Positive energy districts methodology and its replication potential. Proceedings **20**, 8 (2019). https://doi.org/10.3390/proceedings2019020008
11. Bridging the Gap between Real and Simulated Environments: A Hybrid Agent-Based Smart Home Simulator Architecture for Complex Systems | IEEE Conference Publication. IEEE Xplore. https://ieeexplore.ieee.org/document/7816848. Last accessed 2021/05/27
12. Ma, W., Xue, X., Liu, G.: Techno-economic evaluation for hybrid renewable energy system: application and merits. Energy **159**, 385–409 (2018). https://doi.org/10.1016/j.energy.2018.06.101
13. Ala-Juusela, M., Crosbie, T., Hukkalainen, M.: Defining and operationalising the concept of an energy positive neighbourhood. Energy Convers. Manag. **125**, 133–140 (2016). https://doi.org/10.1016/j.enconman.2016.05.052
14. Nijkamp, P.: Energy problems and regional development: editorial note. Reg. Sci. Urban Econ. **10**, 299–301 (1980)
15. Balta-Ozkan, N., Watson, T., Mocca, E.: Spatially uneven development and low carbon transitions: insights from urban and regional planning. Energy Policy **85**, 500–510 (2015). https://doi.org/10.1016/j.enpol.2015.05.013

16. Martínez-Gordón, R., Morales-España, G., Sijm, J., Faaij, A.P.C.: A review of the role of spatial resolution in energy systems modelling: lessons learned and applicability to the North Sea region. Renew. Sustain. Energy Rev. **141**, 110857 (2021). https://doi.org/10.1016/j.rser.2021.110857
17. Allegrini, J., Orehounig, K., Mavromatidis, G., Ruesch, F., Dorer, V., Evins, R.: A review of modelling approaches and tools for the simulation of district-scale energy systems. Renew. Sustain. Energy Rev. **52**, 1391–1404 (2015). https://doi.org/10.1016/j.rser.2015.07.123
18. Gabaldón Moreno, A., Vélez, F., Alpagut, B., Hernández, P., Sanz Montalvillo, C.: How to achieve positive energy districts for sustainable cities: a proposed calculation methodology. Sustainability **13**, 710 (2021). https://doi.org/10.3390/su13020710
19. Martin, C., et al.: The opportunity for smart city projects at municipal scale: implementing a positive energy district in Zorrozaurre. Ekonomiaz **1** (2021)
20. Lund, H., Arler, F., Østergaard, P., Hvelplund, F., Connolly, D., Mathiesen, B., Karnøe, P.: Simulation versus optimisation: theoretical positions in energy system modelling. Energies **10**, 840 (2017). https://doi.org/10.3390/en10070840
21. Castillo-Calzadilla, T., Fessler, S., Borges, C.E., Andonegui, C.M.: Urban district modelling simulation-based analysis: under which scenarios can we achieve a positive energy district? In: 2021 18th International Multi-Conference on Systems, Signals Devices (SSD), pp. 1107–1114 (2021). https://doi.org/10.1109/SSD52085.2021.9429457.

# A Systematic Approach Towards Mapping Stakeholders in Different Phases of PED Development—Extending the PED Toolbox

**Caroline Cheng, Vicky Albert-Seifried, Laura Aelenei, Han Vandevyvere, Oscar Seco, M. Nuria Sánchez, and Mari Hukkalainen**

**Abstract** The development of Positive Energy Districts (PEDs) is arguably the development of an innovation embedded in a community of organisations and individuals (occupants, inhabitants, citizens) who can affect or are affected by the innovation. However, current methods of stakeholder engagement in PED developments do not systematically identify the type of stakeholders by phases of PED development. In this paper, we draw from selected theories on stakeholders in the strategic management literature from a practical viewpoint to outline a systematic approach towards mapping stakeholders in PED developments. The research question addressed is: *How can stakeholders be systematically mapped in the different phases of PED development?* From a case study involving 7 PED projects, we applied a preliminary tool delineating eight categories of actors relevant for the different phases of PED

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development. Based on our analysis, we suggest that it is important to reimagine PED stakeholders as interactive actors since stakeholder roles shift during the PED process and to map them on the building, district and the city scale. The contribution of this paper is twofold. First, in terms of managerial implications, we have outlined a preliminary actor-oriented stakeholder mapping framework that is attuned to the phases of the PED process and the different scale of stakeholders (building level, district level and the city level). Second, in terms of research implications, we have extended the notion of the PED toolbox to not only consider technical tools and non-technical tools but also include a category of managerial tools that merits research attention.

## 1 Introduction

The success of implementing the pioneering concept of Positive Energy Districts (PEDs) will not only depend on adapting technical solutions but also on mobilizing social, political and business commitments (PED solution booklet [1], SET-Plan Action 3.2 [2]. In particular, the engagement of stakeholders in the planning and implementation of Positive Energy Districts (PED) has consistently been identified as one of the key challenges and barriers for implementation of PED projects [3, 4]. The importance of stakeholder engagement in the planning and implementation of PEDs is widely recognized. However, before considering how the stakeholder engagement can be structured and organized, the stakeholders will need to be systematically identified first. The task of stakeholder mapping is understandably fraught with difficulty, and as with all difficult tasks, some tools can be helpful. In this paper, we draw from selected theories on stakeholders in the strategic management literature to outline a systematic approach towards mapping stakeholders in PED developments. We also adopt a practical viewpoint with an eye to develop an easy-to-apply tool that practitioners can use in approaching the task of stakeholder mapping.

In the next section, we review the development of the PED concept in its evolution and interpretation as a process where stakeholder collaborative processes remain a challenge to both researchers and practitioners. PED as a process comprises phases where, during each of the phases of the PED process, stakeholder engagement is important and where stakeholders should be systematically mapped. It seems that there is a paucity of stakeholder mapping tools in PED literature to address the identification of the shifting stakeholder constellations who will design, build, own, operate and use PEDs. We therefore ask the question: *How can stakeholders be systematically mapped in the different phases of PED development?* In the third section, we describe our methodology using a case study involving 7 PED projects and applying a preliminary tool delineating eight categories of actors. Changing gears to a more actor-oriented approach towards mapping stakeholders, we present an analytical discussion in the fourth section, before concluding our paper by outlining the managerial and research implications and our suggestions for further research.

## 2 Outlining a Systematic Approach Towards Identifying the Type of Stakeholders in Different Phases of PED Development

### *2.1 From PED as a Concept to PED as a Process*

The emerging concept of Positive Energy Districts (PEDs) arises within the framework of the European Union's SET-Plan Action 3.2 [2]. This Action enhances the strategic targets for the energy transition and sustainable urban development through an objective of achieving 100 PEDs in Europe by 2025. The SET-Plan's first approach towards a PED definition considers PEDs as '*energy efficient districts that have net zero carbon dioxide ($CO_2$) emissions and work towards an annual local surplus production of renewable energy (RES)*' [5].

In this context, ongoing initiatives such as the EU's Horizon 2020 'Smart Cities and Communities (SCC) Lighthouse Projects', the Joint Programming Initiative Urban Europe (JPI UE) [6] and the European Energy Research Alliance—Joint Programme Smart Cities (EERA—JP SC) have been active to increase the knowledge about the integration of innovative solutions for the planning, deployment and replication of PEDs. In this regard, JPI UE has developed a compilation of PED projects in Europe [7], while JPI UE and EERA JP SC have set out to further elaborate a PED definition, starting from the SET-Plan description and the PED definition as used in the H2020 SCC Lighthouse Project calls [8]. As a part of this process, national consultations within the EU's Member States have supported the definition development. This has led to the following formulation: '*Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability*' [9]. PEDs are understood to rely on three strategic operational pillars that meaningfully integrate a PED in the regional energy system: energy efficiency, flexibility and production [10].

More recently, initiatives such as IEA EBC Annex 83 [4] and the EU Cost Action CA19126 [11] have joined the discussion on PED issues such as a commonly shared definition or the role and relevance of the different stakeholders in realising PEDs. The work on an accepted PED definition is therefore ongoing both at the level of the EU and beyond.

Nonetheless, it is generally accepted to regard PED as a complex process that requires a high degree of coordination due to the multi-stakeholder environment and involves a more disruptive urban transformation at large-scale as it affects blocks of buildings rather than single buildings. The process is complex and considers not only technical but also social, economic, regulatory, legal or financial aspects. Moreover, scaling and replication factors have to be considered in a PED process in order to achieve a relevant impact on the city, aligned within the city strategies integrating energy and spatial planning. The electric mobility is also integrated in addition to the fundamental pillars of energy systems.

A critical point in PED process is ensuring a long-lasting commitment for collaboration and coordination between stakeholders. The conditions facilitating interorganizational collaboration has been addressed in previous studies [12]. In PED developments, it is important to involve not only PED researchers but also PED practitioners in specifying the needs adapted to local contexts and conditions (such as heritage areas). This engagement throughout the process must be facilitated by the process initiators and enabled by profitable and adapted business models, well-conceived governance structures and information and communication technologies such as blockchain or artificial intelligence and machine learning through the provision of urban big data.

## *2.2 Phases of PED Development*

The SCIS PED Solution Booklet, while charting the experiences of several SCC Lighthouse Projects, states that 'A PED is a process, not a product' [1], and its set-up '*will always involve multiple building blocks and a large number of stakeholders and contributors, which will each have their own ambitions, agendas, interests and constraints*'.

The PED project is therefore more aptly a process that is complex and requires a high degree of coordination. The stakeholders are not limited to municipalities, real estate developers, building owners, tenants, energy providers for electricity and heating, research institutes and universities, mobility providers, energy system providers, ICT companies, SMEs, but also non-profits or NGOs, politicians, and last but not least citizens and citizen organisations. In addition, some actors tend to shift their positions or rethink their involvement when moving from one phase to another [13].

The shifting stakeholder roles can be attributed to at least the following factors. First, most PEDs will be confronted with challenges of refurbishment and retrofitting to complement the energy system upgrades and to achieve the necessary demand reduction. Changing any historically grown energy infrastructure at the district or urban scale is more disruptive than transforming individual building installations. Second, regarding the PED's interaction with its surrounding urban and regional energy infrastructures, the meaningful integration of different types of energy assets (e.g. energy production or storage units at the individual-, district- or macro-scale) require an overarching planning exercise that accounts for the entire regional energy landscape, both from a technical and a spatial planning point of view [14]. Merging urban, spatial and energy system planning further adds to the complexity of building PEDs. Managing the corresponding urban transformation process will require a well-conceived governance structure and robust stakeholder engagement strategies.

**Table 1** Key phases in PED development

| | PED as a process |
|---|---|
| I | Master planning |
| II | Energy planning (Mobility, Renewables, Flexibility) |
| III | Construction/refurbishment planning |
| IV | Implementation |
| V | Operation |
| VI | Monitoring |
| VII | Post occupancy evaluation |

Given its complexity and its intersection among sectors such as construction, energy, real estate, and the built environment in general, the phases of PED development and the levels of granularity are still subject to research and discussion. Phases of PED development would be dependent on whether the project is a new build or a refurbishment/retrofit and the building scale vs. district scale infrastructures [15]. Phases of PED development can also be elaborated upon within each phase. For example, the Integrated Energy Design is a method for achieving high performance buildings and districts towards to sustainable communities. IED represents a collaborative process that focuses on the planning, design, construction/implementation, operation, monitoring and occupancy of a building over its complete lifecycle. However, for the purpose of mapping stakeholders in the PED process in this paper, and taking a more practical viewpoint, one point of departure could be looking at the key phases in PED development shown in Table 1.

During each of the phases of the PED process. Stakeholder engagement is important. However, before considering how the stakeholder engagement can be structured and organized, the stakeholders will need to be systematically identified first. Addressing stakeholders in PED literature tend to focus on collaborative and involvement processes [13, 16]. It seems that there is a paucity of stakeholder mapping tools in PED literature to address the mapping of the shifting stakeholder constellations who will design, build, own, operate and use PEDs. It is therefore of priority to support PED practitioners and researchers with tools to approach the task of stakeholder mapping.

### *2.3 Actor-Oriented Stakeholder Mapping in PED Processes*

In our effort to develop a tool to address stakeholder mapping in PED developments, we look to relevant stakeholder literature within strategic management, as previous studies have done [16]. The field of strategic management has progressed significantly in the past 50 years into an applied area providing practical insights to executives confronted with assessing key strategic choices on a daily basis [17].

Stakeholder analysis is a widely discussed theme in strategic management literature [18]. In strategic management literature, stakeholder is a concept that can be defined in a narrow sense or a wide sense. In a wide sense, a stakeholder is any identifiable group or individual who can affect the achievement of an organisation's objectives or who is affected by the achievement of an organisation's objectives. Narrowly speaking, a stakeholder is any identifiable group or individual on which the project or organization is dependent for its continued survival. Instead of a faceless entity, stakeholder can be interpreted as full-faced actors in that they can affect or are affected by the development of the PED. In other words, stakeholder are actors who act and react in the process which is interactive, evolutionary and responsive [19] whether they are municipalities, real estate developers, building owners, tenants, energy providers for electricity and heating, research institutes and universities, mobility providers, energy system providers, ICT companies, SMEs, non-profits or NGOs, politicians, citizens and citizen organisations.

Stakeholder processes typically involve four aspects—who, why, what and how [18]. In the context of PED development, the first is the question of who—who are the potential counterparts with whom the owner or driver of that PED phase must involve and engage? The second aspect is the question of why—why do the parties need to engage with each other or one another? The third aspect is the question of what—what type of influences determine the involvement or engagement? The fourth aspect is the question of how—how can the involvement or engagement be structured and organized to let them function in the manner intended? We contend that prevailing discussions of stakeholder engagement in PED literature do not include systematic approaches toward mapping stakeholders. This first aspect of the stakeholder process merits immediate research attention.

Stakeholder theories can also be understood as "managerial", which points to recognizing the responsibility to identify stakeholders and the validity of their diverse interests, and attempting to respond to them [20]. Just as the smart city idea increasingly adopt a local, collaborative posture to drive home the importance of considering the collaborative efforts of organisations and the multiple-stakeholder perspective [21], PED developments can likewise benefit from an additional lens to scrutinize the actors in each local context and condition systematically to contribute our understanding of stakeholder collaborative and involvement processes. In other words, more effort is needed to understand stakeholders in the narrow sense, down to the actor level where they are not passive faceless entities but interactive full-faced actors.

The rationale for drawing from strategic management literature is two-fold. Firstly, the field has had tremendous momentum in taking a practical stance and in being concerned and investigating the real and tangible "things" of strategy, such as the use of managerial tools, in recent years [22]. Its motivation to generate research which is of practical value to practitioners and to demonstrate the utility of strategic management concepts is relevant to our quest for a suitable stakeholder mapping managerial tool. Secondly, the field is a fertile ground to explore relevant tools for stakeholder mapping given strategic management's preoccupation with what can be called "network level" strategy [23, 24], which sheds light on the tricky strategy tensions between competition and cooperation, and on whether firms should develop long term collaborative relationships with other firms or should remain essentially independent [25]. These are the realities confronted by PED stakeholders looking to foster long-lasting commitment for collaboration and coordination in their multi-stakeholder environment. In our effort to help PED practitioners approach the first aspect of the stakeholder process—the task of stakeholder mapping—in PED developments, we ask the research question: *How can stakeholders be systematically mapped in the different phases of PED development?*

The SET-Plan Action 3.2 recognized the necessity to develop guides and tools based on the needs of stakeholders for the successful planning and designing, implementation and operation, as well as replication and mainstreaming of PEDs. It identified a list of focus areas where further development of guides and tools are recommended. Among the broad spectrum of focus areas (technical, business, legal and educational) are guides and tools on stakeholder involvement. Stakeholder mapping as a prerequisite of stakeholder involvement is, therefore, expected to come top in the PED toolbox. To date, the development of PED guides and tools has been centered on the technical domain (e.g. energy system simulation, digital planning and energy trading), the development of non-technical guides and tools is in its infancy. We further posit that the PED toolbox needs another category of tools, managerial tools, oriented towards practitioners. Managerial tools are understood to act as a guide to thinking and a starting point for structuring activity [26] and are simple and easy to apply [27].

## *2.4 Extending the PED Toolbox*

We suggest that a systematic approach towards identifying the type of stakeholders in PED developments starts with a better understanding of the interaction between the owner or driver of the PED project and the entities in its network context. One particular managerial tool facilitates a systematic analysis of the web of relational actors by categorizing eight major groups of external actors with whom the firm can, or must, interact [18]. Among these eight major groups of actors, a distinction can also be made between industry and contextual actors. *Industry actors* are those entities that perform value-adding activities or consume the outputs of these activities while *contextual actors* are those entities whose behaviour, intentionally or unintentionally, sets the conditions under which the industry actors must operate. Figure 1 shows these eight categories of industry and contextual actors that could be relevant for different phases of PED development.

Delineating these eight categories of actor imply a shift of gears to a more actor-oriented approach towards stakeholder mapping. Stakeholders are understood as full-faced external parties with whom the owner or driver of the PED can, or must, interact in PED developments. Besides the shifting stakeholder constellations who will design, build, own, operate and use PEDs, it can also be expected that the owner or driver of the PED can shift from one phase of development to another. The next section describes how we have approached our study.

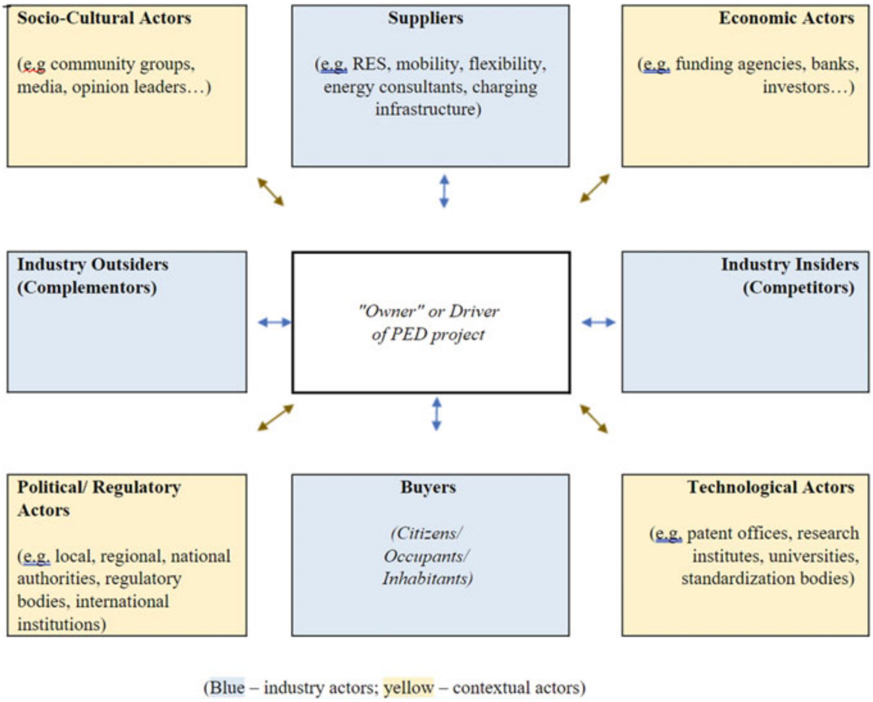


**Fig. 1** Categories of industry and contextual actors that could be relevant for different phases of PED development (building on de Wit and Meyer [18])

# 3 Methodology

## *3.1 Purposeful Sampling to Understand Applicability of Stakeholder Mapping Tool in PED Developments*

In our effort towards developing a preliminary understanding of the applicability of a stakeholder mapping managerial tool in PED developments, we rely on purposeful sampling. Purposeful sampling, or specifically criterion sampling, is widely used in qualitative research for the identification and selection of information-rich cases related to the phenomenon of interest [28].

Palinkas et al. pointed out a range of diverse strategies that can be used in purposeful sampling in accordance with different objectives [29]. Strategies for purposeful sampling include the identification of unusual phenomena from extreme cases as well as the identification of patterns of variation from heterogeneous cases. It can also include the simplification of the analysis and similarity emphasis from homogeneous cases or convenience emphasis collecting information from willing participants. While the first two strategies focus on describing the variability or dispersion of values, the third is used primarily to reduce the range of variation and identify similarities.

In line with the objective of this study towards tool development, we relied on the third strategy as the idea is to develop a preliminary understanding of the applicability of a stakeholder mapping managerial tool to a sample of PED cases based on the projects in which the authors are involved, and providing, to the best of our knowledge, detailed insights of the categories of actors involved. This methodology is particularly interesting in this type of stakeholder mapping approach, where relationships between actors extend both horizontally, between organizations at the same level in the network context, and vertically from state to local stakeholders.

### *3.2 Overview of Cases*

To illustrate practical first steps for PED practitioners and researchers in mapping stakeholders, we tried to select PED cases in different phases of PED developments in different national contexts (see Table 2).

For each project, the eight categories of actors were mapped out. The working stakeholder maps of these cases will not be presented in detail in this paper but will be readily available upon request. The process of mapping the stakeholders provides insights to further develop the tool, which we discuss in the next section.

## 4 Analytical Discussion

### *4.1 Mapping "Owners", Drivers and Users, Contextual Actors and Industry Actors*

From our mapping exercise, determining the owner and the driver of the PED can be difficult as the boundary between 'owning' or 'using' can be very tricky to discern. Our cases also highlight that it can be easy to lose sight that PEDs are developed for the ultimate users which are occupants, inhabitants, or citizens. PEDs have to be developed bearing in mind the people who are going to live in them and a visual stakeholder mapping tool clearly delineating this category of actors is helpful.

Industry actors are interpreted as those entities that perform value-adding activities or consume the outputs of these activities. Typically, these pertain to suppliers such as energy consultants, battery storage suppliers, PV suppliers. The direct horizontal (industry insiders) and indirect horizontal (industry outsiders) are possible to identify with the PED phases we have worked with. Identifying the industry actors can be tedious but doable since their business interests, capacities and agendas are more or less recognizable.

**Table 2** Overview of cases

| | Case (the PED site) | Coun-try/climate | Energy planning, types of RES | Area, no. of buildings | Phase of development (the phase in which the PED site is in now) |
|---|---|---|---|---|---|
| 1 | CEDER-CIEMAT [30] | Spain | Thermal Plant: biomass boiler, Solar thermal, Geothermal<br>Power generation Plant: wind power, PV systems, reversible hydraulic system<br>Storage: Lead-Acid and Ion-Lithium batteries, thermal storage, elevation change water tank | 13,000 $m^2$ constructed in 640 ha<br>6 buildings | • Electrical grid (in operation)<br>• Thermal network (in implementation) |
| 2 | SPARCS-Lippulaiva [31, 32] | Finland | Regenerative geoenergy, PVs, battery storage, VPP | around 140,000 $m^2$, 10 buildings | Construction/refurbishment planning |
| 3 | SPARCS-Sello [31] | Finland | PVs, battery storage, VPP, building structures as heat storage | 268,000 $m^2$ heated floor area, 4 buildings | Implementation |
| 4 | SPARCS-Kera [31] | Finland | system planning on-going, with low temperature district heating | 22 ha (532,000 $m^2$ for housing, 148,000 $m^2$ for retail and business) | Master planning |
| 5 | SusCity-Lisbon [33] | Portugal | Planning building refurbishment, PV, energy flexibility potential mapping | 200 ha,2000 buildings | Energy planning (Mobility, Renewables, Flexibility) |

(continued)

**Table 2** (continued)

| | Case (the PED site) | Coun-try/climate | Energy planning, types of RES | Area, no. of buildings | Phase of development (the phase in which the PED site is in now) |
|---|---|---|---|---|---|
| 6 | POCITYF-Évora [34] | Portugal | Building refurbishment, PV, P2P energy storage management, Virtual Power Plant, Smart V2G, Citizen driven co-creation | Old city center with about 113 ha 10 buildings, industrial park with building area of 8900 $m^2$ and other commercial area of 3833 $m^2$ | Energy planning, construction refurbishment implementation |
| 7 | POCITYF-Alkmaar [34] | Nether-lands | Building refurbishment, PV, P2P energy storage management, Virtual Power Plant, Smart V2G, Citizen driven co-creation | The Westrand, hosting 6050 households | Energy planning, construction refurbishment implementation |

Contextual actors are those entities whose behaviour, intentionally or unintentionally, sets the conditions under which the industry actors must operate. The list of contextual actors relevant for PED development is often comprehensive and the work to map them out is difficult but recognized to be very important. In-depth local knowledge is required to understand contextual actors.

## 4.2 Shifting Roles in Different Phases of PED Development

Our preliminary exercise also highlights the dynamism in stakeholder roles in the different phases of PED development, depending on the issues in which they have a stake. As outlined in Table 1, the key phases in PED development include but are not limited to master planning, energy planning, construction/ refurbishment planning, implementation and operation. This insight can be used to avoid problems in handing over responsibilities, for example, from city planners in municipalities to technical stakeholders in the energy sector. This is especially important as PEDs become smarter and energy systems more complex, users will need to become more involved in the management of neighborhood-based systems and can be exposed to technical challenges. The delivered project must match the occupant´s expectations and investments, including environmental, affordability, and functionality benefits. This may include a healthier environment, green housing features, and lower operating costs due to enhanced energy efficiency. Priority needs to be given to smoothen the exchange of experiences among stakeholders and to capture the learnings from planning to implementation. Having a visual stakeholder map done on a regular basis would be helpful to pinpoint areas and to implement steps for minimizing the loss of knowledge between stakeholders and avoid performance discrepancies on a user level.

## 4.3 Regarding Stakeholders as Partners for Co-creation on a Building Level, District Level and the City Level

Our preliminary exercise also hinted at the possibility to categorise the stakeholders on at least three distinct levels: on a building level, district level and the city level, zooming in and out when necessary. In other words, in addition to PED phases, this consideration of scale on a building level, district level and the city level would also be commensurate. Whether adopting a top-down or bottom-up approach in PED developments, this consideration of scale on a building level, district level and the city level can also help to make visible the benefits of PEDs for the different categories of actors involved in a more systematic way. This would provide the opportunity to allow respective end-users (i.e. occupants on a building level, inhabitants on the district level, citizens at the city level) to have a stronger say in the specification of their needs.

### *4.4 A Systematic Approach Towards Mapping Stakeholders in PED Developments—Extending the PED Toolbox*

The development of PEDs is arguably the development of an innovation embedded in a community of organisations and individuals (occupants, inhabitants, citizens) who can affect or are affected by the innovation. Like all innovations, it can be expected to be a messy process. There is no strait jacket for PED operationalization and implementation. Every PED has different preconditions, as well as local context and local conditions. PED researchers and practitioners can make use of tools to help them navigate the multi-stakeholder environment of every PED. Returning to our research question: *How can stakeholders be systematically mapped in the different phases of PED development?*

The PED stakeholder map is a dynamic one, changing as often as local context and conditions changes, and as stakeholder roles shift. As mentioned, stakeholder processes typically involve four aspects—who, why, what and how [18]. In this paper, we have explored developing a tool to address the first aspect—mapping the "who"—with the aim of getting to the other three aspects. We have posited that establishing a systematic approach towards this first aspect involves actor-oriented stakeholder mapping. From our preliminary case study involving the 7 PED projects, we further distil what would contribute to a systematic approach towards mapping stakeholders in PED developments. This then would pave the way to get to the other three aspects in order to develop robust stakeholder engagement strategies. It is therefore critical to get first aspect of the stakeholder process—the task of stakeholder mapping—to be in a good position to facilitate keeping in view the diverse *ambitions, agendas, interests and constraints* of stakeholders in order to work towards long-lasting commitment for collaboration and coordination between stakeholders.

We suggest that addressing the first aspect of the stakeholder process—the task of stakeholder mapping—in PED developments should be supported by three analytical buttresses. First, it is important to distinguish between industry actors and contextual actors to view PED developments as a system of multilateral actors whose actions and reactions (hence "interactions") can enable the innovation to materialise but can also derail the innovation process. The eight categories of actors outline in Fig. 1 is a useful starting point to adopt an actor-oriented stakeholder mapping approach to think about the actions and reactions of different actors (such as municipalities, real estate developers, building owners, tenants, energy providers for electricity and heating, research institutes and universities, mobility providers, energy system providers, ICT companies, SMEs, non-profits or NGOs, politicians, citizens and citizen organisations) in the PED process. Second, in such an actor-oriented stakeholder mapping approach,

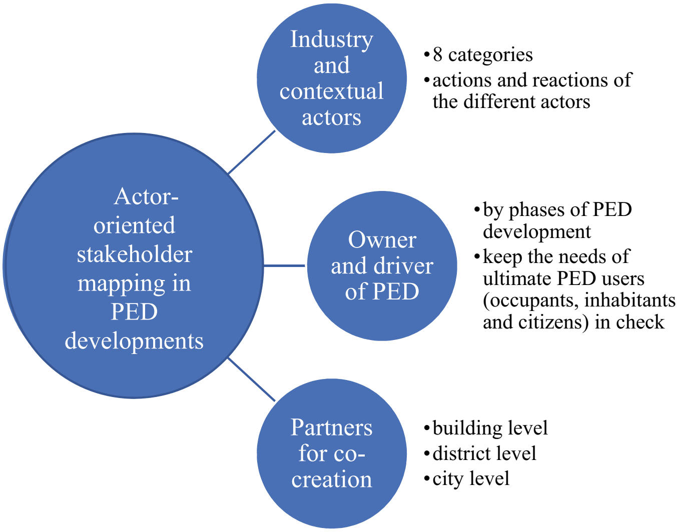


**Fig. 2** Three analytical buttresses for actor-oriented stakeholder mapping in PED developments

it is central to specify the owner or driver of the PED dynamically in a process orientation corresponding to key phases of the PED development, as suggested in Table 1 and also keep the needs of ultimate PED users (which are occupants, inhabitants, or citizens) in check at every phase of the PED process. Finally, we suggest that a systematic approach towards mapping stakeholder in PED developments requires a shift in mindset to regard stakeholders not only as actors but also as partners for co-creation. Because mapping them can be messy, it can be useful to break them down on a building level, district level and the city level.

An actor-oriented stakeholder mapping in PED developments supported by three analytical buttresses is depicted in Fig. 2.

## 5 Conclusion, Implications and Further Research

This paper has applied a preliminary stakeholder mapping tool delineating eight categories of actors relevant for the different phases of PED development and further developed it into an actor-oriented stakeholder mapping framework to consider the building, district and the city scale since stakeholder roles shift during the PED process.

The contribution of this paper is twofold. First, in terms of managerial implications, we have outlined a preliminary actor-oriented stakeholder mapping framework that is attuned to the phases of the PED process and the different scale of stakeholders (building level, district level and the city level). This tool is expected to be helpful in identifying the type of stakeholders to prioritize and to engage, and also for shaping up a dialogue of understanding PEDs as a process. The concept of PEDs will be increasingly introduced in the energy planning of many cities and communities in the next years. At the same time, the plethora of PED terms can be expected to proliferate [35] and this can be very confusing to practitioners. While it may take some time to arrive at a framework of definitions for PEDs, it is urgent to offer practical advice to practitioners to regard stakeholders not as challenges but as partners for co-creation. The task of stakeholder mapping is fraught with difficulty, and as with all difficult tasks, some tools can be helpful. The framework may be a useful point of departure for practitioners who feel a need for mapping out PED stakeholders systematically before meetings and workshops, for example. It can also be useful to foster the thinking of PEDs as a process with multi-sectorial dimensions that encompass parallel development of building and district technologies, social acceptance and integration in the local built environment, as well as meet the city's ambition.

Second, in terms of research implications, we have extended the notion of the PED toolbox to not only consider technical tools and governance tools but also include a category of managerial tools that merits research attention. Extending the PED toolbox to include managerial tools for stakeholder mapping and analysis would contribute to the ongoing effort to develop guides and tools to support the implementation of PEDs.

Further research could analyse deeper into the 7 cases and also include more cases of PED developments utilizing all three buttresses in Fig. 2 to gain additional insights into stakeholder categories, PED phases and the applicability of the building, district and city scales. More tools from strategic management can be consulted to better understand the wide diversity of interests, viewpoints and time horizons of the wide array of stakeholders relevant for PED developments [24]. This will further open up the research agenda in identifying and developing useful managerial tools for PED developments. In this regard, drawing from theories on business interaction in the strategic management literature from an inter-organizational perspective seems like a promising avenue [19, 25].

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## References

1. Ahlers, D., et al.: Positive Energy Districts Solution Booklet,. Vandvyvere H., EU (2020). https://smart-cities-marketplace.ec.europa.eu/insights/solutions/solution-booklet-positive-energy-districts. Last accessed 2021/05/31
2. SET-Plan ACTION n°3.2 Implementation Plan: Europe to become a global role model in integrated, innovative solutions for the planning, deployment, and replication of Positive Energy Districts. https://setis.ec.europa.eu/system/files/2021-04/setplan_smartcities_implementationplan.pdf. Last accessed 2021/05/31
3. Bossi, S., Gollner, C., Theierling, S.: Towards 100 positive energy districts in Europe: preliminary data analysis of 61 European cases. Energies **13**(22), 6083 (2020)

4. Hedman, Å., et al.: IEA EBC Annex83 positive energy districts. Buildings **11**(3), 130 (2021)
5. European Commission's Directorates-General for Energy, Research and Innovation and Joint Research Centre: SET Plan delivering results: The Implementation Plans, 2018 edn. European Union, EU, p. 28 (2018). https://op.europa.eu/en/publication-detail/-/publication/a3b22c5b-ed41-11e8-b690-01aa75ed71a1/language-en/format-PDF/source-803647918. Last accessed 2021/05/31
6. JPI Urban Europe—ERA-LEARN. https://www.era-learn.eu/network-information/networks/urban-europe. Last accessed 2021/05/31
7. Gollner, C., et al.: Europe Towards Positive Energy Districts. A Compilation of Projects Towards Sustainable Urbanization and the Energy Transition, 2020 edn. JPI Urban Europe, Vienna (2020). https://jpi-urbaneurope.eu/wp-content/uploads/2020/06/PED-Booklet-Update-Feb-2020_2.pdf. Last accessed 2021/05/31
8. European Commission: Horizon 2020 Work Programme 2018–2020. 10. Secure, Clean and Efficient Energy, pp. 171. https://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-energy_en.pdf. Last accessed 2021/05/31
9. Positive Energy Districts (PED): JPI Urban Europe. https://jpi-urbaneurope.eu/ped/ . Last accessed 2021/05/31
10. JPI Urban Europe/SET Plan Action 3.2: White Paper on Reference Framework for Positive Energy Districts and Neighbourhoods—Key Lessons from National Consultations, 2020 edn. JPI Urban Europe, Vienna, pp. 7 (2020). https://jpi-urbaneurope.eu/wp-content/uploads/2020/04/White-Paper-PED-Framework-Definition-2020323-final.pdf. Last accessed 2021/05/31
11. COST Action CA19126 Positive Energy European Network. https://www.cost.eu/actions/CA19126/#tabs|Name:overview. Last accessed 2021/05/31
12. Gray, B.: Conditions facilitating interorganizational collaboration. Hum. Relations **38**(10), 911–936 (1985)
13. Hamdan, H.A.M., Andersen, P.H., de Boer, L.: Stakeholder collaboration in sustainable neighborhood projects—a review and research agenda. Sustain. Cities Soc. **68**(1), 102776 (2021)
14. Vandevyvere, H., Delnooz, A., Hannoset, A., Legon, A.C., Peeters, L.: The impact of the EU's changing electricity market design on the development of smart and sustainable cities and energy communities. In: Smart Cities Information System Policy Paper (2021). https://smart-cities-marketplace.ec.europa.eu/insights/publications/impact-eus-changing-electricity-market-design-development-smart-and. Last accessed 2021/05/31
15. Zaleski, S., Shanti P., Ben P.: Communities of the future: accelerating zero energy district master planning. In: 2018 ACEEE Summer Study on Energy Efficiency in Buildings Pacific Grove, Preprint. National Renewable Energy Laboratory, Golden, CO. NREL/CP-5500–71841 Proceedings, California (2018). https://www.nrel.gov/docs/fy18osti/71841.pdf. Last accessed 2021/05/31
16. Kua, H.W.: A new integrated framework for stakeholder involvement in sustainability policymaking—a multidisciplinary approach. Sustain. Dev. **24**(5), 281–297 (2016)
17. Bowman, E.H., Singh, H., Thomas, H.: The domain of strategic management: history and evolution. In: Pettigrew, A.M., Thomas, H., Whittington, R. (eds.) Chapter 2 of Handbook of Strategy and Management, 1st edn. Sage Publications Ltd., London (2002)
18. de Wit, B., Meyer, R.: Strategy: An International Perspective, 5th edn. Cengage Learning, United Kingdom (2014)
19. Håkansson, H., Ford, D.: How should companies interact in business networks? J. Bus. Res. **55**(2), 133–139 (2002)
20. Donaldson, T., Preston, L.E.: The stakeholder theory of the corporation: concepts, evidence, and implications. Acad. Manag. Rev. **20**(1), 65–91 (1995)
21. Oberg, C., Graham, G., Hennelly, P.: Smart cities a literature review and business network approach discussion on the management of organisations. IMP J. **11**(3), 468–484 (2017)
22. Whittington, R.: Completing the practice turn in strategy research. Persp. Strategy Pract. **27**(5), 613–634 (2006)

23. Cheng, C.: Relationship and Networking Strategy Tools—What Are They and How do Managers use them in Practice? (PhD thesis). Norwegian University of Science and Technology, Trondheim, Norway (2018)
24. Vuorinen, T., Hakala, H., Kohtamäki, M., Uusitalo, K.: Mapping the landscape of strategy tools: a review on strategy tools published in leading journals within the past 25 years. Long Range Plan. **51**(4), 586–605 (2018)
25. Ritter, T., Wilkinson, I.F., Johnston, W.J.: Managing in complex business networks. Ind. Mark. Manage. **33**(3), 175–183 (2004)
26. Whittington, R., Molloy, E., Mayer, M., Smith, A.: Practices of strategizing/organizing: broadening strategy work and skills. Long Range Plan. **39**, 615–629 (2006)
27. Wright, R.P., Paroutis, S.E., Blettner, D.P.: How useful are the strategic tools we teach in business schools? J. Manage. Stud. **50**, 92–125 (2013)
28. Creswell, J.W.: Mapping the field of mixed methods research. J. Mixed Methods Res. **3**(2), 95–108 (2009)
29. Palinkas, L.A., et al.: Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. Adm. Policy Ment. Health **42**(5), 533–544 (2015)
30. Soutullo, S., Alenei, L., Per Sieverts, N., Ferrer, J.A., Gonçalves, H.: Testing platforms as drivers for positive-energy living laboratories. Energies **13**(21), 5621 (2020)
31. SPARCS (H2020): Sustainable Energy Positive and zero carbon communities. Espoo a frontrunner in smart city development in Europe. https://sparcs.info/index.php/cities/espoo. Last accessed 2021/05/31
32. Hukkalainen, M., et al.: D3.1 Detailed plan of the Espoo Smart City Lighthouse Demonstrations. SPARCS project deliverable (2020). https://www.sparcs.info/sites/default/files/2020-09/SPARCS_D3.1_Detailed_plan_Espoo.pdf. Last accessed 2021/05/31
33. SusCity: Urban Data Driven Models for Creative and Resourceful Urban Transitions. https://www.uc.pt/en/org/inescc/Projects/projects/suscity. Last accessed 2021/05/31
34. POCITYF (H2020): Involving Cities with Heritage Sites in Europe's Renewable Energy Transition. https://pocityf.eu/. Last accessed 2021/05/31
35. Brozovsky, J., Gustavsen, A., Gaitani, N.: Zero emission neighbourhoods and positive energy districts—a state-of-the-art review. Sustain. Cities Soc. **72**, 103013 (2021)

# Reviewing Challenges and Limitations of Energy Modelling Software in the Assessment of PEDs Using Case Studies

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**Abstract** Positive Energy Districts (PEDs) have the potential of accelerating the decarbonization of urban areas and promoting scalability between cities. The development and real-world implementation of such innovative concepts can be enhanced through urban energy modelling. However, assessing PEDs can be challenging, and information on this topic is scarce and fragmented. The main contribution of this paper is collecting and analyzing challenges and limitations of energy modelling software for assessing PEDs through five case studies in Italy, Spain, The Netherlands, Denmark and Canada. Case studies are assessed first from a modelling approach, then the main identified challenges and limitations of modelling tools for PEDs are discussed, and finally, various ongoing trends and research needs in this field are suggested.

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## 1 Introduction

One key aspect to evolve towards more sustainable city energy systems is to develop integrated or multi-energy systems, incorporating new developments and building retrofits, distributed generation schemes and on-site exploitation of endogenous resources [1], where electricity, heating, cooling, and transport interact with each other at various levels [2]. The Positive Energy District (PED) concept, developed as part of the Smart Energy City strategy [3], has the potential to accelerate the decarbonization of urban district energy systems and promote scalability between cities [4]. The Strategic Technology Plan (SET Plan), Action No. 3.2., defines PEDs as districts with annual net zero energy import and carbon emissions, working towards an annual local surplus production of renewable energy [5]. The Joint Programming Initiative (JPI) Urban Europe also states that PEDs require integrating different systems (e.g. buildings, energy, mobility, ICT) and interactions between stakeholders to optimize the liveability of the urban environment [6]. Nevertheless, designing and planning the implementation of PEDs following a holistic approach can be difficult, since extensive knowledge on different areas, volume of data and involvement of multiple stakeholders are required. According to [7], energy modelling can be used as a decision support tool to reduce risks and engage different actors to achieve a specific objective.

Simulation tools for urban-scale energy systems have already been overviewed in previous literature [8]. Overall, existing reviews on urban energy modelling tend to focus on tools for simulating the energy demand of the building stock [9], multi-objective, multi-carrier, multi-scale optimization of building energy systems [10], GIS-based models [11] and visualization of energy qualities [12]. However, there are no established approaches for energy modelling at district and urban scales to support the selection of the best scenario [13]. According to [8], Urban-Scale Energy Modelling (USEM) is capable of modelling building characteristics and multisectoral energy flows, which allows for accurately simulating urban district energy systems. From a technical perspective, district-centered modelling approaches are highly complex due to their requirements, which include: detailed time–space patterns of building energy demand and resource availability [14], large amounts of input data, advanced models to simulate technology performance [15], energy simulations and optimizations, or handling a great number of outputs from energy calculations [8]. In the particular case of PEDs, a special consideration of the interactions with external grids, the spatial resolution and boundaries of the district are also required to ultimately achieve a positive energy balance [16]. Consequently, designers, engineers or researchers who plan to analyze PEDs face a number of challenges and limitations, and should develop a common modelling framework accordingly.

This paper aims to provide city planners, researchers and designers who intend to assess PEDs, with a critical overview of challenges and limitations of modelling tools and approaches for urban district energy systems, using five selected case studies.

## 2 Assessment of Selected Case Studies

Five case studies were identified from members of the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC) Annex 83 [17]. Annex 83 is the main platform for international scientific debate and research on PEDs. The Annex 83 members form part of a technical working group focusing on the development of methods, tools and technologies for realizing PEDs. The selected case studies represent a cross-section of PED and towards-PED projects from across Europe and Canada that demonstrate the application of different approaches and energy modelling tools in the assessment of PEDs.

The case studies were first classified according to the stage of PED development (e.g. feasibility study, under construction), modelling objective and target audience (Fig. 1). The limitations and challenges of the case studies were assessed using thematic analysis. Source data for the analysis was derived from the members of the Annex 83 technical working group. The source data from the case studies was coded according to the thematic categories, which were further divided based on the analysis of the source data. Counts against the thematic subcategories were recorded for each case study and used to generate a chart of results.

### 2.1 Case Study in Catania, Italy

The Italian district is located in a North-Western suburban area of Catania, South Italy, and comprises more than 360 buildings spread over 0.67 km$^2$. Most buildings have

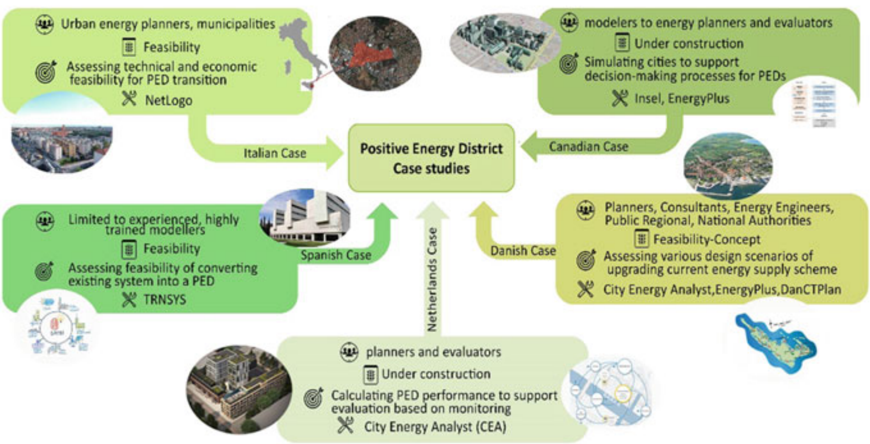


**Fig. 1** Overview of selected case studies. The pictograms illustrate: the target audience, PED case study status, modelling objective and modelling tool, respectively

residential or mixed use, and include schools, supermarkets and warehouses. The area has around 4000 inhabitants, with average yearly electricity and thermal energy consumptions of 1135 kWh and 2283 kWh, respectively. An energy-modelling tool was developed with the aim of proposing sustainable and practicable solutions to orient urban energy actions focusing on the PED transition. The resulting study area is eligible to become a PED, although is not planned in a short term.

The energy features necessary to model the performance assessment of the case study refer to technological aspects as well as building characteristics. Thus, the buildings final use, age of construction, stratigraphy, envelope properties, surfaces and volumes are necessary to plan retrofit actions prior to achieving the positive balance objective to become a PED. Afterwards, technological specifications are implemented, including photovoltaic (PV) panels coupled with electrical energy storages (EES) and district heating or combined heat and power systems from biomass (considering the strategic proximity of the selected area to the industrial zone). The impact of decentralized energy systems for the PED definition should also be considered with respect to the energy distribution infrastructures arising from the emergent autonomy of buildings. In this direction, thermal and electrical balances of urban districts depend on the level of virtually or physically exchanged energy flows.

The PED modelling tool is divided into three main stages: pre-simulation data assessment, simulation of near-optimal decentralized distribution configurations and post-simulation data processing. For the pre-simulation data assessment, Q-GIS [18] is used to obtain geo-referenced data, including aspects related to the choice of retrofit actions and energy saving potentials. Energy production data from PV panels are obtained from Global Solar Atlas [19], considering radiation components, air temperature and PV system configuration (installed capacity, tilt and orientation of panels, building function). Information about biomass availability and related energy yields for the chosen conversion technology are derived from IRENA, Biomass Atlas [20]. The data is then elaborated within NetLogo [21], an open-source multi-agent programmable environment. The main aspects considered for the selection of this software include the need to ensure replicability, free open-sourcing, user-friendly interface, and the capability for managing complex and emergent behaviors of interacting parts of a system, such as buildings in urban districts. Finally, post-processing results are exported according to the needs of the energy planner.

### *2.2 Case Study in North-Western Spain*

The selected district consists of a university campus in Northwestern Spain, which includes: public buildings, apartment blocks and university facilities, and was the object of previous developments focused on the smart management and upgrading of energy systems [22]. The district consists of 31 buildings located in different parts of the city and interconnected through an internal high-temperature (90 °C) district heating (DH) network, hence the PED has functional boundaries. The PED is currently in the feasibility study phase, and the potential conversion of the district into a PED is not considered in a short term. Different types of PED were included in the study; however, a special focus was placed on dynamic PEDs, hence different energy exchanges with external networks were considered for a positive energy balance.

The modelling study mainly aims at assessing the technical feasibility of converting the existing system into a PED, including the calculation of system performance. The outcomes of the study will be considered in the definition of potential interventions for the upgrading of the energy system of the campus.

The main interventions included in the feasibility study to convert the district into a PED include: reducing the operating temperature of the existing DH network from 90 to 40 °C, removing existing oil boilers and installing heat pumps at building level, improving the energy performance of existing buildings, installing rooftop solar technologies for electricity and heat production, and integrating electrical batteries.

The modelling process was limited to the available data from previous projects. Consequently, a selection of energy modelling tools was performed considering data restrictions and modelling requirements, including: hourly data resolution, multi-level scale, multi-energy vector modelling or scenario optimization. The main result of this assessment is the absence of one only tool capable of covering all modelling requirements. For this particular study, TRNSYS [23] was selected for modelling the energy balance of the system, including multiple scenarios and their optimization.

Due to the limitations of TRNSYS, the modelling strategy consisted of implementing reduced-order models for each system [24, 25]. Nevertheless, additional tools were required to provide necessary inputs for energy-balance calculations. In particular, Meteonorm [26] provided a weather file for this specific location, the web service of the Spanish cadaster [27] was used to obtain the constructive characteristics of buildings within the district, and CAD software was used to process cadastral data to estimate the available surface for solar systems.

### *2.3 Case Study in Amsterdam, the Netherlands*

ATELIER [28] is an EU-funded Smart City project aiming to create and replicate PEDs in the Lighthouse Cities of Bilbao and Amsterdam, and six Fellow Cities across Europe. The Amsterdam PED is located in the former industrial harbor neighborhood of Buiksloterham, and consists of two new developments (of mixed use) and an existing residential development, completed in 2019. The PED is currently in the implementation phase and will be operational in 2023. The PED is expected to achieve an annual primary energy surplus of 249 MWh, according to first estimations before detailed design, within a virtual boundary. The PED will have dynamic exchanges with external networks to compensate for momentary surpluses and shortages.

PED features relevant to the assessment of the energy system include; high-performance building design, a DH connection, heat pumps combined with a sub-soil Aquifer Thermal Energy Storage (ATES) system, smart micro-grids (3) connected to a centralized smart energy management system, 1000 kWp of high-performance photovoltaics, biogas production, a 1 MW stationary battery and electro-mobility.

The objective of the energy modelling exercise is to calculate PED performance, to support evaluation based on monitoring. PED performance calculations were undertaken during the EU proposal stage, prior to the detailed design phase and engineering calculations. Preliminary calculations were based on theoretical values, e.g., Dutch building standards and typical technical component efficiencies.

Through a review of existing studies and online research, 30 tools were selected for assessment. The tools selected were evaluated against criteria relevant to the Amsterdam PED energy system. The criteria included; district scale assessment, free license, hourly data resolution, user-friendly interface, assessment of multiple energy sources and technologies including, but not limited to, electro-mobility and energy storage. Also included in the assessment was suitability of use for educational purposes.

The outcome of the evaluation highlighted that in order to gain a detailed and accurate assessment, multiple tools are required. In the case of Amsterdam, City Energy Analyst (CEA) [29] was selected for modelling the Amsterdam PED, PVGIS [30] was used to generate energy production profiles and EnergyPlus [31] was used to generate weather files. EnergyPLAN [32], a deterministic model used to optimize energy systems, will be used to balance supply and demand as well as the optimization of renewable energy sources using large-scale battery storage.

CEA is a free open-source tool for the analysis and optimization of urban energy systems. The CEA tool takes a grey box (or hybrid) modelling approach which is of use where limited information on building characteristics is available. The CEA model used in combination with inputs from the Dutch Energy Performance Coefficient (EPC) provides a route to support transparency in PED calculations.

## *2.4 Case Study in Ærø Island, Denmark*

Ærø is a small island located in the southern archipelago of Denmark with a total area of 88 km$^2$ and around 6200 inhabitants. Ærø has an overall goal to become the first $CO_2$ neutral and renewable energy self-sufficient Danish island by 2025, along with becoming fossil-fuel free by 2030 [33]. Over 55% of the island's energy supply comes from solar, wind and biomass-driven systems [34]. Ærø has currently six 2 MW wind turbines which together produce more power than the island itself consumes. PV systems are deployed on a large scale in the residential sector with a current capacity of around 1.35 MW. Regarding heat supply, Ærø has three major DH plants, covering around 65% of the total island heat consumption [35]. The three plants are 100% driven by renewable energy sources with 55% from solar thermal collectors.

Considering the ambitious energy and environmental aims of Ærø island, the goal of the energy modelling in this case study is to investigate the capability of establishing Ærø as a PED and assess various design scenarios and possibilities of upgrading/modifying the current energy supply scheme to aid the goal. The study will provide preliminary results which will form a basis to aid energy system future retrofitting and upgrading. The goal was to perform the analysis using a readily available tool which has the capability to investigate and assess various energy system design possibilities and scenarios. Thus, the decision was made to use CEA tool [29] for modelling Ærø island. In terms of the tool methodology, CEA employs seven databases and six calculation modules and has a user-friendly interface for inputs and a comprehensive results presentation section. Using CEA, around half of the Ærø island was modelled and various scenarios were implemented and assessed. Overall, CEA's integrated modelling and simulation platform with the supporting databases and calculation modules has major advantages and large capabilities in the field of urban scale modelling. This includes mainly the detailed and comprehensive modelling approach, possibilities for multiple scenarios design and simulations and user-friendly interface and detailed results presentation platform. However, the tool is also associated with major limitations and challenges hindering the scalability and the generic aspect of the modelling activity and limiting the potential users.

Recently, DanCTPlan, the first initiative towards developing a holistic energy planner tool for energy efficient and interconnected cities and neighborhoods in Denmark was launched. The platform methodology relies on two main pillars, (1) EnergyPlus whole building dynamic energy performance simulations and (2) data from the Danish building standard BR18 [36]. DanCTPlan considers the type, age and use of buildings in predicting and the corresponding heating and electricity demands. In addition to energy consumption and system capacity estimation, the tool permits investigating various system design scenarios including wind turbines, PV units, biomass systems and solar thermal collectors. Moreover, it allows the user to evaluate if the district is performing as expected, by comparing the predicted performance with the actual reported performance in case of existing buildings.

### *2.5 Case Study in Montreal, Canada*

This case study includes the SGW campus of Concordia University, in Montreal downtown. The Montreal municipality provided an action plan to make the city more sustainable considering carbon mitigation goals and challenges such as reducing GHG emissions by 80% by 2050, compared to the 1990 baseline [37]. Together with the University sustainability action plan, the study aims to evaluate the steps to transform the campus to zero carbon.

Insel4Cities is an urban simulation platform under development at Concordia University by the CERC in Smart, Sustainable and Resilient Communities and Cities. Its final objective is to model cities in a holistic way including, buildings and their demands, but also transport, renewable energy systems and networks, as well as waste and wastewater management. Its main characteristic is, therefore, its modularity, which allows the development of the different aspects of the city independently, hence in parallel, as well as individual updates and improvements.

The platform is supported by two main components: a structure to create and save a digital twin of the city (a digital copy that handles all data required for the simulation and saves the results), and the software INSEL [38], which performs the simulation processes. INSEL is a modular simulation tool to understand, plan, monitor, and visualize energy systems. It offers users ready-made simulation models organized in blocks for a quick start, but also allows users to design entirely new blocks for many system applications. Furthermore, Insel4Cities includes automation of data integration facilitating the simulation of large areas. Because Insel4Cities intends to extend its functionalities to be a useful tool for the urban-scale energy modelling community, it also allows the connection to an increasingly growing set of third-party tools.

Insel4Cities is designed in workflows, each performing a specific simulation, from building demand calculation, PV or solar passive heating potential, to energy system simulations. For example, a workflow to simulate buildings dynamically starts acquiring geometrical data using different formats such as CityGML, lidar point cloud, and open street map. The data is saved as a digital twin, and enriched by information from various libraries such as construction material and occupant behavior libraries.

Buildings and building attribute archetypes are categorized based on the building use type and year of construction. The footprints of buildings can be used as a common key between CityGML, open street map, and building characteristics, and spatial join techniques are used to create a master dataset containing building geometry and attributes. After the enrichment, the digital twin is fed into Insel4Cities simulation engine. A urban-scale radiation model to consider shading and multiple reflections, the Simplified Radiosity Algorithm (SRA) [39] and EnergyPlus [31] to calculate building energy demand and consumption, are used for this case study.

## 3 Limitations and Challenges

The limitations and challenges of the Annex 83 case studies have been assessed using thematic analysis. The following overarching thematic categories were identified as common to all cases irrespective of the approach or the modelling tool: (1) input data, (2) meteorological data, (3) geometrical data, (4) building energy modelling, (5) energy system modelling, (6) user interface and complexity, (7) modelling process and accuracy, and (8) data integration. An overview of the limitations and challenges derived from the analysis of the five PED case studies is shown in Fig. 2.

The main source of limitations and challenges is associated with input data, particularly around access to accurate input data and a lack of comprehensive data on building attributes. Energy system parameters and building energy modelling are ranked second in importance in terms of limitations and challenges. The main limitations relating to energy system parameters are building definitions and typologies and the manual customization of parameters. For the category of building energy modelling, customization requirements and a lack of energy system characteristics are identified as key challenges. A final limitation is related to the scope of the analysis itself, which focuses on the limitations of modelling in general for PED assessment

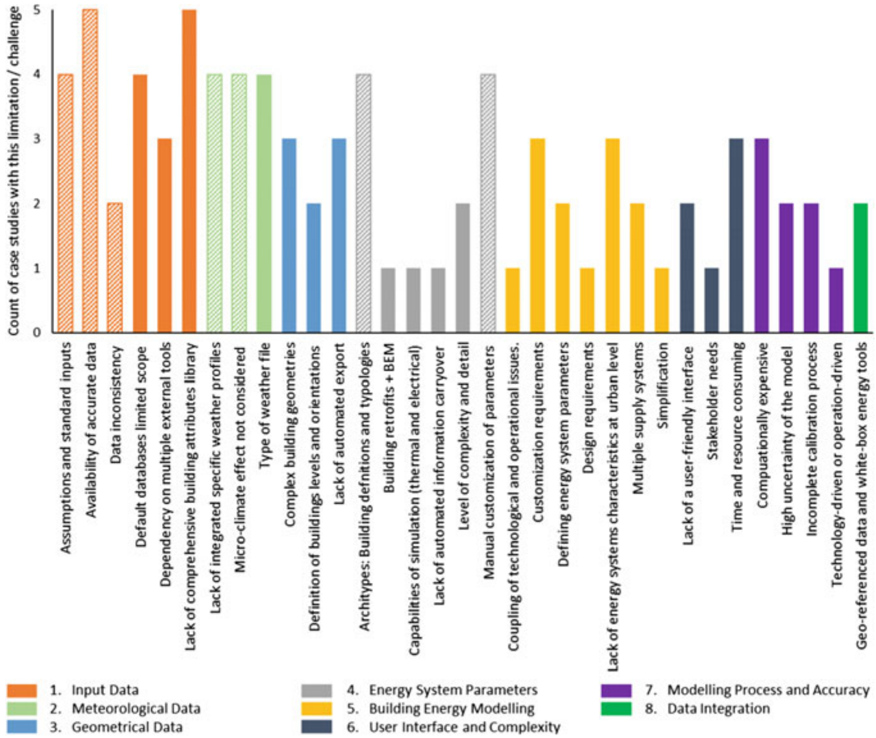


**Fig. 2** Overview of limitations and challenges in energy modelling software from PED cases, distinguishing between tool-specific (solid fill) and general (pattern fill) limitations/challenges

and does not seek to provide detailed analysis on tool-specific challenges. Figure 2 shows the majority of the limitations identified were tool-specific.

The broad categories of limitations and challenges are further elaborated to provide greater insights into the specific challenges identified.

(1) Input data: Multiple tools and external input sources are required for all cases, increasing the complexity, and making data collection and integration a major challenge of the modelling process. Obtaining accurate data is usually very time and resource consuming, while using standard data generally entails significant assumptions, which potentially increase the uncertainty of the models. Furthermore, the use of external data brings about issues of ownership, sharing or data protection.

(2) Meteorological data: In all cases, weather profiles are not integrated in the tools, or only a limited set is included by default. Consequently, specific meteorological files from external sources are necessary, hence micro-climate effects in the models cannot be considered. Additionally, modelling tools usually restrict the type of weather files that can be integrated.

(3) Geometrical data: In most cases modelling complex building geometries was not possible or was very complicated, as buildings were usually considered as extrusions above and below ground. The simplification of building geometries may be useful during an early design stage but can also lead to inaccuracy in the simulation and performance calculation. Complex geometries require the use of additional tools. In some cases, tools were not able to automatically read the number of floors for each building and building orientation was also found to be limited in some cases. In addition, other objects such as sheds, bins and empty boxes were read as buildings.

(4) Energy system parameters: Defining some types of building services, HVAC and renewable systems is limited for several tools. Most tools do not allow for multiple supply systems at building level, making it difficult to accurately model such systems. Default parameters are usually included for most energy elements, but accurate results require actual values, including very technical and advanced specifications.

(5) Building energy modelling: In some cases, limitations were identified with building definitions, where every shape was assumed as a conditioned building space, including sheds and storage rooms. Even with the most comprehensive and well-established tools, there is still a need for manual inspection, modifications, deletion of objects and components.

(6) User interface and complexity: Several tools do not have a user-friendly interface and their adoption requires a deep knowledge of energy systems, usually limiting its use to experienced and highly-trained energy modelers. Generally, simulation efforts are proportional to the level of detail of energy features and specifications, especially when tailored to the stakeholders' needs. In these cases, a cost-effective evaluation between highly detailed and time-consuming simulations should be conducted.

(7) Modelling process and accuracy: Most modeling tools are technology or operation driven, whilst pursuing both issues is usually computationally expensive. A solution in this sense consists of introducing simplifications in terms of the number of modeled variables, resolution time, number of buildings or technological parameters, thus harnessing the accuracy of the models.

(8) Data integration: The lack of integration between geospatial data and white-box energy tools has been identified in two case studies, which calls for purpose-defined routines and code programming to include these features within the models.

Every tool used in the assessed case studies has unique features in terms of modelling resolution, solution algorithms, addressed target audience, modelling options, ease of use, etc. Simulation tools with the most powerful modelling capabilities, and which have undergone the most rigorous validation studies, are all legacy software programs (e.g. EnergyPlus, TRNSYS). Although these tools are subject to regular updates, their basis and architecture are invariable. The existence of aforementioned limitations and challenges when modelling PEDs have resulted in new developments and approaches to partially overcome some of those limitations. Some parallel trends and future perspectives capable to further improve the impact of simulation-based design, research and engineering of PEDs are needed, such as: advanced design support opportunity (uncertainty propagation, sensitivity analysis methods and optimization); parametric and generative design tool mostly driven by dedicated plug-ins that interface Building Performance Simulation (BPS) software with CAD tools; or co-simulation and ongoing research aiming at reconceiving modelling approaches from a bottom-up perspective (development of simulation libraries).

## 4 Conclusions

This paper paves the way for a critical thinking on the main challenges and limitations of energy modelling software that urban planners and energy specialists face when assessing PEDs. Five case studies in Italy, Spain, The Netherlands, Denmark and Canada have been presented and discussed. On this basis, a comprehensive overview of application-oriented, general-purpose and control capabilities for the modelling and simulation of PEDs was presented. The case studies did not find a single tool with all the capabilities and required information to model PEDs. In all cases, the main source of limitations and challenges was related to the limited access to input data, which implied requiring different external tools and data sources to construct the model (e.g. PVGIS, IRENA, EnergyPlus, building architypes). In addition, the customization of input parameters from default databases required significant time resource to accurately model the local PED context, which is a common limitation.

In reference to the case studies presented in the paper, the Italian case, for instance, found as a significant challenge considering the impact of decentralized energy systems of the PED in external grids. A relevant challenge for the Spanish case was associated to the increase of complexity and computation time of the model when accurately considering the inertia of the DH network and the dynamic coupling of thermal and electrical systems to achieve positivity in the PED. Canada's case faced a significant challenge to integrate the energy-related information of the different district components, such as building, transportation, energy systems, and waste, to organize them into a schema. In the case of Amsterdam, the consideration of energy supply from both central and distributed systems at a building level was identified as a key challenge. In the Danish case, a general challenge identified related to the uncertainty of the model and the calibration process. For example, data was available for DH consumption of the island, however, data on the heating solutions of individual buildings was missing, and thus the model calibration was incomplete and inaccurate. Simulating PEDs typically involve a high number of multi-domain interactions and corresponding reciprocal exchange with energy systems in buildings. Therefore, developing suitable simulation strategies is important for modelers, by carefully matching the performance assessment objectives with the capabilities and limitations of the different modelling tools available. Future work will tackle aspects not assessed in detail in this article, such as a cross-analysis between challenges and limitations in the case studies or an in-depth discussion of specific challenges for each modelling tool.

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## References

1. Girardin, L., Marechal, F., Dubuis, M., Calame-Darbellay, N., Favrat, D.: EnerGis: a geographical information-based system for the evaluation of integrated energy conversion systems in urban areas. Energy **35**(2), 830–840 (2010)
2. Sola, A., Corchero, C., Salom, J., Sanmarti, M.: Simulation tools to build urban-scale energy models: a review. Energies **11**, 3269 (2018)
3. JPI Urban Europe | Joint Programming Initiative: https://jpi-urbaneurope.eu/. Last accessed 2021/06/05
4. Gouveia, J.P., Seixas, J., Palma, P., Duarte, H., Luz, H., Cavadini, G.B.: Positive energy district: a model for historic districts to address energy poverty. Front. Sustain. Cities **3**, 648473 (2021)
5. European Commission: SET-Plan Action No. 3.2. Implementation Plan (2018)
6. Bossi, S., Gollner, C., Theierling, S.: Towards 100 positive energy dis-tricts in Europe: preliminary data analysis of 61 European cases. Energies **13**, 6083 (2020)
7. Bukovszki, V., Magyari, Á., Braun, M.K., Párdi, K., Reith, A.: Energy modelling as a trigger for energy communities: a joint socio-technical perspective. Energies **13**, 2274 (2020)
8. Allegrini, J., Orehounig, K., Mavromatidis, G., Ruesch, F., Dorer, V., Evins, R.: A review of modelling approaches and tools for the simulation of district-scale energy systems. Renew. Sustain. Energy Rev. **52**, 1391–1404 (2015)
9. Mancarella, P.: MES (multi-energy systems): an overview of concepts and evaluation models. Energy **65**, 1–17 (2014)
10. Fonseca, J.A., Nguyen, T., Schlueter, A., Marechal, F.: City energy analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. Energy Build. **113**, 202–226 (2016)
11. Cerezo Davila, C., Reinhart, C.F., Bemis, J.L.: Modeling boston: a workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets. Energy **117**, 237–250 (2016)
12. Fonseca, J.A., Schlueter, A.: Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. Appl. Energy **142**, 25 (2015)
13. Stanica, D.I., Karasu, A., Brandt, D., Kriegel, M., Brandt, S., Steffan, C.: A methodology to support the decision-making process for energy retrofitting at district scale. Energy Build. **238**, 110842 (2021)

14. Niemi, R., Mikkola, J., Lund, P.D.: Urban energy systems with smart multi-carrier energy networks and renewable energy generation. Renew. Energy **48**, 524–536 (2012)
15. Lund, H.: Renewable Energy Systems: The Choice and Modeling of 100% Renewable Solutions. Elsevier, London (2010)
16. Luigi Bottecchia, L., Gabaldón, A., Castillo, T., Soutullo, S., Ranjbar, S., Eicker, U.: Fundamentals of energy modelling for Positive Energy Districts. In: SEB-21 Conference, no. Under Review (2021)
17. IEA EBC—Annex 83—Positive Energy Districts. https://annex83.iea-ebc.org/. Last accessed 2021/06/05
18. QGIS Homepage: https://qgis.org/en/site/. Last accessed 2021/06/05
19. Global Solar Atlas Homepage: https://globalsolaratlas.info/. Last accessed 2021/06/05
20. IRENA Homepage: https://www.irena.org/. Last accessed 2021/06/05
21. NetLogo Homepage: https://ccl.northwestern.edu/netlogo/. Last accessed 2021/06/05
22. GIRTER Project: https://www.cartif.es/en/girter-en/. Last accessed 2021/05/24
23. Transient System Simulation Tool (TRNSYS) Homepage: https://www.trnsys.com. Last accessed 2021/06/05
24. Heidarinejad, M., Mattise, N., Dahlhausen, M., Sharma, K., Benne, K., Macumber, D., Brackney, L., Srebric, J.: Demonstration of reduced-order urban scale building energy models. Energy Build. **156**, 17–28 (2017)
25. Kim, D., Bae, Y., Braun, J.E., Horton, W.T.: A tool for generating reduced-order models from building energy simulation input files to enable optimal design and control analysis. In: 5th International High-Performance Buildings Conference 2016, West Lafayette, IN, vol. 3641, pp. 1–9 (2018)
26. Meteonorm Homepage: https://meteonorm.com/en/. Last accessed 2021/06/05
27. MiniStry of Finance. Government of Spain: Spanish Cadastral Electronic Site (2017). https://www1.sedecatastro.gob.es/. Last accessed 2021/06/05
28. Amsterdam Bilbao Citizen Driven Smart Cities (ATELIER): https://smartcity-atelier.eu/about/. Last accessed 2012/06/05
29. City Energy Analyst (CEA): https://cityenergyanalyst.com/. Last accessed 2021/06/05
30. Photovoltaic Geographical Information System (PVGIS) | EU Science Hub. https://ec.europa.eu/jrc/en/pvgis. Last accessed 2021/06/05
31. EnergyPlus Homepage: https://energyplus.net/. Last accessed 2021/06/05
32. EnergyPLAN | Advanced energy systems analysis computer model. https://www.energyplan.eu/. Last accessed 2021/06/05
33. Ærø will be CO2-neutral already in 2025: https://www.aeroedagblad.dk/article/ro-bliver-co2-neutral-allerede-i-2025-30849. Last accessed 2021/06/05
34. Aero—A Renewable Energy Island. http://www.aeroe-emk.dk/eng/aeroe_energy_island.html. Last accessed 2021/06/05
35. Marstal Fjernvarme—A Solar District Heating Plant on the Island of Ærø, Denmark. http://co2mmunity.eu/wp-content/uploads/2019/03/Factsheet-Aer%C3%B6-Marstal.pdf. Last accessed 2021/06/05
36. Danish Building Regulation (BR18). https://bygningsreglementet.dk/. Last accessed 2021/06/05
37. Sustainable Montréal 2016–2020. https://montreal.ca/en/articles/sustainable-montreal-2016-2020-8944. Last accessed 2021/06/05
38. INSEL Homepage: https://insel4d.ca/en/home_en.html. Last accessed 2021/06/05
39. Robinson, D., Stone, A.: Holistic radiation modelling with a fast simplified radiosity algorithm. In: IBPSA 2005—International Building Performance Simulation Association 2005, no. Appendix 1, pp. 1043–1050 (2005)

# State of the Art on Sustainability Assessment of Positive Energy Districts: Methodologies, Indicators and Future Perspectives

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**Abstract** The concept of Positive Energy District is one of the main areas of research and extensive applications of the principles of the clean energy transition within the building sector. In the past years, the most widely accepted definitions have focused specifically on carbon neutrality, while several other aspects regarding all sustainability approaches (including environmental, social and economic perspective) were

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included qualitatively or to a lesser degree. This paper proposes a discussion on the state of the art of the sustainability assessment of Positive Energy Districts, by investigating environmental, social and economic sustainability applications. The three sustainability dimensions are investigated individually first, while discussing methodological insights, key performance indicators used and quantitative results, as well as in an integrated perspective. Finally, the paper describes research gaps and areas for further development on the topic.

## 1 Introduction

The concept of Positive Energy Districts (PED) is one of the main initiatives in Europe for clean energy transition in the built environment. This initiative is advocated by energy policies and international working groups to accelerate the decarbonization of urban areas and promote the potential for scalability between cities.

PEDs are the main focus of several activities on the EU scale as well as focus of international research by the International Energy Agency Energy in Buildings and Construction Annex 83 "Positive Energy Districts". Although a common and comprehensive definition is still being widely discussed, it is generally accepted that Positive Energy Districts are specific areas with annual net zero energy import and net zero $CO_2$ emissions, working towards an annual local surplus production of renewable energy. These districts are a key part of the transformative process from carbon-intensive cities towards sustainable urban development through a diverse set of solutions, including technological ones (buildings' interaction, ICT, mobility, low-carbon building materials and technologies) as well as legal, economic and social ones [1].

PEDs are notable for their innovative capacity, they also represent, at the same time challenges as well as opportunities for local and global sustainable development [2]. The actual impact of PEDs over local sustainable development targets, meanwhile, remains uncertain. This is mainly because intangible elements abound in the environmental, social, cultural and institutional perspectives of sustainable development beyond the economic one and in the open, complex and dynamic ecosystems that constitute the cities in which these technologies are deployed [3]. To support the monitoring of relevant projects and initiatives, Key Performance Indicators (KPIs) can be a useful instrument to evaluate the progress of PEDS or smart city strategies [4] as, when chosen correctly, allow to model and describe effectively complex phenomena through quantitative indicators [5]. KPIs, in general, measure the effectiveness of a project towards the achievement of specific key objectives. Consequently, cities use KPIs to set measurable targets and monitor progress towards their goals [4]. Furthermore, KPIs are used to establish common metrics and transparency

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in governance, to communicate benefits of investments, to manage city operations [6], to evaluate how well the city is performing in different areas and as support in decision-making [4, 5].

The paper proposes an analysis on the state of the art of PEDs focused on the sustainability assessment of Positive Energy Districts, through an environmental, economic and social perspective.

## 2 Environmental Sustainability of Positive Energy Districts

The approach of assessing the environmental sustainability of PEDs varies in terms of system boundaries and environmental KPIs adopted as metrics.

The methodologies adopted have different depths as per the object of the study: they are variable between the mere use stage perspective with a usual focus on the modeling/monitoring of energy use and emissions assessment up to a more comprehensive Life Cycle Assessment (LCA) approach. Thus, in general, it is worth assessing the following macro-areas of methodological applications:

- Operation stage-oriented assessments [7]. These studies usually encompass larger system boundaries, often including not only buildings, but also mobility, external lighting, with a simplified depth and not pursuing the life cycle perspective. They usually focus on few indicators, usually on energy consumption-based and greenhouse gas emissions expressed in $CO_2$ equivalents (eq) and have a primary focus on the operational energy consumption of the district of interest;
- LCA based assessments [8]. LCA is applied to a wider range of solutions and processes of the urban environment, ranging from food products [9], mobility [10], single building and multiple buildings environmental impact assessment.

On top of these two main streams of scope alternatives, the following aspects of assessment can be incorporated although usually extended also a more integrated sustainability assessment including other aspects:

- Multi objective criteria and optimization [11]. In this aspect, the foundation of the assessments is focused on the quantification of specific KPIs. After that, weighting factors can be introduced for these KPIs, and multi-criteria decision support analysis can be performed through the ranking of alternatives and/or mathematical optimization of the design variables;
- Building stock modeling and integration of GIS [12]. Generally based either on top-down (through statistical approaches) or bottom-up (through detailed energy modeling based on building archetypes), these studies aim at modeling the whole building stocks at district- or city- level. The integration of GIS usually comes along with the building stock modelling, and allows for investigation of further aspects, such as e.g. e-mobility integration and renewable energy systems planning;

- Certification schemes [13]. Several solutions are available within the district certification for the PED and district context (e.g. LEED—ND, BREEAM Communities, DGNB for Districts). Although not directly tailored towards PED sustainability assessment, they usually indirectly focus on the improvement of the environmental performances of the district through credits for sustainability design aspects (e.g. by adding solar photovoltaics, improved insulation and energy-efficient measures), recycling/waste management, easy access to public transport, etc.

As for the main KPIs used, a wide range of indicators have been used in past assessments, including direct specific emissions (e.g. greenhouse gases, nitrogen oxide, sulfur dioxide, ozone, particulate matter), LCA-based indicators (e.g. recommended midpoint impact categories by International Reference Life Cycle Data System (ILCD) [14]/Environmental Product Declaration (EPD)), energy-based KPIs (share of renewables, decarbonization of the energy generation mix, covering of the electricity loads through renewable systems). Other indicators are based on circular economy strategies (e.g. percentage of recycled waste, generation of municipal solid waste), quantitative information on water consumption (e.g. grey and rain water use, water exploitation index), mobility (e.g. fuel mix in mobility), urban heat island (e.g. maximum difference in air temperature within the city compared to the countryside).

The quantitative assessment of the most part of the KPIs mentioned are often not directly comparable, since most studies available in literature use very diverse system boundaries and methodological assumptions. Taking the impact category of global warming potential (GWP) as an example, in some cases the quantitative metric evaluated corresponds to the area of district, in others to the walkable area of the built environment, sometimes being annualized or merely reported as a lump-sum emissions. The system boundaries are also variable with distinction to the facilities and aspects of the district (e.g. onsite energy supply systems, buildings, mobility, impacts allocation) as well as to the life cycle stages to be included.

Thus, the state-of-the-art for environmental impact assessment of PEDs can be briefly summarized as below:

- There is a specific need for a standardized approach when assessing environmental impacts at district scale, with different scopes and indicators;
- It is very common to merely mention and calculate KPIs without investigating trade-offs between design alternatives. Integrated and systematic analyses to address this aspect should be favored and further investigated;
- The focus of assessment should not only be on operation phase, but also other life cycle stages. For greenhouse gas emissions, this means not only direct emissions should be considered, but also the indirect emissions caused by the buildings, infrastructures and activities within the district.
- The spectrum of indicators for Life Cycle Impact Assessment should not be limited to GWP and/or cumulative energy demand (CED) only, but extended to other impact categories relevant for district planning, such as resource depletion and air-pollution related impacts along the supply chain of materials;

- For LCA-based assessment: system boundaries, temporal horizon of the assessment, building life cycle stages considered, functional units, among others, vary across studies, which makes the inter-study comparison of results very difficult. There is a need for transparent LCA results at the district level with possibility of flexible disaggregation;
- Uncertainty and sensitivity analyses are rarely performed (although highly suggested) and should be therefore addressed with proper methods;
- Most of the available studies, do not yet account for long-term developments in technologies and improvements in production processes for the replacement materials, more dynamic approaches, systematic and transparent integration with other modeling scenarios (e.g. energy scenarios) should be investigated (e.g. dynamic LCA).
- Linkage between the assessment result of PEDs with higher-level environmental targets (e.g. climate goals at city and national levels) are current missing and should be better addressed.

## 3 Economic Sustainability of Positive Energy Districts

Synnefa et al. [15], Isaac et al. [16], Becchio et al. [17], ur Rehman et al. [18], European Commission [19], Angelakoglou et al. [20] the state of the art review differentiates the undertaken analysis, e.g., by the local climate and the type of buildings (newly built vs. renovations) and the urban density. Most approaches report on local/national case studies where a building is subject to energy efficiency improvements. Activities mostly regard local trading (energy, flexibility), energy efficiency measures, load management and the choice/combination of technologies as well as spatial planning.

The methods presented mostly aim at the "cost-optimal", "cost-efficient" or "cost-effective" achievement of different goals, for example meeting a specific target of energy efficiency [15]. The "classical" dynamic investment analysis methods [16–18] are most often proposed, partly considering life-cycle costs [18]. Some approaches use cost–benefit analysis comparing investment costs to the overall savings [17] or derive net savings to the customers and society [15, 18].

One specific case is the EU methodology on cost-optimal levels of minimum energy performance requirements as it is featured in an official and binding regulation (Regulation (EU) No 244/2012 [19]). This framework introduces a method to define reference buildings on the national level. As this method serves as a basis for the national economic assessment of energy performance solutions in the EU, it plays an essential role and is referred to in the literature [21]. This framework covers a timespan of 30 years for residential and public buildings and 20 years for commercial and other non-residential buildings. Financial as well as macroeconomic analyses are distinct by the inclusions of taxes, VAT charges and subsidies for the financial perspective while these are disregarded in the macroeconomic approach. Instead, in the latter, costs due to greenhouse gas emissions are taken into account. It is proposed to undertake a sensitivity analysis for cost input data including energy prices and discount rates.

Most approaches focus on the business economics of decision making for, e.g., technology choices on an individual case basis (e.g. building level). Some approaches take a broader perspective by comparing different business models. A multi-criteria (decision) analysis (MCDA, Macbeth) is presented in [20] in combination with classic economic analysis methods, which allows for an integrated sustainability evaluation taking qualitative and quantitative aspects, environmental, social and economic aspects into consideration. Macroeconomic perspectives are taken, for example, to calculate employment impacts or to investigate the net savings to society [18, 21]. Many of the mentioned methodologies show overlaps with more technology and energy-system oriented assessments, such as energy system modelling/simulations [17]. In addition, links to environmental aspects can be observed, in particular relating to emissions [15–17].

The indicators adopted usually encompass typical investment-related indicators providing for indicators such as the net present value (NPV) [16], pay-back period [16, 17], internal rate of return (IRR) [16, 18] and different type of cost–benefit ratios [17], but also net savings to the customers and society [18] or life-cycle/global costs [18, 21]. Other indicators purely refer to the energy domain such as the level of energy self-supply, or provide energy-related economic indicators such as levelized cost of electricity (LCOE)/levelized cost of heat or (net) energy cost savings [22]. In several studies long-term costs (e.g. over a period of 25 years) are considered [16, 23].

More macro-economic oriented approaches use social KPIs such as employment factor or impact (number of jobs per €1 million investment, jobs created over a period of 40-years), the net saving to society, including the value of externalities (e.g. sum of the lifetime energy cost savings and value of externalities, less the lifetime investment) [18, 21], or impacts on fuel poverty [20]. Economic KPIs are often closely related to KPIs for technical domains referring to thermal comfort, energy labelling, energy savings, primary energy demand, grid impact/deferred grid investment and are also closely related to environmental metrics such as carbon costs. Moreover, economic KPIs can include awareness on economic benefits of reduced energy consumption or consider grants (share of investment that is covered by grants) [20].

In terms of gaps of the literature reviewed, life-cycle cost analysis is represented only to a small extent. Also, a more integrated market perspective including, e.g. potential revenues from flexibility trading would be of value added for the economic assessment of PEDs.

## 4 Social Sustainability of Positive Energy Districts

Social sustainability can be defined as specifying and managing both positive and negative impacts of systems, processes, organizations, and activities on people and social life [24]. The concept of social sustainability has evolved into a multi-layered complex and triggering an integrated network of stakeholders [25]. Existing literature acknowledges that a sustainable development cannot be successful in the provision of residents' well-being until it addresses social sustainability [26] calling for research that focus explicitly on the social dimension of sustainability [27]. A diverse set of stakeholders are involved in initiatives to apply social sustainability approaches as a planning practice with a particular focus on the social outcomes of urban development, housing and regeneration. However, social sustainability and the respective assessment methodology specifically for PED are lacking in research. Existing studies addressing main themes related to the concept and definition of PED are presented here. In sustainability of urban developments [26], some of the important aspects of sustainable district reflected in existing studies include effective and accessible local services; safety from crime and accidents; aesthetics environment; affordable price of housing; opportunity for social participation; good environmental conditions (pollution, clean air, low level of noise); employment and opportunity for business. In the context of energy communities, a quantitative framework for evaluating the social impacts and benefits is missing. However, identified benefits are enhanced social cohesion, improved energy literacy, the development of social networks, the promotion of global partnerships and reduced energy poverty [28]. In addition, urban energy systems directly affect the well-being and happiness of urban inhabitants. Generating energy within the city, improving energy efficiency and achieving carbon neutrality would rely on citizen involvement and therefore would face behavioral challenges [29]. Related research addresses psychological processes which determine particular human behavior (motivation, acceptance, support) [30]. Consequently, social inclusiveness and participation of various stakeholders are important success factors in establishing citizens centric carbon free energy solutions. In this context, the concept of energy citizenship becomes highly relevant as citizens become actively involved in energy transition as consumers and users [31]. Authors also address social innovation structures related to citizen-led energy transitions [32], and how government responds to them [33]. Furthermore, the energy demand estimates at PED design phases—and hence the overall district energy balance—are intrinsically related to users' energy practices. Households and communities are not passive consumers, yet their practices are shaped by varied and not particularly predictable factors. It is of course worth stating that informed and engaged 'Positive Energy Citizens', as PED residents, can significantly impact the energy performance targets, by managing to articulate demand while maintaining IEQ goals within the energy production profiles at district level. They contribute to shape the district energy performance to a positive energy balance within a specific timeframe and might be able to react and to adapt their energy needs towards PED energy limits. These implies significant attention to household and social practices under varied and specific cultural, climatic and boundary conditions. The conventional approach tends to set up a dominant ideal energy consumer, a characterized 'persona' who is intended to develop functional and rational decisions about her energy uses in function of the building typology. Academic studies [34] refer to disrupt this concept of the ideal consumer. Energy demand also implies significant agency by households and energy communities. In fact, this is limited and is subject to broader societal expectations that are constantly changing and inevitably ramping up; over the past few decades alone, expectations of cleanliness, comfort and convenience have changed rapidly, and individual households and single communities, however committed, cannot remain unaffected by these wider societal trends. Social-scientific energy research may support accommodating users' diversity into Social Impact Assessment processes of PEDs communities. The adoption of frameworks and methodologies such as the Energy Cultures Framework [34] or Time Geography research [35] could be useful and bring new ways of understanding the social implications of PEDs and how to integrate those into a comprehensive Impact Assessment KPIs' Frame for PED.

The importance of the social dimension and respective measuring indicators for cities and communities have been recognised internationally through standards and initiatives such as the UN Sustainable Development Goals, ISO 37120: Sustainable cities and communities—Indicators for city services and quality of life and the United Nations Economic Commission for Europe (UNECE). The SDGs set the international agenda to make cities and human settlements inclusive, safe, resilient and sustainable and defines indicators to, among others, ensure access to adequate, safe and affordable housing and basic services and upgrade slums, provide access to safe, affordable, accessible and sustainable transport systems for all, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable hu-man settlement planning and management. ISO 37120 defines specific social related indicators also based on the UN SDGs and addressing the issues defined in ISO 37101:2016 Sustainable development in communities—Management system for sustainable development—Requirements with guidance for use. They are classified into core, supporting and profile indicators, with the former essential for steering and assessing the performance management of city services and quality of life [36]. The UNECE endorsed a set of indicators under the dimension Society and Culture to address Education, Health, Culture, Safety, Housing and Social inclusion categories.

Frameworks and methodologies to assess social performance of cities, communities and similar human settlements have been designed according to the different scopes in which these sets of indicators are used and serve to further analyse the overall impact of specific urban design principles. Each method or approach has its ad-vantages and disadvantages and can be based on qualitative and/or quantitative assessments. Social Impact Assessment (SIA) includes the processes of analysing, monitoring and managing intended and unintended social consequences—both positive and negative—of planned interventions, as well as any social change processes caused by them, ex-ante and ex-post [37] (Social Impact Assessment (iaia.org)) [38]. Specific to the built environment, SIA has been applied to assess urban planning, renewable energy projects [39]. Methodologies for sustainable city indexes and green building schemes have been developed incorporating defined social performance indicators. The level of integration of these indicators varies greatly from one methodology to another [40]. e.g., A set of KPIs expressed in monetary units, for smart cities based on the Gross Social Feel-Good Index, [41] which includes 13 Society and Culture KPIs as part of a framework which intends to assess and rank cities based on how smart and sustainable they are. The "people" dimension is one of the 5 dimensions embedded in this framework developed under the EC CityKeys project [42].

Limited research and methodological development have been done in the specific field of PEDs. However, as previously detailed, low carbon city aspects have been investigated, resulting in various assessment frameworks including KPIs under the Social and living Category. Moreover, under Smart Cities and Communities (SCC) lighthouse projects, the POCITYF project focused on KPIs for energy transition and creation of PEDs. Specifically, the social KPIs aim to assess the extent to which projects favour collaboration of governments with citizens and provides an open innovation ecosystem for citizens to engage in PED co-creation [43]. Methodological developments and case studies applying the Social Life Cycle Assessment (S-LCA) approach are clearly missing despite the more than 10 years of activities from the publication of the 2009 UNEP SETAC Guidelines of S-LCA of Products. The energy- and in particular renewable energy relevance in PEDs indicates the importance to assess social impacts across the entire life cycle. The concept of life cycle is further strengthened in the recently revised S-LCA Guidelines alongside the inclusion of impacts on all relevant Stakeholder Categories. The ISO 14075: Principles and Framework for S-LCA under development in ISO TC 207 SC 5 standardisation activities, is a concrete opportunity to enhance S-LCA implementations and in particular related to PEDs.

## 5 Integrated Sustainability Analysis

Although the three spheres of sustainability have briefly been discussed in their applications towards PEDs, it is also appropriate to delve into the integration among them, since the mere juxtaposition of different approaches does not allow to achieve a true holistic and integrated methodology.

The analysis of the reviewed literature shows that in most cases the methodological approach includes general framework of KPIs and criteria grouped under different assumptions inspired to the traditional sustainability pillars (Fig. 1 shows the main dimensions investigated by the literature reviewed KPIs); other approaches are based on different integrated rating system inspired by similar sustainability considerations.

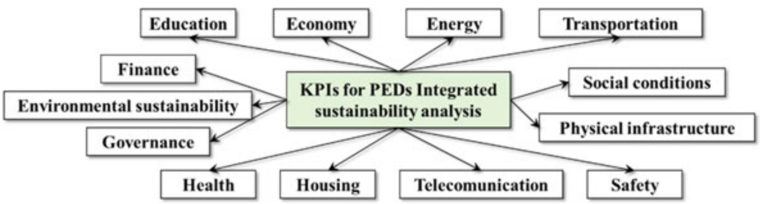


**Fig. 1** Literature dimension of KPIs for PEDs Integrated sustainability analysis [6, 20, 36, 44]

In some cases, KPIs are categorized according to recurrent smart city dimensions (e.g. technical, environmental, economic, social, ICT and legal) and are considering the whole urban dimension, at least in some dimensions [6, 20, 44]. A smaller fraction of the available literature performs urban metabolism studies, multi criteria decision making (thus building up on the available KPIs frame-works) [45] or spatial analyses or introduces the concept of "positivity labels" [46]. Other research still focused on the optimum combination of technologies and financial performances to achieve environmental targets, neglecting other areas (e.g. social aspects), although referring to a more comprehensive KPIs framework [23].

Although it is not surprising to find that the most frequent approach towards urban sustainability assessment is the use of a wide set of indicators framework, it is worth mentioning that some concerns are available [17, 47] as on how this kind of approaches might not always be based on clear sustainability principles, and that the approach should be organized and based a more integrated perspective. Also a clear understanding of drivers and benefits for district scale refurbishment, as well as barriers to the implementation of possible solutions deserves careful consideration to unlock investments in energy refurbishment at district level [48].

Therefore, this is one of the major research gaps traced within sustainability assessment of PEDs: the limited connections and interactions between the different sustainability dimensions lies in methodological solutions that often are only developed in parallel with no horizontal connections.

Other specific potential areas for research investigation lie in:

- Weighting and categorizations of indicators and different sustainability pillars. More objective and scientifically grounded approaches should be explored;
- Standardization of the modeling of PED urban sustainability assessment boundaries and methodological framework. Results within sustainability assessment are often difficult to be compared on equal ground;
- The robustness of the hierarchies between sustainability indicators and pillars should be largely investigated through use of sensitivity analyses;
- Characterization of available methodologies towards the site-specific modeling and assessment;
- Need to adopt integrated methodologies not only as an ex-post approach to assess results and impacts. Sustainability assessment in PEDs should also become an active part of the early design process and influence the ranking of the design alternatives being evaluated, for example by involving stakeholders in the identification of expected impacts, to better understand what the expected changes are or monitor impacts with reference to the SDGs framework applied at the local level.

## 6 Conclusions

The sustainability assessment of Positive Energy Districts is fundamental to support the clean energy transition of the built environment, yet the field is still largely fragmented. At the moment, several methodologies, approaches, and indicators have been evaluated and discussed within the scientific community, but they are intended for either different levels of assessment (technology, operation, LCA) or different methods (GIS-based tools, optimization models) or even different scopes (planning, technological design). Thus, the question of how to address cross-cutting and complex interactions occurring in urban areas and specifically in future PEDs remains open.

Undoubtedly, there is agreement on the need to move towards a sustainability approach incorporating but going beyond the specific needs of third parties and, thus, encouraging a systemic and integrated future vision for PEDs. To reach this vision, the sustainability paradigm will continue to rest upon the well-known three pillars, i.e., environmental, economic, and social aspects. The evaluation of the three main spheres of sustainability is well supported by the definition of key performance indicators, widely used to measure the impact of PEDs over specific objectives and targets. Among the environmental indicators, the most frequently surveyed in assessment studies encompass specific emissions' rates or energy performances (share of renewables, decarbonization of the energy mix). The economic evaluation usually refers to investment-related indicators, such as NPV or payback time, energy-related economic indicators, as the LCOE. The majority of studies complement the economic assessment with environmental impacts evaluation, usually referring to emissions. Social impacts are measured in terms of accessibility of local services, air quality, affordable price housing, and energy poverty. However, it comes clear out how the intrinsic participative nature of PEDs will require the acknowledgment of a novel sociality, made also of energy interactions for the achievement of a net positive energy balance of the area.

The discussion conducted so far highlights the need for a comprehensive understanding of the different aspects impacting the sustainability assessment of PEDs. In this sense, although highly advisable, an integrated and systemic approach for the sustainability assessment of PEDs has been still not consolidated and the main environmental, economic and social pillars are usually treated as separate spheres with limited interlinked issues. In conclusion, building a representative methodology for sustainability assessment of PEDs as well as defining comparable, measurable and reliable indicators specifically targeted for the district scale is a challenging but fundamental task to be accomplished in the short term. Also, there is a real need to focus on dynamic and sensitive approaches to encounter for future energy scenarios, macro-economic aspects, and related social impacts deriving from interoperability activities in urban areas.

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## References

1. Saheb, Y., Shnapp, S., Paci, D.: From Nearly-Zero Energy Buildings to Net-Zero Energy Districts (2019)
2. Benites, A.J., Simões, A.F.: Assessing the urban sustainable development strategy: an application of a smart city services sustainability taxonomy. Ecol. Indic. **127**, 107734 (2021)
3. Magro, E., Wilson, J.R.: Complex innovation policy systems: towards an evaluation mix. Res. Policy **42**, 1647–1656 (2013)
4. Dameri, R.P.: Smart City Implementation. Prog. IS. Springer Genoa, Italy (2017)
5. Hiremath, R.B., Balachandra, P., Kumar, B., Bansode, S.S., Murali, J.: Indicator-based urban sustainability—a review. Energy Sustain. Dev. **17**, 555–563 (2013)
6. Huovila, A., Bosch, P., Airaksinen, M.: Comparative analysis of standardized indicators for smart sustainable cities: what indicators and standards to use and when? Cities **89**, 141–153 (2019)
7. Janssens, A., Rebollar, J.V., Himpe, E., Delghust, M.: Transforming social housing neighbourhoods into sustainable carbon neutral districts. Energy Procedia **132**, 549–554 (2017)
8. Guarino, F., Longo, S., Hachem Vermette, C., Cellura, M., La Rocca, V.: Life cycle assessment of solar communities. Sol. Energy **207**, 209–217 (2020)
9. Cerón-Palma, I., Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.-I., Ponce-Caballero, C., Rieradevall, J.: Towards a green sustainable strategy for social neighbourhoods in latin america: case from social housing in Merida, Yucatan. Mexico. Habitat Int. **38**, 47–56 (2013)
10. Lausselet, C., Lund, K.M., Brattebø, H.: LCA and scenario analysis of a Norwegian Net-Zero GHG emission neighbourhood: the importance of mobility and surplus energy from PV technologies. Build. Environ. **189**, 107528 (2021)
11. Riera Pérez, M.G., Rey, E.: A multi-criteria approach to compare urban renewal scenarios for an existing neighborhood. Case study in Lausanne (Switzerland). Build. Environ. **65**, 58–70 (2013)
12. Mastrucci, A., Marvuglia, A., Leopold, U., Benetto, E.: Life cycle assessment of building stocks from urban to transnational scales: a review. Renew. Sustain. Energy Rev. **74**, 316–332 (2017)
13. USGBC: U.S.G.B.C. LEED v4 for neighborhood development. Päivitetty **2** (2018)
14. Handbook, I.: Recommendations for Life Cycle Impact Assessment in the European Context. Publications Office of the European Union, Luxembourg (2011)
15. Synnefa, A., Laskari, M., Gupta, R., Pisello, A.L., Santamouris, M.: Development of net zero energy settlements using advanced energy technologies. Procedia Eng. **180**, 1388–1401 (2017)
16. Isaac, S., Shubin, S., Rabinowitz, G.: Cost-optimal net zero energy communities. Sustainability **12**, 2432 (2020)
17. Becchio, C., Bottero, M.C., Corgnati, S.P., Dell'Anna, F.: Decision making for sustainable urban energy planning: an integrated evaluation framework of alternative solutions for a NZED (Net zero-energy District) in Turin. Land Use Policy **78**, 803–817 (2018)
18. ur Rehman, H., Reda, F., Paiho, S., Hasan, A.: Towards positive energy communities at high latitudes. Energy Convers. Manag. **196**, 175–195 (2019)
19. European Commission Delegated Regulation (EU) No. 244/2012 of 16 January 2012 Supplementing Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings by Establishing a Comparative Methodology Framework for Calculating. Off. J. Eur. Union (2012)
20. Angelakoglou, K., Nikolopoulos, N., Giourka, P., Svensson, I.-L., Tsarchopoulos, P., Tryferidis, A., Tzovaras, D.: A methodological framework for the selection of key performance indicators to assess smart city solutions. Smart Cities **2019**(2), 269–306 (2019)
21. ZEBRA D5.1: Nearly Zero-Energy Building (NZEB) Technology Solutions. Cost Assessment and Performance (2016)
22. Kim, M.-H., Kim, D., Heo, J., Lee, D.-W.: Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. Energy **187**, 115916 (2019)

23. Sougkakis, V., Lymperopoulos, K., Nikolopoulos, N., Margaritis, N., Giourka, P., Angelakoglou, K.: An investigation on the feasibility of near-zero and positive energy communities in the Greek context. Smart Cities **3**, 362–384 (2020). https://doi.org/10.3390/smartcities3020019
24. Balaman, Ş.Y.: Chapter 6—Basics of decision-making in design and management of biomass-based production chains. In: Balaman, Ş.Y.B.T.-D.-M. (ed.), pp. 143–183. Academic Press (2019)
25. Arcese, G., Lucchetti, M.C., Merli, R.: Social life cycle assessment as a management tool: methodology for application in tourism. Sustainability **5** (2013)
26. Shirazi, M.R., Keivani, R.: The triad of social sustainability: defining and measuring social sustainability of urban neighbourhoods. Urban Res. Pract. **12**, 448–471 (2019)
27. Marchal, V., Dellink, R., Van Vuuren, D., Clapp, C., Chateau, J., Magné, B., Van Vliet, J.: OECD Environmental outlook to 2050. Organ. Econ. Co-Oper. Dev. **8**, 397–413 (2011)
28. Gjorgievski, V.Z., Cundeva, S., Georghiou, G.E.: Social arrangements, technical designs and impacts of energy communities: a review. Renew. Energy **169**, 1138–1156 (2021)
29. Kammen, D.M., Sunter, D.A.: City-integrated renewable energy for urban sustainability. Science **352**, 922 LP-928 (2016)
30. Steg, L., Perlaviciute, G., van der Werff, E.: Understanding the human dimensions of a sustainable energy transition. Front. Psychol. **6**, 805 (2015)
31. Campos, I., Marín-González, E.: People in transitions: energy citizenship, prosumerism and social movements in Europe. Energy Res. Soc. Sci. **69**, 101718 (2020)
32. Walker, G., Devine-Wright, P., Hunter, S., High, H., Evans, B.: Trust and community: exploring the meanings, contexts and dynamics of community renewable energy. Energy Policy **38**, 2655–2663 (2010)
33. Warbroek, B., Hoppe, T.: Modes of governing and policy of local and regional governments supporting local low-carbon energy initiatives, exploring the cases of the Dutch regions of Overijssel and FryslâN. Sustainability **9**, 75 (2017)
34. Stephenson, J., Barton, B., Carrington, G., Gnoth, D., Lawson, R., Thorsnes, P.: Energy cultures: a framework for understanding energy behaviours. Energy Policy **38**, 6120–6129 (2010)
35. Ellegård, K.: Time Geography in the Global Context: An Anthology. Routledge (2018)
36. International Organization for Standardization ISO 37120: 2018 Sustainable Cities and Communities—Indicators for Smart Cities (2018)
37. Vanclay, F.: International principles for social impact assessment. Impact Assess. Proj. Apprais. **21**, 5–12 (2003)
38. Dufour, B.: State of the art in social impact measurement: methods for work integration social enterprises measuring their impact in a public context. In: Proceedings of the 5th EMES International Research Conference on Social Enterprise: Building a Scientific Field to Foster the Social Enterprise Eco-System (2015)
39. Sairinen, R.: Assessing social impacts of urban land-use plans: from theory to practice. Boreal Environ. Res. **9**, 509–517 (2004)
40. Hara, M., Nagao, T., Hannoe, S., Nakamura, J.: New key performance indicators for a smart sustainable city. Sustainability **8**, 206 (2016)
41. Akande, A., Cabral, P., Gomes, P., Casteleyn, S.: The Lisbon ranking for smart sustainable cities in Europe. Sustain. Cities Soc. **44**, 475–487 (2019)
42. Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., Huovila, A.: CITYkeys Indicators for Smart City Projects and Smart Cities. CITYkeys Rep (2017)
43. Angelakoglou, K., Kourtzanidis, K., Giourka, P., Apostolopoulos, V., Nikolopoulos, N., Kantorovitch, J.: From a comprehensive pool to a project-specific list of key performance indicators for monitoring the positive energy transition of smart cities—an experience-based approach. Smart Cities **3** (2020)
44. Bisello, A.: Assessing multiple benefits of housing regeneration and smart city development: the European project SINFONIA. Sustainability **12**, 8038 (2020)
45. Becchio, C., Bottero, M., Corgnati, S.P., Dell'Anna, F.: A MCDA-based approach for evaluating alternative requalification strategies for a net-zero energy district (NZED). In: Zopounidis, C.,

Doumpos, M., (eds.) Multiple Criteria Decision Making, pp. 189–211. Springer International Publishing (2017)
46. Ala-Juusela, M., Crosbie, T., Hukkalainen, M.: Defining and operationalising the concept of an energy positive neighbourhood. Energy Convers. Manag. **125**, 133–140 (2016)
47. Sharifi, A., Dawodu, A., Cheshmehzangi, A.: Limitations in assessment methodologies of neighborhood sustainability assessment tools: a literature review. Sustain. Cities Soc. **67**, 102739 (2021)
48. Mosannenzadeh, F., Bisello, A., Diamantini, C., Stellin, G., Vettorato, D.: A case-based learning methodology to predict barriers to implementation of smart and sustainable urban energy projects. Cities **60**, 28–36 (2017)

# Definitions of Positive Energy Districts: A Review of the Status Quo and Challenges

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**Abstract** This paper presents an overview of PED definitions used in five prominent EU programmes and nine PED-relevant projects across Europe. By drawing similarities and finding discrepancies between them, the paper aims to identify the gaps and challenges in existing work. Through systematic comparison, the paper recognises common traces and differences between existing definitions. The main challenges include the definition of PED boundaries, the method for calculating energy balance, the scope of non-energy matters and the assessment of qualitative requirements. As the PED definitions are to be applied to locations with considerably different local

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contexts, it would be sensible to develop PED definitions in the form of an adaptive framework. This review marks the start of a quest for a universal framework of PED definitions that addresses the existing challenges. The goal is to provide the evidence base for policymakers and other relevant stakeholders in strengthening the PED concept and ease its implementation.

## 1 Introduction

Positive Energy Districts (PEDs) are recognised as one of the central pillars for driving the urban energy transition in Europe. The concept of PEDs can be traced back to the concept of net-zero energy districts (NZEDs) that corresponds to the transformation at the neighbourhood level triggered by the implementation of the EU 2020 energy and climate targets. The concept marked a shift from individual buildings to the neighbourhood level as a way to scale up the efforts and speed up the pace of the global energy transformation [1]. Building on NZED, the Energy Efficient Building Committee of the European Construction, Built Environment and Energy Efficient Building Technology Platform (ECTP) designed the concept of Positive Energy Blocks (PEB) to stimulate the citywide energy transition in Europe [2]. The concept was strongly promoted by the European Innovation Partnership on Smart Cities and Communities (EIP-SCC), which established an initiative on PEBs in 2016. The main goal of the initiative was to facilitate the deployment of 100 PEBs throughout EU and neighbouring countries by 2020 [3].

A step up from PEBs came the concept of Positive Energy Districts (PEDs). The European Commission (EC) endorsed the SET Plan Action 3.2 “Smart Cities and Communities” in June 2018. The main objective of Action 3.2 is to develop integrated and innovative solutions for the planning, deployment, and replication of PEDs. According to the Action, 100 PEDs are expected to be in concrete planning, construction or operation, synergistically connected to the energy system in Europe by 2025 [4].

The concept of PEBs/PEDs is fully recognised by the EC. Through pilot projects financed by the Horizon 2020 programme, the EC supports a large deployment of PEBs/PEDs. Since the implementation of the SET Plan Action 3.2, there has been a growing number of PED-oriented initiatives and projects at both the EU and national levels. However, there is not yet a universal definition of PEDs and as a result, different notions of PEDs are in use. The lack of a common definition means that different projects set different baselines and therefore, it is hard to compare between projects. In addition, current PED definitions have a general character that allows for different interpretations of the requirements and system boundaries.

The Joint Programming Initiative Urban Europe (JPI UE) developed a framework definition of PEDs. The framework seeks to create a joint vision on PEDs across Europe [5]. Despite being widely acknowledged by key stakeholders, a number of important questions concerning PED definitions still need to be further discussed.

This paper aims to contribute to the discussion by providing an overview of PED definitions used by different programmes, initiatives and projects at the EU and national levels. By drawing similarities and finding discrepancies between existing definitions, the paper will identify the gaps and challenges concerning PED definitions. The findings of the paper will offer answers to some of the open questions and shed light on the further development of the PED definition framework.

## 2 Overview of PED Definitions

### *2.1 PED Definitions Used by EU Organisations and Programmes*

At the European level, there are several major organisations or programmes, which have a stake in driving the deployment of PEDs. They are (i) the SET-Plan Action 3.2, (ii) the Horizon 2020 Framework Programme—Smart Cities and Communities calls, (iii) EC Joint Research Centre (JRC), (iv) the JPI UE and (v) the European Energy Research Alliance (EERA). The PED definitions developed by them are widely adopted and are presented as follows.

**SET-Plan Action 3.2**. The SET-Plan defined PED as 'a district with annual net zero energy import, and net zero $CO_2$ emissions working towards an annual local surplus production of renewable energy'. They are expected to be implemented in newly built, retrofitted or mixed districts. According to the SET-Plan, PEDs should be driven by renewable energy and be an integral part of the urban and regional energy system. They should be based on high energy efficiency and make optimal use of technologies to reduce energy use and greenhouse gas (GHG) emissions. Besides the energy aspect, PEDs should offer affordable living for the inhabitants [4].

**Horizon 2020 Framework Programme—Smart Cities and Communities**. According to the proposal call for the Smart Cities and Communities lighthouse projects, 'Positive Energy Blocks/Districts consist of several buildings (new, retrofitted or a combination of both) that actively manage their energy consumption and the energy flow between them and the wider energy system. Positive Energy Blocks/Districts have an annual positive energy balance. They make optimal use of elements such as advanced materials (e.g. bio-based materials), local RES, local storage, smart energy grids, demand-response, cutting edge energy management (electricity, heating and cooling), user interaction/involvement and information and communications technology (ICT). Positive Energy Blocks/Districts are designed to be integral part of the district/city energy system and have a positive impact on it (also from the circular economy point of view). Their design is intrinsically scalable and they are well embedded in the spatial, economic, technical, environmental and social context of the project site' [6].

**EC Joint Research Centre (JRC)**. PED is considered as an area with defined borders that has an overall positive energy balance over a year. It has buildings with a near zero or very low energy demand owing to their very high energy performance complying with applicable minimum energy performance requirements and local building codes. The building demand is covered to a very significant extent, or more, by renewable energy sources produced on-site or nearby. The primary purpose of a PED is to provide environmental, economic or social community benefits based on open and voluntary participation. A PED is autonomous, and is effectively controlled by its citizens [7].

**JPI UE**. The reference framework definition for PEDs developed by JPI UE states that "Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero GHG emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability". Each PED is expected to find its own optimal balance between energy efficiency, energy flexibility and local/regional energy production on its way towards climate neutrality and energy surplus. While the resilience and security of energy supply are important guiding principles, the development of PEDs should also respect sustainability and inclusiveness and, in more general terms, enhance the quality of life [5].

**EERA Joint Programme Smart Cities (EERA JPSC)**. According to EERA JPSC, PEDs are 'mixed-use energy-efficient districts that have net zero CO2 emissions and actively manage an annual local surplus production of renewable energy. They require interaction and integration between buildings, the users and the regional energy, mobility and ICT system, while ensuring social, economic and environmental sustainability for current and future generations' [8].

Beyond the general description, EERA JPSC has proposed to consider different PED types according to the way the energy balance is achieved. The purpose is to allow for system flexibility and better operational optimization in the realisation of PEDs. The four PED types proposed are as follows:

- PED-autonomous: Net positive yearly energy balance within the geographical boundaries of the PED and internal energy balance at any moment in time (no imports from the hinterland) or even helping to balance the wider grid outside.
- PED-dynamic: Net positive yearly energy balance within the geographical boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages.
- PED-virtual: net positive yearly energy balance within the virtual boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages.

- Pre-PED: no net positive yearly energy balance within the geographical boundaries of the PED but energy difference acquired on the market by importing certified green energy (i.e. realizing a zero-carbon district).

Hereby virtual boundaries refer to 'limits of the PED in terms of contractual boundaries e.g. including an energy production infrastructure owned by the PED occupants but situated outside the normal geographical PED boundaries [9, 10].

## 2.2 PED Definitions Used in Relevant Projects or National Programmes

There has been a booming of PED projects in recent years and each project interprets the concept of PEDs in its own way. As a result, there exists multitude of PED definitions. This section reviews the PED definition used in nine prominent projects in the landscape of PEDs including five Smart Cities and Communities lighthouse projects and four others at the European and national levels.

**Project 'ATELIER'**. ATELIER aims to create and replicate community-driven PEDs in two lighthouse cities (Amsterdam and Bilbao) and six fellow cities to save $CO_2$ emissions and to demonstrate that integrated smart urban solutions support the deployment of PEDs. According to the project, PED is defined as a district that produces more renewable energy than it consumes on an annual basis. In addition to renewable energy production, the PED concept also considers energy efficiency and flexibility, energy autonomy and zero direct emissions of non-biogenic $CO_2$. The PED demonstrations are composed of areas connected geographically as well as virtually through smart grids. The project developed a framework for the monitoring and evaluation of PEDs based on a set of Key Performance Indicators (KPIs) covering energy, environment, economy, electro-mobility, citizen engagement and governance. Besides, environmental impacts are evaluated from the life cycle perspective including the consumption of products and services within the PEDs [11].

**Project '+CityxChange'**. +CityxChange (Positive City Exchange) aims to develop, deploy and scale up PEBs and PEDs in two lighthouse cities (Limerick and Trondheim) and five fellow cities to support the European Clean Energy Transition. The project not only focuses on the technical solutions around PEBs/PEDs but also the interaction between buildings, users, cities, the wider energy system, as well as the implications on city planning, digitalization, citizen involvement, regulations, socio-economic issues and so on. According to the project, PEB is defined as a compact area comprising at least three mixed use buildings (>15,000 $m^2$), which produces more energy than it consumes over a year by including local renewable energy production and measures to reduce energy demand. For PEDs, the project adopted the definition from SET-Plan Action 3.2 [12].

**Project 'MAKING-CITY'**. MAKING-CITY aims to develop new integrated strategies to address the low-carbon urban energy transformation through large-scale demonstrations in two lighthouse cities (Groningen and Oulu) and six fellow cities. The project seeks to establish evidences on using the PED concept as a foundation to progress towards sustainable urban transformation. The project defines PED as an urban area with clear boundaries comprising buildings of different typologies that actively manage the energy flow among them, as well as the larger energy system to reach an annual positive energy balance [13]. The PED concept used in the project includes positive energy buildings, on-site renewable energy systems, energy sharing, flexibility and optimization and smart control. The project developed guidelines for PED design, guidelines to calculate the annual primary energy balance [14] and a GIS based methodology for identification of PED concept boundaries in cities.

**Project 'POCITYF'**. POCITYF aims to implement and demonstrate innovative solutions at the building and district level that enable the increase of energy self-consumption, energy savings and locally produced renewable energy. The project adopted the PED definition from the Horizon 2020 Framework Programme. The PED concept is achieved through measures such as building integrated photovoltaics, P2P energy markets, storage solutions, integrated electro-mobility, integrated ICT solutions, active citizen engagement. The project facilitates the development of PEDs in mixed use urban districts with a focus on cultural heritage areas. Two lighthouse cities (Alkamar and Évora) serve as large-scale demonstrations of the proposed solutions and six fellow cities support the replication.

**Project 'SPARCS'**. SPARCS aims to create a network of sustainable energy positive and zero carbon communities in two lighthouse cities (Espoo and Leipzig) and five fellow cities. SPARCS largely adopted the PED definition framework developed by EERA JPSC with three types of PEDs, namely, PED-autonomous, PED-dynamic and PED-virtual. Both PED-autonomous and PED-dynamic have clearly defined geographical boundaries. PED-autonomous is completely self-sufficient with energy demand covered by onsite renewable sources. PED dynamic allows the import of external energy insofar as the annual energy balance is positive. PED-virtual operates within virtual boundaries, which allows the use of renewable energy sources or energy storage outside the geographical boundaries. However, renewable energy generation or energy storage that locate outside must be an asset of the district [15].

**Project 'syn.ikia'**. syn.ikia puts forth the concept of Sustainable Plus Energy Neighbourhood (SPEN) that strongly aligned with the broad concept of PEDs. SPEN is defined as a group of interconnected buildings with associated infrastructure, located within both a confined geographical area and a virtual boundary. It aims to achieve more than 100% energy savings, 90% renewable energy generation triggered, 100% GHG emission reduction, and 10% life cycle costs reduction, compared to the level of 2020 nearly zero-energy buildings (nZEBs). Additionally, a SPEN covers five main objectives including (i) net-zero GHG emissions, (ii) active management of energy surplus, (iii) cost efficiency and economic sustainability, (iv) improved indoor environment, and (v) social inclusiveness and affordable living. The project developed a methodological framework for the evaluation of SPEN including the assessment of the positive energy balance. syn.ikia aims to increase the share of SPENs with surplus renewable energy in different contexts, climates and markets in Europe [16].

**Project 'Zukunfsquartier—Vienna'**. The Project 'Zukunftsquartier' (literally 'Future Neighbourhood') explores the feasibility of applying the plus energy neighbourhood concept in four project sites in Vienna [17]. The project aims to develop a scientifically sound and practical definition that can be used to assess and certify PEDs as a cornerstone to support the national climate neutral target. The PED concept focuses on 100% renewable energy supply. In addition to energy, economic feasibility and other sustainability requirements are taken into account. Based on the setup of system boundaries, the project proposes three types of PEDs:

- PED Alpha: a district that reaches a positive annual primary energy balance based on all energy services (operational energy and user electricity) and monthly conversion factors. A credit or discount based on structural density is applied.
- A PED Alpha + Mobil: meets the above criteria with the inclusion of private everyday mobility and a per capita RES credit for surpluses of the energy system by large RES power plants.
- A PED Omega: covers all the above energy services as well as the embodied energy for structure, building and mobility. On the basis of hourly conversion factors, the PED achieves a global warming potential below 500 kg/cap/annum. The definition can be extended to include emissions from individual consumption as a way to connect to individual carbon budgets.

**Project 'PHVision—Heidelberg'**. The City of Heidelberg in Germany envisions to transform the Patrick-Henry-Village into a PED with mixed living and working space for around 15,000 people [18]. The project defines PED as a district that produces more renewable energy than it consumes on an annual basis. The proposed PED is composed of a clearly defined geographical area and virtual system boundary that allows dynamic energy exchanges with the wider region. The project developed a method for calculating the energy balance including space heating, cooling, domestic hot water and electricity use in buildings as well as energy use in transportation. Concerning transportation, local public transport, private and business mobility are assumed to be entirely electric in the project and included in the energy balance calculation. In addition, the embodied energy related to the construction and renovation of buildings is considered. The project also devised a method for estimating the district's share in the total renewable energy potential of the region, which serves as a cap for potential green energy import [19].

**ZEN Centre**. The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities is a Norwegian research centre. ZEN combines the concept of PEDs with climate neutrality. It aims to reduce its direct and indirect GHG emissions towards zero over its lifetime. The ZEN Centre developed a definition of ZENs and KPIs to assess them. A neighbourhood is defined as a group of interconnected buildings with associated infrastructure located within a confined geographical area. However, the system boundary for analysis of energy facilities serving the neighbourhood can include infrastructure for exchange, generation and storage of electricity and heat outside of the geographical boundary.

The total GHG emissions are accounted based on a life-cycle assessment in all phases of the neighbourhood development including planning, implementation, operation and demolition. ZENs compensate the emissions through onsite renewable energy production during the operation phase and achieve a positive energy balance on a yearly basis. In addition to GHG emissions, other KPIs include energy, load, mobility, economy, spatial qualities and innovation. The definition and KPIs are tested in nine neighbourhood-scale demonstration sites in Norway [20, 21].

### 2.3 Comparison of Existing Definitions

Table 1 extracts a set of key elements in the PED concepts and compares them across the fourteen programmes and projects under study. Based on the comparison, similarities and differences between the existing definitions are identified.

Concerning the calculation of balance, all programmes and projects consider a positive energy balance on an annual basis. Two thirds of them include net zero $CO_2$ emissions as an additional target. About half of the programmes and projects define PEDs as districts with geographical and virtual boundaries. For the scale of development, the terminology used varies from 'several buildings' and 'groups of connected buildings' to 'district' and 'neighbourhood'. This points to the need of a unified glossary to avoid confusion.

Around half of the programmes and projects devised their own method for the calculation of energy balance although the approaches used vary, this is further discussed in Sect. 3.2. Regarding the means to achieve PEDs, the programmes and projects share close similarities with the application of renewable energy supplies and energy efficiency measures as essential. Buildings are considered as a key component in the PED concept but many projects also recognise the roles of transportation, energy storage and ICT. Besides energy-related matters, almost all programmes and projects include social, economic and environmental aspects in the PED concept. Different non-energy considerations are mentioned (e.g. inclusiveness, affordable living, citizen engagement, etc.) but their descriptions are rather general without clear requirements. Further discussion on the scope of PEDs including non-energy aspects is presented in Sect. 3.4.

## 3 Challenges in PED Definitions

This section presents the main challenges, critical issues and open questions identified based on the findings in Sect. 2.

**Table 1** Comparison of existing PED definitions

| | Calculation of balance | | | | Scale | Boundary | Key energy concepts | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy | $CO_2$ emission | Time-frame | Method | | | Renewable supplies | Energy efficiency | Energy storage | Building | Transport | ICT |
| SET-Plan Action 3.2 | + | Net zero | Yearly | – | District | – | ✓ | ✓ | – | – | – | – |
| Horizon 2020 | + | – | Yearly | – | Several buildings | – | ✓ | – | ✓ | ✓ | – | ✓ |
| JRC | + | – | Yearly | – | – | Defined borders | ✓ | ✓ | – | ✓ | – | – |
| JPI UE | + | Net zero | Yearly | – | Groups of connected buildings | – | ✓ | ✓ | – | ✓ | ✓ | ✓ |
| EERA JPSC | + | Net zero | Yearly | – | District | 4 types | ✓ | ✓ | – | ✓ | ✓ | ✓ |
| ATELIER | + | Net zero | Yearly | – | District | Geographical and virtual | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| + CityxChange | + | Net zero | Yearly | – | District | – | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| MAKING-CITY | + | – | Yearly | ✓ | District | Geographical | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| POCITYF | + | – | Yearly | ✓ | District | Geographical and virtual | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| SPARCS | + | Net zero | Yearly | ✓ | District | 3 types | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Syn.ikia | + | Net zero | Yearly | ✓ | Group of interconnected buildings | Geographical and virtual | ✓ | ✓ | ✓ | ✓ | – | – |
| Zukunfsquartier | + | Net zero | Yearly | ✓ | District | 3 types | ✓ | ✓ | ✓ | ✓ | ✓ | – |
| PHVision | + | Net zero | Yearly | ✓ | District | Geographical and virtual | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

(continued)

**Table 1** (continued)

| | Calculation of balance | | | | Scale | Boundary | Key energy concepts | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy | $CO_2$ emission | Time-frame | Method | | | Renewable supplies | Energy efficiency | Energy storage | Building | Transport | ICT |
| ZEN Centre | + | Net zero | Yearly | ✓ | Neighbourhood | Geographical and system | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

| | Non-energy consideration | | | Other considerations |
|---|---|---|---|---|
| | Social | Economic | Environ-mental | |
| SET-Plan Action 3.2 | ✓ | – | – | Urban/regional Integration, affordable living |
| Horizon 2020 | ✓ | ✓ | ✓ | Urban integration |
| JRC | ✓ | ✓ | ✓ | Renewable onsite/nearby, NZEB, citizen participation |
| JPI UE | ✓ | ✓ | ✓ | Energy flexibility, regional integration, inclusiveness, quality of life |
| EERA JPSC | ✓ | ✓ | ✓ | Regional integration, mixed-use areas |
| ATELIER | ✓ | ✓ | ✓ | Energy flexibility, energy autonomy, electro-mobility, citizen engagement, life-cycle assessment |
| + CityxChange | ✓ | ✓ | ✓ | Build up from PEBs |
| MAKING-CITY | ✓ | ✓ | ✓ | PEBs, renewable onsite, non-renewable primary energy, energy community |
| POCITYF | ✓ | ✓ | ✓ | Heritage districts |
| SPARCS | ✓ | ✓ | ✓ | Energy flexibility, electro-mobility, citizen engagement |
| Syn.ikia | ✓ | ✓ | ✓ | NZEB, energy flexibility, life-cycle assessment, indoor environment, inclusiveness, affordable living |
| Zukunfsquartier | ✓ | ✓ | ✓ | Primary energy balance, embodied energy, density-based adjustment |
| PHVision | ✓ | ✓ | ✓ | Passive house, self-sufficiency, embodied energy, regional integration |
| ZEN Centre | ✓ | ✓ | – | Energy flexibility, life cycle assessment (LCA) for buildings 60 years and infrastructure 100 years |

Table notation: ‘ + ’: positive, ‘✓’: included, ‘–’: unspecified

### 3.1 Beyond Positive Energy and Towards Climate Neutrality

Although the notion of PEDs emphasises a positive energy balance, the surplus energy production should not be the sole objective. PEDs should not be seen as an ultimate goal on its own but rather a stepping stone towards climate neutrality. According to Table 1, a majority of the programmes and projects consider net zero direct carbon emissions as a requirement in the PED definition. The challenge to incorporate carbon emissions in the PED definition is to establish a common approach for their handling. In view to this, the three-scope emission classification widely used in international GHG accounting can serve as a reference.

### 3.2 Beyond Qualitative Description and Towards Quantitative Definition

Existing PED definitions are largely qualitative, which describe the essence of PED and the means to achieve it. However, there is an increasing demand for a quantitative definition for objectively evaluating PEDs. The challenge is to formulate a universal methodology for the calculation of the energy balance that is applicable to different local contexts. In order to do so, many open questions are yet to be addressed. The definition of the district boundaries is one of the first to be tackled and the issue is further discussed in Sect. 3.3. Energy use for transportation makes up a large share of the total energy use, it would make sense to consider it in the evaluation. Nevertheless, it is hard to include mobility in the calculation in practice as it is challenging to define the boundary for transportation use and obtain reliable data at the district level.

### 3.3 Definition of PED Boundaries

Existing projects adopt different approaches in the selection of PED boundaries, some based on rigid geographical areas while others apply a more flexible approach that allows renewable energy generation outside the geographical boundaries of the district. There is currently a lack of guidance on how best to define the size and boundaries for PED developments considering different local contexts. The challenge is to create a holistic approach in the selection of PED boundaries. In physical terms, renewable energy potential, land use patterns, urban built form and layout of infrastructure are important considerations. In addition to technical and environmental factors, the selection of PED boundaries should also capture political, economic, social, legal and spatial barriers and enablers. In order to create affordable, liveable and inclusive PEDs, it is crucial to harmonise urban and energy planning strategies and take into account the interests of different stakeholders involved. Eventually, the PED boundaries can evolve beyond the districts and cover a wider city area over time.

### 3.4 Scope of PEDs Beyond Energy

Although the fundamental definition of PEDs centred on energy, according to existing PED programmes and projects, the scope of PEDs goes beyond a mere energy surplus. Besides buildings, transport and ICT, existing PED definitions also require the fulfilment of social, economic and environmental sustainability and the provision of affordable living for all through inclusive social development and citizen engagement. The Temporary Working Group (TWG) of the SET-Plan Action 3.2 has developed an integrative approach to PED including technological, spatial, regulatory, financial, legal, environmental, social and economic perspectives. According to the TWG 3.2, PEDs will be developed in an open innovation framework, driven by cities in cooperation with industry and investors, research and citizen organisations [4]. It is important to include non-energy requirements in the PED concept to ensure the creation of desirable city districts. However, an overly broad description can risk diluting the notion of PEDs. The challenge is to devise a PED definition that strikes a fair balance between the two ends. Another challenge relates to the difficulty in developing a method to objectively assess qualitative requirements (such as affordable living).

### 3.5 A Framework of Definitions for Diverse Local Contexts

The PED definitions are to be applied to districts and cities with remarkably different boundary conditions. Due to the inherited local characteristics and potential of local resources, it would be easier for some to achieve PEDs while harder for others. The challenge is how to devise a universal definition and assessment method that can account for local diversity in order to provide a level playing field for different districts and cities across Europe. There is not a single one-size-fits-all energy strategy and due to the different local contexts, energy strategies should be spatially differentiated to achieve optimal outcome [22]. A narrow and exclusive definition might risk putting off PED development in more demanding locations. To this end, it might make sense to devise a PED definition in the form of an adaptive framework instead of a rigid set of requirements.

## 4 Conclusions and Outlook

This paper presented a review of PED definitions used in five prominent EU programmes and nine PED-relevant projects with an aim to identify the challenges and gaps in existing work. Although the fourteen PED definitions under study have a lot in common, there are still significant differences that need to be addressed. The main challenges include the definition of PED boundaries, the method for calculating energy balance, the scope of non-energy matters and the assessment of qualitative requirements. As the PED definitions are to be applied to locations with considerably different local contexts, it would be sensible to develop PED definitions in the form of an adaptive framework.

Prior to diving deeper into the journey of PED definitions, the fundamental purposes and applications of the definitions need to be clearly set out as the content of the PED definition framework should follow its intended applications. This review marks the start of a quest for a universal framework of PED definitions. The goal is to provide the evidence base for policymakers and other relevant stakeholders in strengthening the PED concept.

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## References

1. Marique, A.-F., Penders, M., Sigrid, R.: From zero-energy building to zero-energy neighbourhood: urban form and mobility matter. In: Proceedings: PLEA2013—29th Conference, Sustainable Architecture for a Renewable Future (2013)
2. Polly, B., Kutscher, C., Macumber, D., Schott, M., Less, S., Livingood, B., Van Geet, O.: From zero energy buildings to zero energy districts. In: Proceedings: 2016 ACEEE Summer Study on Energy Efficiency in Buildings (2016)
3. ECTP Secretariat. Smart Cities & Communities Call on Positive Energy Blocks. http://e2b.ectp.org/news-events/news/news-detail/smart-cities-communities-call-on-positive-energy-blocks/
4. EIP-SCC. Positive Energy Blocks Infographic. https://smart-cities-marketplace.ec.europa.eu/sites/default/files/PostiveEB.pdf
5. SET-Plan Temporary Working Group 3.2. SET-Plan Action n°3.2 Implementation Plan
6. JPI Urban Europe/SET Plan Action 3.2. White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods: Key lessons from national consultations
7. European Commission: Horizon 2020 Work Programme 2018–2020: 10. Secure, clean and efficient energy
8. Shnapp, S., Paci, D., Bertoldi, P.: Enabling Positive Energy Districts across Europe: energy efficiency couples renewable energy (EUR 30325 EN)
9. Wyckmans, A.: Strategic Research Agenda of the EERA Joint Programme Smart Cities. https://www.iqs.se/library/4893/eera-jpsc-ped-sra_wyckmans.pdf
10. Vandevyvere, H.: PED Definition Development, Working Group Minutes: PED Programme Cities Workshop—Towards a European Positive Energy Cities Network
11. Wyckmans, A., Karatzoudi, K., Brigg, D., Ahlers, D.: +CityxChange - D9.4: Report on Intra-Project Collaboration Including Study Visits and Peer-to-Peer Workshops

12. University of Deusto, Amsterdam University of Applied Science, Paul Scherrer Institute: ATELIER Monitoring and Evaluation Framework—Deliverable 9.1: Repository of Definitions of Terms, Key Characteristics Archetypes, and a Set of KPIs
13. +CityExchange: Knowledge Base: Glossary. https://cityxchange.eu/article-categories/glossary/
14. Alpagut, B., Gabaldón, A.: Guidelines for Positive Energy District Design: How to Transform a District into a PED
15. Gabaldón Moreno, A., Alpagut, B., Hernández Iñarra, P.: Guidelines to Calculate the Annual Primary Energy Balance of a Positive Energy District
16. Lindholm, O., Rehman, H.U., Reda, F.: Positioning positive energy districts in European cities. Buildings **11** (2021). https://doi.org/10.3390/buildings11010019
17. Salom, J., Tamm, M.: WP3 Technology Integration in Smart Managed Plus Energy Buildings and Neighbourhoods: Methodology Framework for Plus Energy Buildings and Neighbourhoods
18. Leibold, J., Schneider, S., Tabakovic, M., Zelger, T., Bell, D., Schöfmann, P., Bartlmä, N.: 'Zukunftsquartier'—On the Path to Plus Energy Neighbourhoods in Vienna. In Sustainability in Energy and Buildings, pp. 199–209. Springer, Singapore (2020). ISBN 978-981-32-9868-2
19. IBA Heidelberg: Project Development of Patrick-Henry-Village. https://iba.heidelberg.de/en/projects/phvision (accessed on 9 June 2021)
20. Stryi-Hipp, G., Triebel, M.-A.: Internal Report: PHV—Energy Requirements of the Entire Quarter (in German) (2019)
21. Wiik, M.K., Fufa, S.M., Fjellheim, K., Lien, K.S., Krogstie, J., Ahlers, D., Wyckmans, A., Driscoll, P., Brattebø, H., Gustavsen, A.: Zero Emission Neighbourhoods in Smart Cities: Definition, Key Performance Indicators and Assessment Criteria (Version 2.0)
22. Wiik, M.K., Fufa, S.M., Baer, D., Sartori, I., Andresen, I.: The ZEN definition: A Guideline for the ZEN Pilot Areas (Version 1.0)
23. Trutnevyte, E., Stauffacher, M., Schlegel, M., Scholz, R.W.: Context-specific energy strategies: coupling energy system visions with feasible implementation scenarios. Environ. Sci. Technol. **46**, 9240–9248 (2012). https://doi.org/10.1021/es301249p

# Qualitative Assessment Methodology for Positive Energy District Planning Guidelines

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**Abstract** Positive Energy Districts (PEDs) have recently become an important concept for urban development. However, the number of publications on the transfer of the PED concept to practice is still very limited. This conference paper presents an analysis of the current state of the art in guidelines regarding the planning and implementation of PEDs based on the analysis of 25 PED guidelines reported by anonymous contributors, collaborating in the development of the IEA EBC Annex 83 activities. From this analysis, it becomes clear that nearly all documents including were produced in the period 2018–2020. Most guidelines address local and/or regional governments, focusing predominantly on urban development and planning processes or technological solutions, mostly at the scale level of the district or city, and less often at building block or individual building level. Although some of the documents are journal papers with a very narrow view on specific technological design or implementation aspects, seven guidelines can provide city administrations, urban

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stakeholders, solution providers and research with overall information on and suggestions for the process of planning, implementing, monitoring and evaluation of PEDs, and a description of the potential impact of PEDs. They result of the analysis will serve as baseline for the future work within IEA Annex 83, in particular for drafting IEA Annex 83 guidelines for the planning and implementation of PEDs.

## 1 Background/Introduction

Positive Energy Districts (PEDs) have recently become an important concept for urban development. However, the number of publications on the transfer of the PED concept to practice is still very limited. This conference paper gives an overview of the current state of the art in guidelines regarding the planning and implementation of PEDs. The analysis is based, on the analysis of 25 PED guidelines reported by anonymous contributors, collaborating in the development of the IEA EBC Annex 83 activities. It will serve as a baseline for the future development of documents that can facilitate the planning and construction of future PED initiatives.

A major driver for the research on PEDs is the climate and energy policy of the European Union and its member states. With the publication of the Set Plan Action 3.2, [1] several European initiatives have started working on the topic of PEDs looking with the objective to support the development and implementation of the at least 100 PEDs by 2025. These include funding programs, such as the "Smart Cities and Communities Lighthouse Projects" within Horizon 2020 and the "Positive Energy Districts and Neighbourhoods for Sustainable Urban Development" Programme of the Joint Programme Initiative (JPI) Urban Europe, as well as research networks, such as the European Energy Research Alliance Joint Programme on Smart Cities (EERA JPSC) that coordinates energy research along the SET-Plan objectives, the COST Action 19,126 "Positive Energy Districts European Network", and the IEA Annex 83 "Positive Energy Districts", that brings together researchers from European and non-European countries working on Positive Energy Districts.

Outside Europe a PED research community is emerging as well. In the United States of America, for example, researchers from the National Renewable Energy Laboratory (ENREL) have developed a definition for a "Zero Net Energy Community" [2]. Furthermore, NREL has developed ideas for a Zero Energy District for the Smart City project Peña Station in Denver [3].

IEA Annex 83 is a research and dissemination network established for four years under the umbrella of the International Energy Agency (IEA). It is open for research organizations and universities and from all IEA member states working on PEDs. The objective of the Annex 83 is to address the PED multidisciplinary dimensions, facilitating the development of PEDs in different worldwide urban contexts. Annex 83 is structured into four subtasks: (1) Subtask A "Definitions and context" works on an in-depth definition taking into account complexities of PEDs as far as possible, (2) Subtask B "Methods, Tools and Technologies for Realizing PEDs" maps methods, tools and technologies for realizing PEDs, including energy technologies, smart technologies as well as modelling, simulation tools", (3) Subtask C "Organizing principles and impact assessment looks at methods for impact assessment from economic, environmental and social viewpoints, (4) Subtask D "Demos, implementation and dissemination" entails several activities, such as building a database with demo cases, analyzing, planning and implementation methodologies and guidelines, as well as all dissemination activities of the annex.

# 2 Methodological Approach

One of the aims of Subtask D is to compile and analyze planning guidelines from the countries involved in IEA Annex 83 to document the current state and to identify communalities and differences in the understanding of the PED concept and its translation into practice. This conference paper presents our methodological approach and first results of the analysis. The scope here is to set out what a PED planning guideline will and will not cover in order to create a framework for the development work based on existed projects and initiatives.

The collected guidelines aim to facilitate the implementation of PEDs and cover multiple aspects ranging from technical and social to economic and legal issues, the spatial and temporal scales, the stakeholders involved in the design, construction, operation, and management of PEDs and to different technical, environmental, social, and economic assessment methodologies for PEDs.

## *2.1 Dimensions of the Analysis*

The first step in the analysis is to respond to the basic questions: **WHEN, WHERE** and **WHAT**, related to the appearance and publication of the mentioned guidelines.

- **WHEN**: By studying the publication date of the different guidelines we can determine the kick-off for the promotion of the PED initiatives, as well as the appearance of this coined term, that is not equally spread all around the word.
- **WHERE**: The study of the origin of the different guidelines can determinate the geographical coverage of the promotion of PEDs. The survey performed to collect the guidelines includes their audience, referring to the international, national, or local dimension of the documents, as well as the language.
- **WHAT**: This is, by far, the most difficult aspect to be analyzed in the guidelines since they may cover many prospects. The framework we propose relies on organizing the retrieved guidelines pointing at four different dimensions:
  - **Technical aspects**: This dimension covers all the technological solutions that need be integrated and optimized to reach a positive energy balance.

– **Institutional and economical ecosystem**: This dimension includes the legal and regulatory framework, the political ambition, financial resources and new business models.
– **Innovation ecosystem (co-creation)**: This dimension tackles the social sustainability of PED initiatives, paying special attention to the e-governance and the potential enablers.
– **Monitoring and evaluation**.

## *2.2 Methodology and Analytical Steps*

Even if the number of documents received during the first phase of collection is limited to about twenty, it is necessary to consider that the documents available for analysis will be many more. The selected methodology therefore had to consider the complexity of the analysis of numerous documents, each containing numerous pages of text and their potential heterogeneity.

Furthermore, the methodology is based on the following **research questions** that emerged during the consultation phase of the Subtask D experts:

- How many guidelines currently exist related to the development of PEDs? Which concepts and therefore which guidelines can be traced back to the concept of PED?
- What kind of content and aspects do the guidelines currently published cover?
- What are the most recurring aspects and therefore considered most important by the guidelines?
- What aspects, on the other hand, are left out, even with respect to the current definitions of PED?

In particular, the methodology is composed of the following elements:

- **Brainstorming with the experts**: The methodology was developed and validated during an expert consultation process (i.e. using online workshops tools like Mural). This step allowed to identify the objectives and expectations from the analysis, the methods and tools applicable to the analysis, the aspects of the guidelines that are interesting for a comparison
- **Data collection and pre-classification of the guidelines**: Definition of specific questions in the questionnaire that allows the prior classification of spatial scale, audience and main contents
- **Meta-analysis, automatic or semi-automatic analysis**: The defined analysis process can be classified as semi-automatic to meet the need to be able to process a large amount of text documents in a short time. Recent advances in the theory and practice of automatic text analysis [4] and discourse analysis [5] have suggested the use of the following automatic tools, such as automatic text and taxonomy analysis, cluster analysis and discourse analysis. Thanks to these automatic analyzes it is possible to define the domains of competence of the

guidelines, the most common topics and keywords, the relationship between the most common concepts in the guidelines, and the aspects least covered by the guidelines. Furthermore, it is possible to classify and cluster documents received on the basis of their origin, reference scale and main objectives, and analyze the content of the documents.

- **Complementary manual analysis**: The analytical process is complemented by manual qualitative analyzes such as the identification of the main objectives of the guidelines, the identification of the tools proposed to promote stakeholder participation, and the benchmark with respect to the expectations of the stakeholders.

## 3 Preliminary Result

The process of collecting the guidelines is successful and efficient only if it is well structured and planned beforehand. It is important to define the aspects of the guidelines which are useful to be compared or help with better categorization of the collected documents.

### *3.1 Data Collection and Pre-classification of the Guidelines*

The study is based on 25 guidelines submitted by anonymous users through an online survey. The first information to be collected was the title and source of the guideline. As the PED guideline collection was done on international level and the documents were coming from around the world, the language was another aspect. 19 of them were written in English, 3 in Spanish and 3 in German. It was crucial to collect guidelines which are not outdated, therefore the date of the last version of the guideline was stored. Most of the submitted guidelines were published between 2018 and 2020.

Regarding the content of the guideline, the following aspects were considered: spatial scale, audience, and main contents of the guideline.

For the spatial scale, four categories were specified: single building, buildings block, district/neighbourhood, urban/city. Almost 80% of the guidelines were classified to district/neighbourhood level from which half of them were also classified as urban/city and a few as building blocks and single buildings.

For the audience of the guideline, we differentiated three groups: local (city/region level), national (country level) and international level. 15 guidelines referred to local audience from which 14 referred also to either national, international or all of the audience.

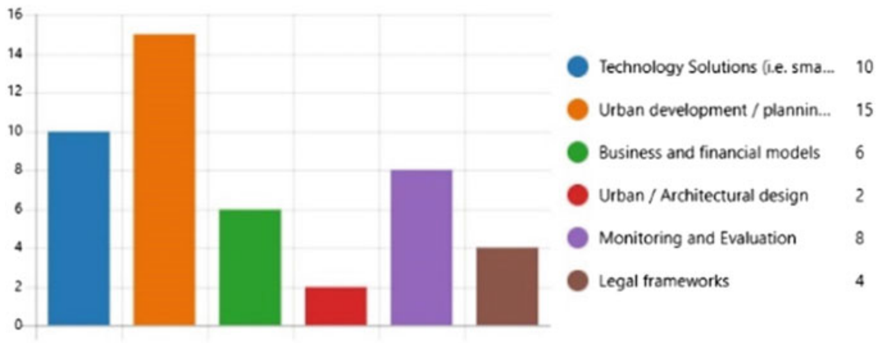


**Fig. 1** Main contents of the guidelines

Regarding the main content, six main groups were determined: technology solutions (i.e. smart grids, buildings, storage, res, etc. …), urban development or planning processes, business and financial models, urban or architectural design, monitoring and evaluation, and legal frameworks.15 of the guidelines were classified as urban development or planning processes. The second most popular was a category referring to technology solutions. Business and financial models stand equally with monitoring and evaluation (Fig. 1).

## 3.2 *Meta-Analysis, Automatic and Semi-Automatic Analysis*

A preliminary exploratory analysis to verify the feasibility of the analytical steps was tested on the collected documents. In particular, the following automatic analyses have been developed using the NVIVO software.

**Keyword analysis and word cloud production**: The analysis of the keywords has basically led to the identification of the magnitude in the use of the keywords. In particular, the following keywords: "District", "Building", "System", "Energy" and "Smart" emerge from the analysis, while the keywords "Integration" and "Mobility" are less frequent (Fig. 2).

**Analysis of content clusters**: In this preliminary analysis it was instead possible to identify the most frequent word clusters and therefore it was possible to put forward some hypotheses relating to the most recurrent concepts. In particular, the following 5 clusters have been identified (1) Energy, efficiency, renewable, demand, district, electric, analysis, system, solar, cost, heat, zero, heating; (2) Plan, project, local, stakeholders, implementation, information, solutions, data, cities, public, (3) Design, community, environmental, neighborhoods, area, quality, space, (4) Electricity, generation, consumption, districts, case, and finally (5) Services, urban, management, technology, transport. The clusters were identified by the NVIVO software and later named by the authors of this article (Fig. 3).


**Fig. 2** Word cloud

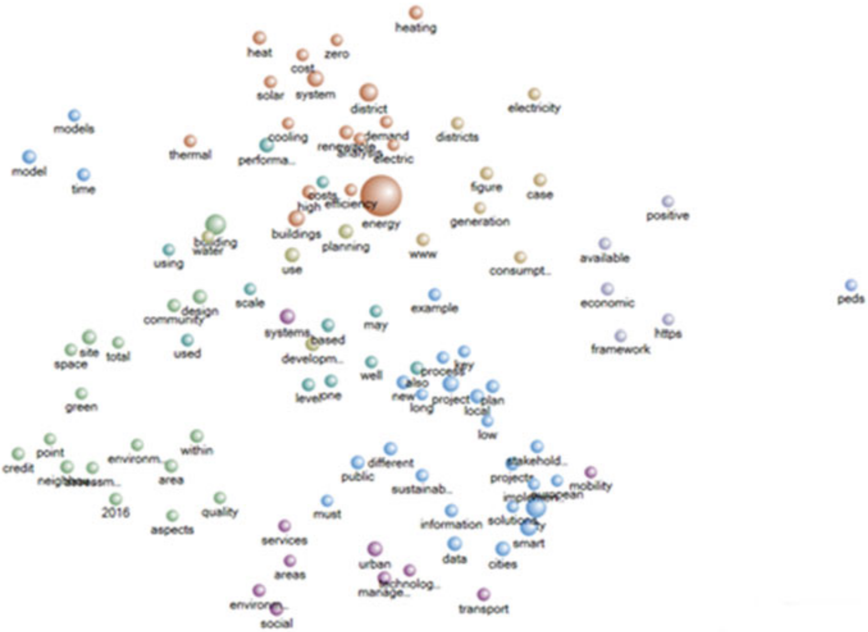


**Fig. 3** Cluster analysis

### 3.3 Qualitative Text Analysis

The following presents a very brief summary of the analysed documents:

The *Leitfaden Plusenergie-Quartier* report [6] and accompanying folder [7] uses the abbreviation PEQ instead of PED. The aim of the project is to deliver a clear definition of sustainable development in the building sector and thereby contribute to the implementation of the Energy Strategy 2050 of the Swiss federal government. The guide defines the cornerstones of PEQs, serves as an implementation aid and demonstrates how a PEQ is created.

The project Smart-BEEjS has produced two relevant reports. The first report, *Socio-economic factors and Citizens' practices, enabling Positive Energy Districts—Challenging 'silo thinking' for promoting PEDs* [8], is a literature review on how to overcome "silo thinking", i.e. different sectors not communicating and collaborating efficiently, and tries to enhance collaboration between disciplines, sectors, institutions, and communities, since this is an essential part of successful planning and implementation of Positive energy districts (PEDs). The second report, *Techno-economic Aspects and Pathways towards Positive Energy Districts—Status quo and framework conditions as a basis for developing techno-economic pathways in selected case studies* [9] presents framework conditions for the development of PEDs in European countries. In this report framework covers: Policy framework, building stock analysis, energy systems, mobility and stakeholders.

A report in Spanish, *Distritos de Energia Positiva* [10], tries to facilitate and promote the planning, dissemination and replicability of Positive Energy Districts (PEDs). The following aspects are described in the report: the definition, properties/characteristics and requirements of PEDs; Priorities for planning/dissemination of PEDs; The strengths and weaknesses for the development of PED projects; The economic, fiscal, technical, social and environmental impacts of the implementation of the PEDs.

The report *Guidelines for Positive Energy District Design—How to Transform a district into a PED* [11] is a very brief guideline for PEDs. The main purpose of the guideline is to provide an approach for planning and designing Positive Energy Blocks (PEB) and Positive Energy Districts (PED) in cities.

Enabling *Positive Energy Districts across Europe: energy efficiency couples renewable energy* [12] aims to understand how to handle energy performance targets by moving beyond individual buildings towards a district level. One route towards this could be to have the minimum energy performance requirements imposed by the EPBD also be applied to a cluster of buildings in a specific district. In practice, this means setting legal requirements that enable communities to become zero or positive energy districts (municipal or regional requirements).

The syn.ikia project is an innovation project within the EU Horizon 2020 framework. Their recent report *Methodology Framework for Plus Energy Buildings and Neighbourhoods* [13] has a main aim to present a methodology for the evaluation of positive energy buildings and neighbourhoods. The common evaluation framework defines the Key Performance Indicators (KPIs) for the evaluation of demonstration projects at two levels: building and neighbourhoods. The Sustainable Positive Energy Neighbourhood (SPEN) is defined as a group of interconnected buildings with associated infrastructure, located within both a confined geographical area and a virtual boundary.

In the report *A Guide to Energy Master Planning of High-Performance Districts and Communities* [14] focus is not specifically on "positive" or "plus energy" districts, but instead the report presents a framework for districts, campuses, and communities, illustrating an iterative process of building support for, planning, and implementing high-performance districts by engaging stakeholders, setting aggressive energy goals, completing technical and financial planning, and implementing a high-performance energy master plan.

### 3.4 First Findings

A systematic process set up to analyses 25 different planning guidelines using different methods delivered interesting first findings. From this analysis, it becomes clear that nearly all documents including the PED term were produced in the period 2018–2020, with one document possibly dating earlier, namely from 2007. This shows the relative newness of the topic, possibly incited by the precondition for European Smart City Lighthouse projects to deliver a PED in their demonstration since 2017, and the establishment of a SET Plan 3.2 Program around PEDs since 2018 (Set-Plan Temporary Working Group 3.2, 2018). In terms of geographical distribution, the PED term seems to be foremost European, while guidelines from other parts of the world refer to similar experiences like "energy master planning". This does not come as a surprise, as the concept and term are rooted in European initiatives. Nevertheless, it might mean that a broader search could be desirable in future to prevent missing relevant guidelines featuring other terms.

Most of the guidelines appear to address local and/or regional governments, focusing predominantly on urban development and planning processes or technological solutions, mostly at the scale level of the district or city, and less often at building block or individual building level. It would be interesting to "map" all guidelines analyzed more specifically on different phases of urban energy transitions. For example, the City-zen project worked these out in six steps from energy analysis to drafting a roadmap with energy interventions and actions [15].

The analysis of keywords with NVIVO showed that mobility is not seen as very relevant. Similarly, integration has not been mentioned frequently, what is surprising as a holistic approach is seen as one of the key tenets of the PED concept. An important outcome of the word cluster analysis clearly indicated three more coherent clusters of related words around: (1) the energy system and energy carriers; (2) procedural, institutional and governance aspects of PEDs; and (3) environmental and spatial quality and the social fabric of areas.

Lastly, the qualitative text analysis revealed that some of the documents seem to be journal papers with a very narrow view on specific technological design or implementation aspects. This has consequences for the practical applicability of the reference framework that is being created here, as scientific publications might not be applicable in practice right away, or the specify of the matter will mean overall applicability is less than desired. It also raises the question if the current differentiation between local/regional, national and international in the current analysis should not be made more detailed, for example with respect to specific roles in the planning, implementation, and maintenance phases of PEDs, than has been the case now. A scientific audience is usually internationally oriented, while practitioners working for the city administration often have a more local and regional focus, and technology and solution providers are generally nationally organized.

However, the qualitative analysis also made clear that at least seven guidelines can provide city administrations, urban stakeholders, solution providers and research with overall information on and suggestions for the process of planning, implementing, monitoring and evaluation of PEDs, and a description of the potential impact of PEDs. This means there is a basis that can be extended further in this IEA Annex 83, which can be instrumental in realizing the huge innovation potential identified in the last generation of smart city lighthouse projects of a combination of investments in the physical energy infrastructure and buildings with societal engagement, such as energy citizenship [16].

## 4 Outlook/Next Steps

As next steps in our research, we will benchmark the results of this review of planning guidelines against stakeholder expectations and other relevant criteria (e.g. financial, regulatory framework conditions, governance) to identify gaps in the current state of the art. To close the identified gaps, we will then draft the IEA Annex 83 guidelines for the planning and implementation of PED in a co-creative process involving the research partners of IEA Annex 83 as well as city representatives, urban planners and other practitioners from the different countries involved in IEA Annex 83.

## References

1. SET-Plan Temporary Working Group 3.2. (2018, June): SET-Plan ACTION n°3.2 Implementation Plan: Europe to Become a Global Role Model in Integrated, Innovative Solutions for the Planning, Deployment, and Replication of Positive Energy Districts. Retrieved from https://setis.ec.europa.eu/system/files/setplan_smartcities_implementationplan.pdf
2. Carlisle, N., Van Geet, O., Pless, S.: Definition of a “Zero Net Energy Community. Technical Report NREL/TP-7A2-46065 (2009). Retrieved from https://www.nrel.gov/docs/fy10osti/46065.pdf
3. Polly, B.: Zero Energy Districts (2018). Retrieved from https://www.nrel.gov/docs/fy18osti/71424.pdf
4. Muller, A., Dorre, J., Gerstl, P., Seiffert, R.: The TaxGen framework: automating the generation of a taxonomy for a large document collection. In: Proceedings of the 32nd Annual Hawaii

International Conference on Systems Sciences. HICSS-32. Abstracts and CD-ROM of Full Papers, pp. 9 (1999). https://doi.org/10.1109/HICSS.1999.772687
5. Stephanie, T.: What is Discourse Analysis? Boomsbury, London (2013)
6. Nyffenegger, U. (ed.): Leitfaden Plus Energie-Quartier, Hauptstadtregion Schweiz, Schauplatzgasse 39, 3011 Bern (2018)
7. Nyffenegger, U. (ed.): Plus Energie Quartiere, Hauptstadtregion Schweiz, Schauplatzgasse 39, 3011 Bern (2018)
8. Yoo, H.K., Nguyen, M-T., Lamonaca, L., Galanakis, K., Ackrill, R.: Socio-economic factors and Citizens' practices, enabling Positive Energy Districts—Challenging 'silo thinking' for promoting PEDs. Project deliverable Smart-BEEjS (2020)
9. Akhatova, A., Bruck, A., Casamassima, L.: Techno-Economic Aspects and Pathways Towards Positive Energy Districts, Project Deliverable Smart-BEEjS (2020)
10. Civiero, P., Sanmarti, M., Garcia, R., Gabaldón, A., Chicote, M.A., Tevar, J.A.F., Ricart, J.E., Franca, P., Escobar, G.J.: Distritos de Energia Positiva, ITP 01-2019, Plataforma Tecnológica Española de Eficiencia Energética (2019)
11. Alpagut, B., Gabaldón, A.: Guidelines for Positive Energy District Design—How to Transform a district into a PED. Project deliverable MAKING-CITY (2020)
12. Shnapop, S., Paci, D., Bertoldi, P.: Enabling Positive Energy Districts Across Europe: Energy Efficiency Couples Renewable Energy, JRC Technical Report, European Commission (2020)
13. Salom, J., Tamm, M.: Methodology Framework for Plus Energy Buildings and Neighborhoods. Project deliverable syn.ikia (2020)
14. Pless, S., Polly, B., Houssainy, S., Torcellini, P., Livingood, W., Zaleski, S., Jungclaus, M., Hootman, T., Craig, M.: A Guide to Energy Master Planning of High-Performance Districts and Communities. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-78495 (2020)
15. Dobbelsteen, A., van den, R.R., Tillie, N., Broersma, S., Fremouw, M., Martin, C.L.: Urban energy masterplanning—approaches, strategies, and methods for the energy transition in cities. In: Droege, P. (ed.) Urban Energy Transition. Renewable Strategies for Cities and Regions, 2nd edn., pp. 635–660. Amsterdam/Oxford/Cambridge, Elsevier (2018)
16. Olivadese, R., Alpagut, B., Revilla, B.P., Brouwer, J., Georgiadou, V., Woestenburg, A., van Wees, M.: Towards energy citizenship for a just and inclusive transition: lessons learned on collaborative approach of positive energy districts from the EU Horizon 2020 smart cities and communities projects. Proceedings **65**(1), 20 (2020). https://doi.org/10.3390/proceedings2020065020

# Sustainable Development Goals and Performance Measurement of Positive Energy District: A Methodological Approach

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**Abstract** The "Positive Energy Districts and Neighbourhoods for Sustainable Urban Development" program launched by the European Union can be considered a milestone towards the clean energy transition and carbon neutrality of urban areas. The achievement of this ambitious transition requires properly defined methodologies and action plans grounded on the main environmental, economic, and social pillars of sustainability. This paper is focused on the definition of a methodology for the characterization of PEDs sustainability assessment in terms of Sustainable Development Goals. In particular, the main research question to be answered regards the allocation of the surplus energy of PEDs to target the sustainable development and growth of living areas. The main implications of SDG7, referring to the modern and reliable energy access for all, are here discussed and shaped around the features of PEDs. Interlinkages with other SDGs are proposed and measured with ad hoc defined indicators. In this sense, this paper can represent an attempt to orient urban planning decisions not only for the definition of PEDs but also for their practical environmental, economic, and social implications in the long term.

## 1 Introduction

The European Union launched the "Positive Energy Districts and Neighbourhoods for Sustainable Urban Development" program as part of the SET-Plan Action 3.2 "Smart Cities and Communities" [1]. According to its most general definition, a Positive Energy District (PED) can be considered as a "*district with annual net zero energy import and net zero $CO_2$ emissions, working towards an annual local surplus production of renewable energy*" [1].

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The “Clean Energy for all Europeans package” paved the way for the regulation of “energy communities” [2]. An energy community promotes collective and citizen-driven actions focusing on the diffusion of renewable energy systems for the reduction of carbon emissions and energy bills and for the increase of awareness on social aspects, such as the inclusiveness of consumers within the energy market and convenient access to energy [3]. Under this perspective, energy communities reflect the efforts done during the last decades in promoting the sustainable development of living areas concerning the environmental, economic, and social dimensions. Moving to the concept of PEDs, they might be compared to energy communities with the particular constraint of net positive energy balance.

Also, the International Energy Agency has developed a joint research activity on this topic: the IEA EBC Annex 83 workgroup “Positive Energy Districts” focuses on the development of an international shared perspective on PEDs [4].

As advocated in the Implementation Plan of Action 3.2, PEDs will contribute to the achievement of the COP21 targets and the achievement of reliable and sustainable urbanization. In the scientific literature, there has been a rising interest in the modeling of PEDs as carbon–neutral and efficient living areas.

Gouveia et al. developed a model to address energy poverty in existing urban agglomerates and defining guidelines to retrofit inefficient buildings [5]. Gabaldòn Moreno et al. proposed a methodology for the calculation of the energy balance at the district level [6]. The authors started with the identification of the boundaries of the district and proceeded with the calculation of energy needs, use, and on-site production to evaluate the final energy balance. However, as highlighted by Lindholm et al. [7], PEDs are in an initial conceptual phase and further studies are necessary to highlight the impact and practical implications of positive energy districts at the societal level. In this sense, particular attention should be devoted to the sustainability assessment of PEDs for raising awareness on environmental, economic, and social effects. Thus, appropriate planning for PEDs focused on sustainability and including interdependencies among the different and peculiar aspects of urban areas should be inspired by the Sustainable Development Goals (SDGs).

SDGs have been conceptualized in the “2030 Agenda for Sustainable Development” by the United Nations Member States [8]. The Agenda includes indications on the achievement of the 17 specific “goals”, described in terms of targets and measured with the aim of purpose-built indicators [9]. In this context, attention should be paid to the evaluation of synergies and trade-offs between energy-related aspects and the application of SDGs for the sustainable development of human societies, as recommended in [10].

Recalling the regulation of the European Union [11], PEDs could be considered as “*communities of buildings*”, but characterized with a net positive energy surplus [12], the particular issue that should be taken into account for applying the SDGs vision to the planning of PEDs. Indeed, there is still the need to develop models and tools to address the issue of how to use this positive energy in a sustainable way. About the management of energy surplus in PEDs several solutions are usually available: energy exchange mechanisms within the district and among districts, smart interactions between buildings [13], trading with the energy networks [14], internal usage for mobility, energy storage [15], and alternative uses e.g. public lighting.

The need for specific guidelines about the allocation of surplus energy to further improve the energy performances of the district and favor its sustainable growth was investigated in previous literature only to a limited extent. It is therefore evident that planning the transition towards PEDs should not be limited to sole energy-related aspects, rather should also include technological, spatial, financial, legal, environmental, economic, and social issues. Therefore, under the current legislative framework, SDGs can serve as roadmaps for the sustainable assessment of PEDs. In this direction, this work sets up the path to orient the planning of PEDs towards the achievement of SDG7, aiming at defining proper policies to "*Ensure access to affordable, reliable, sustainable and modern energy for all*".

In this sense, the shift of existing urban agglomerates into PEDs or the construction of newly-built positive districts could put into practice the theoretical indications of SDG7. Having inclusive, safe, and less-polluting human settlements are strictly correlated to the diffusion of renewable systems, improvements in energy performances, and sustainable mobility.

In this research, particular attention has been devoted to the SDGs and targets that can be applicable for PEDs and on the interaction with the three main pillars of sustainability. Of tremendous importance is the interlinkage among different SDGs [16] and to the scope, SDG11 "*Make cities and human settlements inclusive, safe, resilient, and sustainable*" and SDG13 "*Take urgent action to combat climate change and its impacts*" have been included in the analysis, along with SDG7.

In the following, the methodology for the positive energy calculation and the route for the sustainability assessment of PEDs strictly correlating it to the SDGs and their related targets is proposed.

## 2 Methodology

The first step for linking PEDs to SDGs consists of the identification of a built-up area as a positive energy district. The main idea behind the identification of a district as a PED relies upon its capacity to dispose of a surplus of energy deriving from renewable production after the satisfaction of the global demand of the area. Among the main macroscopic energy features that should be recognized and measured, the scale of the district (i.e. in terms of the number of buildings, inhabitants, …); the quantification of the global energy demand of the district; the energy generation planning of the district; the determination of energy trading mechanisms (virtual or physical peer-to-peer, specific incentives with the main grid operators, …) should be carefully evaluated. More specifically, in [12], an eight-step methodology for the identification of a positive energy district is proposed.

In general terms, steps 1–4 refer to the overall assessment of the buildings of the area related to their physical and geometrical parameters, the potential renewable system as well as the energy system configuration, and the definition and calculations of energy efficiency measures. Steps 5 and 6 consist of the evaluation of the energy demand at the district level and energy systems alternatives (links among buildings, connections to the main grid, smart control, impact of climate conditions, LCA evaluation). Finally, steps 7 and 8 go through cost–benefit calculations of the different energy alternatives and production/demand performances to maximize the positive surplus of the district. The above procedure allows determining the positive energy of a PED as:

$$E = \sum_{i} Prod_{RES_i} - \sum_{j=1}^{N} Dem_{build_j} > 0 \tag{1}$$

In Eq. (1), $PE$ is the positive energy surplus that can be achieved for the specific district of $N$ buildings. For obvious reasons, this quantity has to be strictly positive. It is estimated as the difference between the renewable production deriving from the different $i$ renewable sources, $Prod_{RES_i}$, and the global demand of the district, calculated as the sum of the demand of each $j$ building, $Dem_{build_j}$. It is worth noting that, although not evidenced in Eq. (1), seasonality has been taken into account in both the energy production profiles (here, highly depending from the renewable sources) and the energy consumption profile. The balance is then calculated on the annual basis. Strategies and action plans should be therefore devoted to properly allocate this exceeding energy surplus within the district or, generally, to maximize its potential use for addressing the sustainability targets of PEDs. In this sense, the guidelines of Lindholm et al. [7] can be followed to correctly estimate how to address the energy surplus of districts. Actually, depending on the PED configuration included in the analysis, strategies and energy actions vary consequently both in terms of geographical allocation (autonomous and dynamic PEDs) or in terms of virtual balances (virtual PEDs).

### *2.1 PEDs–SDGs Assessment*

The broad scope of SGD7 is to ensure access to clean energy by increasing the share of renewable energy and enhancing energy efficiency. In this definition, it is not difficult to identify the same goals as PEDs.

SDGs are declined into targets, each of them being measured by one or more specific indicators. Some of the most significant indicators are then characterized to show how to allocate the surplus of positive energy for the enhancement of the environmental, economic, and social sustainability of the district.

Beyond the characterization of the PEDs performances in light of the SDG7, it is of noteworthy relevance to propose interlinked correlations between SDG7 and other SDGs. In this study, taking into consideration the scope of PEDs sustainability assessment in terms of positive energy usage, two other SDGs are here proposed as interlinkage with the SDG7. Particular attention is therefore devoted to:

- SDG11 "*Sustainable cities and communities*", aiming at making cities and human settlement more inclusive, safe, resilient, and sustainable;
- SDG13 "*Climate action*", for the definition of mitigation and adaptation measures to limit climate change.

The SDGs and the related targets of interest for PEDs are reported in Table 1. For each target, one or more indicators can be defined and specified under the PEDs framework.

A synthetic representation of the SDGs translation into the PEDs framework with particular attention to the main pillars of sustainability is reported in Fig. 1 and discussed in the following. The three main goals are framed to include the indicators selected for the PEDs characterization.

SDG7 is articulated into three targets measured by four indicators. Concerning target 7.1, two main indicators are proposed, referring to the proportion of buildings with access to electricity (7.1.1) and the proportion of buildings with primary reliance on renewable sources and technologies (7.1.2). Both indicators are expressed as percentages and have been disaggregated by the urban districts considered as PEDs, as calculated in Eqs. (2) and (3):

**Table 1** SGDs indicators selection for the application to PEDs

| SDG | Target | Indicator |
|---|---|---|
| SDG7 | 7.1 By 2030, ensure universal access to affordable, reliable, and modern energy services | 7.1.1 $P_{EA}$ |
| | | 7.1.2 $P_{RST}$ |
| | 7.2 By 2030, increase substantially the share of renewable energy in the global energy mix | 7.2.1 $P_{RE}$ |
| | 7.3 By 2030, double the global rate of improvement in energy efficiency | 7.3.1 $EI$ |
| | 7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all | 7.b.1 $W_{RES}$ |
| SDG11 | 11.1 By 2030, ensure access for all to adequate, safe, and affordable housing and basic services and upgrade slums | 11.1.1 $P_{HOUS}$ |
| | 11.2 By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities, and older persons | 11.2.1 $P_{TRAN}$ |
| | 11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management | 11.6.2 $PM_{conc}$ |
| SDG13 | 13.2 Integrate climate change measures into national policies, strategies, and planning | 13.2.2 $GHG_y$ |

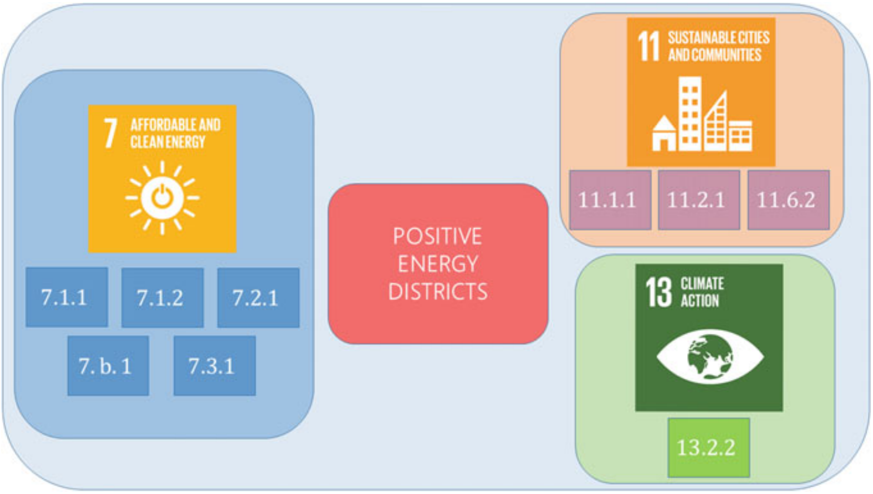


**Fig. 1** PED-SGDs interlinked sustainability assessment

$$P_{EA} = \frac{Number\ of\ buildings\ with\ reliable\ and\ modern\ access\ to\ energy}{Total\ number\ of\ buildings} \tag{2}$$

$$P_{RST} = \frac{Number\ of\ buildings\ served\ by\ renewable\ sources\ and\ technologies}{Total\ number\ of\ buildings} \tag{3}$$

Target 7.2 is measured by the indicator 7.2.1, reported in Eq. (4), and indicating the percentage of renewable energy in the total final energy consumption of the PED. This indicator can be useful for the estimation of renewable energy systems penetration and impact on the district consumption in case of virtual PEDs.

$$P_{RE} = \frac{\sum_{j=1}^{N} EC_{RES_j}}{EC_{PED}} * 100 \tag{4}$$

It is calculated as the ratio between the energy consumption satisfied by each $j$ renewable sources, $EC_{RES_j}$, and the total energy consumption of the district, $EC_{PED}$. This indicator can be disaggregated to take into account the energy consumption fulfilled through the peer-to-peer (P2P) mechanism, i.e. by enabling the active participation of buildings in the energy trading scheme. Finally, the last indicator related to SDG7, 7.3.1, measures the energy intensity of PEDs as in Eq. (5):

$$EI = \frac{Total\ energy\ supply}{Total\ GDP} \tag{5}$$

It correlates the energy production and the economic output (expressed in terms of Gross Domestic Product $GDP$) and establishes how much energy should be produced to produce a unit of economic output.

Finally, indicator 7.b.1, $W_{res}$, measures the installed renewable energy capacity in the PED is referred to the number of buildings of the district, as in Eq. (6):

$$W_{res} = \frac{Installed\ renewable\ capacity}{Number\ of\ buildings} \tag{6}$$

Going forward, SDG11 refers to smart cities and communities; to this goal belong different targets. For this study, the three targets and the corresponding indicators reported in Table 1 have been selected and adapted to the PED features. Target 11.1 and 11.2 measure the proportion of population living in inadequate houses, as reported in Eq. (7) for the indicator 11.1.1, $P_{HOUS}$, whilst indicator 11.2.1, $P_{TRAN}$ shown in Eq. (8) calculates the proportion of population with adequate access to public transport. PEDs transition can significantly facilitate the access to affordable energy prices or, for example, can foster the energy retrofit of existing building for the achievement of energy efficiency targets and, therefore, reducing energy consumptions. Both indicators are referred to the total population of the district.

$$P_{HOUS} = \frac{Number\ of\ population\ with\ inadequate\ housing}{Total\ population} \tag{7}$$

$$P_{TRAN} = \frac{Number\ of\ population\ with\ adequate\ access\ to\ public\ transport}{Total\ population} \tag{8}$$

Indicator 11.6.2, $PM_{conc}$, calculates the annual mean levels of particulate matter. It has been chosen to select the aggregated mean for a district using the number of inhabitants $N_{inhab}$ as a reference, as reported in Eq. (9):

$$PM_{conc} = \frac{PM_{PED}}{N_{inhab}} \tag{9}$$

It is worth noting that the particulate matter concentration of PEDs, $PM_{PED}$, should also include the data referring to the concentration due to internal energy distribution infrastructures, if available.

SDG11 can be discussed also in light of the two targets 11.a and 11.c. The first has been formulated to support national and regional development plans for the enhancement of a positive economy and cooperation between urban and rural areas. The main vision underlying this target consists of the definition of sustainable action plans to account for the increased population dynamics and interlinked development of different areas. The second target, 11.c, highlights the need for building new sustainable and resilient households, especially in the least developed countries.

Finally, the last interlinked goal is SDG13, in particular, target 13.2 and indicator 13.2.2, $GHG_y$, counting the total greenhouse gas emissions per year.

## 3 Discussion and Conclusions

The valorization of the energy surplus of PEDs is determined following the SDGs indicators. However, due to the general nature of their formulation, specific actions should be suggested for the energy allocation within the district.

The two indicators of target 7.1, $P_{EA}$ and $P_{RST}$, refer to the energy use in buildings in terms of reliable and modern access to energy as well as in terms of energy demand fulfilled through the exploitation of renewable sources. Districts are encouraged to complete the transition to renewable energy used as the primary domestic energy source, taking into account the residual percentages of buildings with difficult access to energy for cooking, heating, and lighting. In this direction, data available at the national or regional level stress that, even in developed countries, a substantial percentage of population does not have secure and reliable access to heating. In Italy, as an example, this percentage can be estimated to be around 14% [17]; therefore, the positive surplus of PEDs can be allocated to guarantee the fair satisfaction of the heating needs of the population. These two indicators can be enhanced by paying attention to the indicator 7.2.1, $P_{RE}$, estimating the percentage of renewable energy in the final energy consumption of PEDs. In this sense, since $P_{RE}$ is calculated as the ratio between the energy consumption satisfied through renewable sources and the total energy consumption of the area, better performances can be achieved by either increasing the consumption fulfilled by renewables sources (and, de facto, improving indicators 7.1.1, 7.1.2, indicator 11.1.1 and indicator 7.b.1) or reducing the total energy needs of the district. Achieving this target permits dealing with a higher amount of positive surplus to be managed by local authorities to increase the sustainability of the area. As an example, this energy could be devoted to ensuring modern, accessible, and safe access to transport, as measure from indicator 11.2.1, $P_{TRAN}$. The estimation of the energy needed to fulfill this task and, generally, to improve the basic services to an adequate level can be assumed to range from zero to $0.59 MJ/(passenger * km)$ [18]. From the environmental viewpoints, indicator 11.6.2, measuring the particulate matter concentration per capita, and indicator 13.2.2, evaluating the annual greenhouse gas emissions for the area can be considered as a reference for the long period evaluation of PEDs in terms of sustainable growth and transition to carbon–neutral areas.

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## References


1. S.-P. A. n. 3. I. Plan: Europe to Become a Global Role Model in Integrated, Innovative Solutions for the Planning, Deployment, and Replication of Positive Energy Districts. European Union (2018)
2. t. C. t. E. E. a. S. C. t. C. o. t. R. a. t. E. I. B. Communication from the Commission to the European Parliament, "Clean Energy for All Europeans". COM(2016) 860 final (2016)
3. Hachem-Vermette, C., Guarino, F., La Rocca, V., Cellura, M.: Towards achieving net-zero energy communities: investigation of design strategies and seasonal solar collection and storage net-zero. Solar Energy **192**, 169–185 (2019). https://doi.org/10.1016/j.solener.2018.07.024
4. https://annex83.iea-ebc.org, last accessed June 15th, 2021, [Online]
5. Gouveia, J., Seixas, J., Palma, P., Duarte, H., Luz, H., Cavadini, G.: Positive energy district: a model for historic districts to address energy poverty. Front. Sustain. Cities **3**, 648473 (2021). https://doi.org/10.3389/FRSC.2021.648473
6. Gabaldòn Moreno, A., Vèlez, F., Alpagut, B., Hernàndez, P., Sanz Montalvillo, C.: How to achieve positive energy districts for sustainable cities: a proposed calculation methodology. Sustainability **13**, 710 (2021). https://doi.org/10.3390/SU13020710
7. Lindholm, O., ur Rehman, H., Reda, F.: Positioning positive energy districts in European cities. Buildings **11**, 19 (2021). doi.org/buildings11010019
8. United Nations: Department of Economic and Social Affairs. www.sdgs.un.org/2030agenda (last accessed June 10, 2021) [Online]
9. United Nations: General Assembly. Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development
10. Fuso Nerini, F., Tomei, J., Seng To, L., Bisaga, I., Parikh, P., Black, M., Bor-rion, A., Spataru, C., Castàn Broto, V., Anandarajah, G., Milligan, B., Mulugetta, Y.: Mapping synergies and trade-offs between energy and the sustainable development goals. Nat. Energy Persp. **3**, 10–15 (2018). https://doi.org/10.1038/S41560-017-0036-5
11. European Union: COM(2016) 860 final (2016)
12. Shnapp, S., Paci, D., Bertoldi, P.: Enabling Positive Energy Districts Across Europe: Energy Efficiency Couples Renewable Energy. EUR 30280 EN, Publications Office of the European Union, Luxembourg (2020). ISBN 978-92-76-21043-6. https://doi.org/10.2760/452028
13. Fichera, A., Frasca, M., Palermo, V., Volpe, R.: Application of the complex network theory in urban environments. A case study in Catania. Energy Procedia **101**, 345–351 (2016). https://doi.org/10.1016/j.egypro.2016.11.044
14. Fichera, A., Marrasso, E., Sasso, M., Volpe, R.: Energy, environmental and economic performance of an urban community hybrid dis-tributed energy system. Energies **13**(10) (2020). https://doi.org/10.3390/en13102545
15. Cusenza, M.A., Guarino, F., Longo, S., Ferraro, M., Cellura, M.: Energy and environmental benefits of circular economy strategies: the case study of reusing used batteries from electric vehicles. J. Energy Stor. **25** (2019). https://doi.org/10.1016/j.est.2019.100845
16. Santika, W., Anisuzzaman, M., Bahri, P., Shafiullah, G., Rupf, G.: From goals to joules: a quantitative approach of interlinkages between energy and the sustainable development goals. Energy Res. Soc. Sci. **50**, 201–214 (2019). https://doi.org/10.1016/j.erss.2018.11.016
17. Statistica, I.-I. N. d.: Rapporto SDGs 2020—Informazioni statistiche per l'Agenda 2030 in Italia (2020). ISBN 978-88-458-2020-5
18. Econometrics, C.: Transport and Environment. Cambridge, UK (2017)

# A Panelization Design Tool to Inform Decisions About Façade Geometry and Environmental Performances

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**Abstract** The energy upgrade of existing buildings is crucial to achieve the decarbonization goals of 2050. While the current façade retrofit technologies are effective and well-tested, they present shortcomings in terms of installation time, disruption to users, etc. A paradigm shift is required to overcome these barriers and increase the renovation rate. Modern Methods of Construction (MMC) employing off-site elements offer a promising alternative; however, since practical knowledge about their selection and application is limited, they are still rarely adopted by designers. The objective of this paper is to propose a Panelization Design Tool, able to automate part of the design process in the early stages, to support designers and decision-makers in the choice of specific technologies for retrofitting facades with off-site fabricated panels. The tool provides information about the performances of each technology according to the Building Information Modeling (BIM) n-dimensions. In particular, this paper shows the potential of the tool to solve geometry and energy-related aspects with dedicated indicators.

## 1 Introduction

### *1.1 Existing Building Stock*

According to the World Business Council for Sustainable Development (WBCSD), more than half of Europe's building stock is dated between 1925 and 1975, for a total of about 80 million buildings. In this scenario, with a consumption of 458 Mtoe in EU territories in 2016, buildings account for 41% of the annual energy consumption, two-thirds of which are attributable to the residential sector [1]. Moreover, $CO_2$ emissions related to building energy (which in 2016 amounted to 33% of the total)

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[2] are increased in recent years, reaching 10 $GtCO_2$, and the highest level ever recorded.

The rapid increase in the world population living in urban areas that, according to estimations, will reach 9.7 billion in 2050 [3] may lead to a further rise in GHG emissions [4] for all the inefficiencies mentioned above.

The goal is to promote a less expensive/more efficient development based on environmental, economic, and social criteria (need for integrated and holistic solutions), enhancing the new urban lifestyle assets [5].

Nowadays, the European Union faces a double challenge: increasing the renovation rates while carrying out deep renovations in the sector.

Increasing the current EU renewal rate from 1.2% per year to 2–3% is essential to achieving both the EU 2030 targets—currently disregarded [6]—and fostering the commitment made in Paris in December 2015. A significant energy renovation of the existing building stock would lead to an 80% reduction in energy demand in 2050 compared to 2005 levels [7] while promoting more frequent use of renewable resources such as wood or other biogenic construction products.

### *1.2 Modern Methods of Construction (MMC) and Panelization*

Modern Methods of Construction are a solid answer to the low productivity of the building sector. This industry's production rate is about 1%, compared to 2.8% of the others [8]. The MMC adoption can fill this productivity gap, leading to building industrialization, where off-site production will be the priority. Design for Manufacturing and Assembly (DfMA) is an approach to optimize the passage from production to assembly, reducing delivery costs and risks [9].

The necessity to act on the existing building stock cause a relevant interest in the recladding of '60–70' buildings. Because of their low residual performance and the high demolition cost, it is convenient to refurbish the palimpsest instead of building new volumes. This trend is also confirmed by many European projects [6, 10, 11] and market application [12, 13], especially in historical countries such as Italy. The application of prefabricated panels completed by insulation, services, and finishing gives new structural, thermal, acoustical, and architectural performance to typical buildings, commonly referred to as panelization.

## 2 Digital Design for Retrofit

### 2.1 State of the Art

As widely discussed in the literature, there is a strong need for an intense innovation process in the construction sector focused on reducing costs, intervention times, and energy performance guarantees [14]. Moreover, the global issues related to the excessive energy consumption of the building stock and the need to minimize its climate impact in the short term have led to the development of numerous guidelines, design and assessment tools specifically for retrofitting [15, 16].

Today, there are many digital and informative tools for modelling energy retrofit panels (panelization tools) for existing buildings. While it is clear that the prevailing direction in the development of these tools is increasingly in the direction of BIM [17–21], the fragmentation resulting from their variety and specificity is evident. We can trace the first discriminating factor back to the distinction between company-owned software (or more appropriate tools)—and therefore specific for certain products or types of application—and research-related software.

Many company-owned tools interfaces with the IFC model and guarantees the possibility of carrying out a complete panelling of the building using prefabricated elements (often with the possibility of selecting unique pieces and finishes). A typical gap to this tool and other software—or BIM libraries—is the limitations linked to the low level of automation and, consequently, optimization of the process [22–24].

For this reason, several international research projects aim to streamline the decision-making process and integrate ad-hoc toolkits into the BIM process to facilitate the early-stage decision process. Among the H2020 projects are IMPRESS [25] and BIM4EEB [26], which, through toolkits and open source platforms, integrate the assessment processes and reduce the iterations necessary for operational decisions.

In this scenario, the advantage of parametric tools is the iteration of the design processes and return-optimized information quickly through the definition of constraints and variables. The literature provides several examples of computational tools for energy retrofitting [27–29]. Moreover, the combination of Multi-Objective Optimization (MOO) parametric tools and data visualization tools [30] can help designers and manufacturers choose the best retrofit option in an informed way.

On a general level, the complexity of building envelopes implies that digital tools should take into account constraints and requirements coming from all the phases of the process (analysis, design, production, construction, management, end of life) and from all the stakeholders (among others, architect, engineer, façade designer, manufacturer, supplier, general contractor). Since most of the available tools are developed for specific technologies, there is currently the need for a decision support system that helps designers choose between panels based on different technological solutions.

### 2.2 Information Flow in BIM Environment

As highlighted above, any tool aiming at improved decision-making should nowadays be integrated into a BIM-based digital workflow, allowing a platform-data exchange inside and between organizations [31] and exploiting the various dimensions of BIM (from 2 to 7D: geometry, energy, structure, time, cost, sustainability and facility management) to provide integrated information across different domains.

While, in an ideal BIM-based scenario, data should flow in a frictionless way between different tools, in the real world, there are still several gaps. One is between the model in a BIM environment and the Enterprise Resource Planning (ERP) production software [32]. Another lies in the necessity for producers to often re-model the design team's model because the latter does not fit the production tools. Indeed, the Asset Information Requirements (AIR) and the Product Information Model (PIM) use different languages from the Computer-Aided Design (CAD)/Computer-Aided Manufacturing (CAM) machines. This information translation causes a loss or excess of data.

## 3 Multi-dimensional Panelization Tool

Based on the evidence and gaps discussed in the previous paragraphs, the authors identified a space for innovation in developing a Panelization Design Tool (PDT): a decision support system for designers allowing for a solid and informed decision process. Starting from architectural, structural, manufacturing, logistical and energy-related constraints provided by the different actors of the process, the PDT solves the panel geometry for the model of the specific existing building, and at the same time provides information about the performances of different panel typologies. The latter is based on "meta-technological" solutions optimized for the Industry Foundation Class (IFC), the open-source BIM file format. The tool integrates DfMA and BIM approaches in an open platform that can adapt, modify, change, and evolve flexibly according to requirements from different actors and suppliers. The tool's structure is based on a thorough analysis of the information exchange generally taking place at each stage of the retrofit process and the related software and tools [33]. Figure 1 shows the synthetic structure of this information flow.

The tool goals are:

- providing a decision support system for industrialized and bespoke products using a meta-technical object in a parametrical tool;
- using meta-technical objects instead of a-technical placeholders, carrying information about different BIM dimensions;
- solving the geometrical "airbag" creation with practical, structural, energy-related, logistical and economic implications.

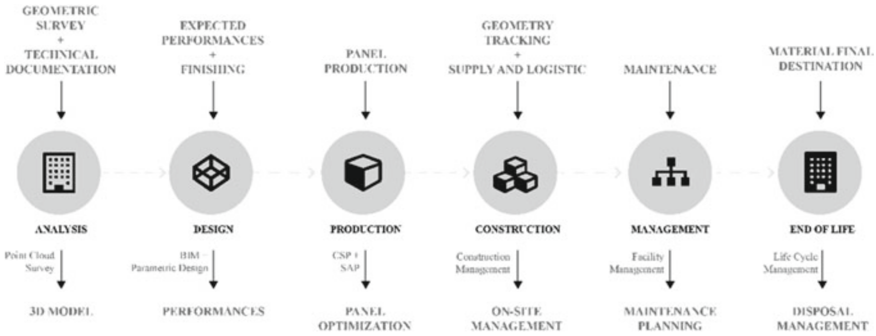


**Fig. 1** In-flow diagram analyzing tasks, tools and data according to different design phases

Compared to the existing ones, this tool provides:

- a multi-objective informed design process, able to provide for the requirements coming from all the actors involved in the process;
- a progressive information addition in the whole design process across all stages, starting from the analysis until the End of Life;
- manufacturing optimization and compatible design with shop drawings production preventing the multiple iteration process between design and production;
- a double sensitivity and analytical assessment on different parameters.

## 4 Articulation of the Tool and Application to a Case Study

Since the tool is still under development, this paper will only present its potential in terms of solving the geometrical problem of panelling an existing building and assessing the structural and energy performances of different panel typologies. These are a lightweight concrete panel and a timber frame panel, whose characteristics are derived from literature; these MMC solutions will also be compared to a traditional External Thermal Insulation Composite System (ETICS) (Fig. 2).

The case study selected to test the first version of the tool is based on a typical building owned by ALER (Azienda Lombarda per l'Edilizia Residenziale), the public housing agency of the Lombardy Region). The building is 65 × 12 m in plan, has eight floors, each 3 m high, for a total height of 24 m, and a gross surface area of the envelope of around 5800 m$^2$.

The goal of the test was to verify the possibility of defining an effective subdivision of the existing facades in panels, respecting the constraints imposed by producers and by the experience of designers; and assessing whether the parameters chosen to describe the structural and energy performances can actually help the designer make informed choices through a significant differentiation of the results.


**Fig. 2** The three different technological solutions

## 4.1 *Tool Steps*

Data input will come from the IFC as-built model of the existing building (geometrical data and building features) and from a file in an accessible exchange format (CSV or XLS) with the constraints expressed by each stakeholder. The script processes these two input typologies to define, for each panel technology, a geometrical solution providing the required performances. The test was conducted on two different types of panels, whose sub-structure and layer composition were based on existing BIM families, not referred to as a specific product but to a concept product [34]. The façade designer can then further detail and modify the technological solution according to the LOD/LOI requirement [35–37] (Fig. 3).

There are two typical approaches to the panelization of facades: stand-alone, small-size panels (e.g. EASEE lightweight concrete panel [38]) and larger wall panels, complete of windows and services (e.g. TES timber panel [39]). The designer can choose between these two options, the treatment of recessed loggias and balconies, the corner solution (priority to one panel, or a 45° cut), the anchoring solution and the material composition/source (Fig. 4).

Panels are catalogued by their typologies and localization, creating a bill of panels automatically with the length, height, and thickness of every single element.

The second domain of optimization is related to energy. The parametric tool combines the engineer and the façade designer's constraints and performance requirements with the layer composition and the possible presence of windows to calculate

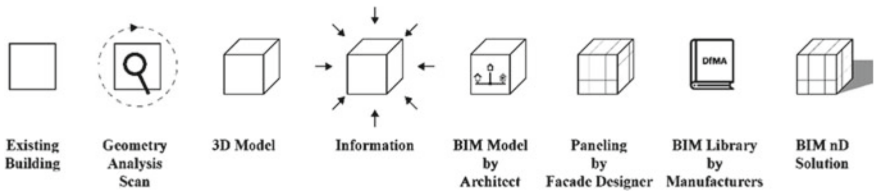


**Fig. 3** Steps of the process: from the existing building, to the information model, to the BIM nD optimization

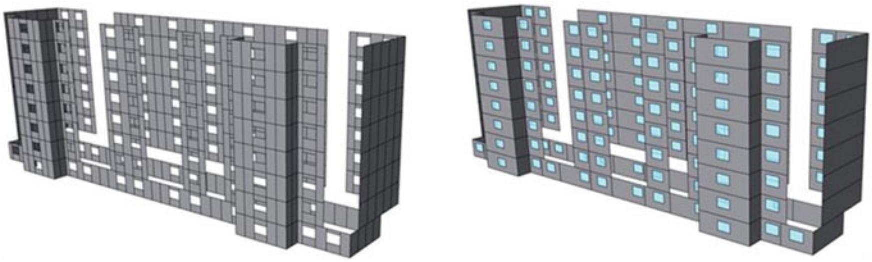

**Fig. 4** Geometrical discretization of facades for concrete (left) and timber panels (right)

the global envelope performance (H’t). It also considers the linear thermal bridges caused by the geometrical subdivision of panels.

## 4.2 Results Synthesis

To result understandable by designers, the outcomes of the parametric analysis have to be summarised in a few parameters that are significant, easy to understand and sufficiently variable to support the decision-making process.

In this first iteration of the tool, the selected parameters and their range [min–max] are the following:

- Number of total panels/Total cladding surface (n/m$^2$) [0–1];
- Number of panel types/Number of total panels (–) [0–1];
- Number of anchors/m$^2$ (no./m$^2$) [0–2];
- Thermal transmittance U (W/m$^2$K) [0.13–0.26];
- Global average heat exchange coefficient H’t (W/m$^2$K) [0.3–0.75].

At this moment, the ranges are related to Italian regulations and the experience of the authors; however, they can be modified to be more consistent with each specific situation, since the purpose of the tool is to support designers and producers to choose the most suitable technology in each specific use case.

The various parameters are represented with radar diagrams to make them more intelligible and to better highlight performances of each technology (Fig. 5).

A second representation of results consists of the synthetic BIM nD radar, where parameters are grouped by typology and averaged by parametrizing the analytical value to a score from 1 (the worst) to 4 (the best):

- Structural Design (2D):
  - Number of anchors/m$^2$ (no./m$^2$);
  - Geometry Definition (3D):
    - Number of total panels/Total cladding surface (n/m$^2$);

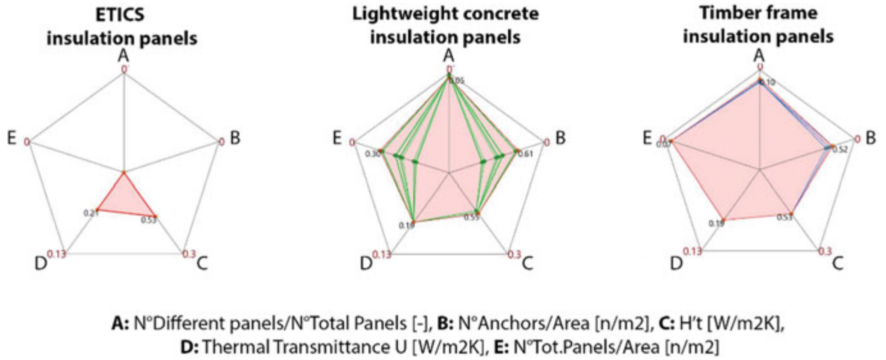


**Fig. 5** Use of radar diagrams for the analytical comparison of different cladding technologies (ETICS, concrete panels and timber panels)

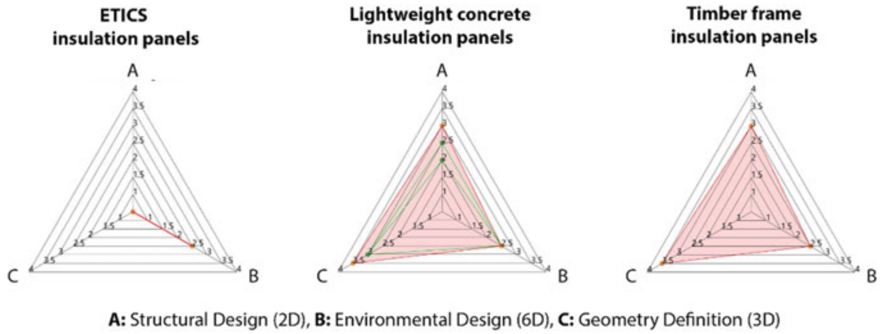


**Fig. 6** Comparison of BIM nD radar diagrams for the different cladding technologies (ETICS, lightweight concrete insulation panels and timber frame insulation panels)

  - Number of panel types/Number of total panels (–);

- Environmental Design (6D):
  - Thermal transmittance U (W/m$^2$);
  - Global average heat exchange coefficient H't (W/m$^2$K) (Fig. 6).

# 5 Discussion

## *5.1 Output Comparison*

The comparison of radar diagrams shows the different behaviour of each technology: ETICS has no evaluation for the geometrical and structural parameters because it does not require anchoring as the panels. The U value of the added layers is comparable in

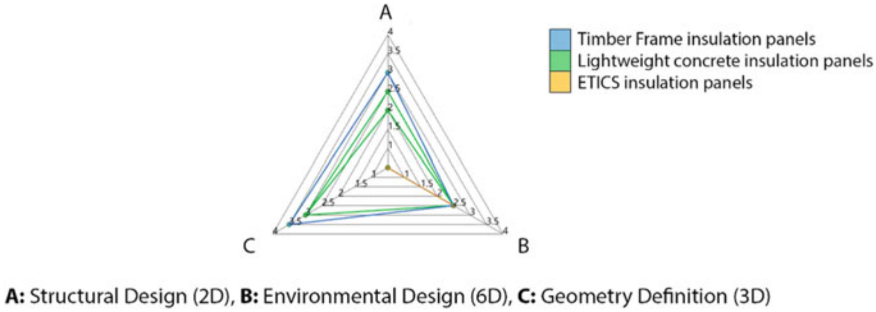


**Fig. 7** Final comparison between the different technologies in the BIM nD radar diagram

all three cases. Due to the window replacement and to a better linear thermal bridge behaviour, the timber panel has an H't value of 0.39 W/m$^2$K compared to 0.51 and 0.5 of ETICS and concrete panels respectively.

The proposed synthetic way to compare all three technologies is the BIM nD radar, where it is possible to see at the same time the score for each dimension, thus facilitating a holistic choice. In this first iteration of the process, all the parameters have the same weight to avoid prioritizing one aspect over the others. However, in future applications it will be possible to integrate a weighing system to represent different sets of priorities deriving from designers, producer's constraints, structural concerns, etc. (Fig. 7).

The results show the radar diagram and the selected parameters are effective in representing the specific characteristics of each cladding technology, allowing designers and to appreciate their strengths and weaknesses during the decision-making process.

## 6 Conclusion

The results of the early tests of the proposed Panelization Design Tool show that it is possible to automatize part of the design process (geometry) and to represent a set of significant performance indicators with the goal of supporting designers and decision-makers in the choice of a specific technology for retrofitting facades with off-site fabricated panels.

Further development of the tool should be rather straightforward thanks to the platform approach used. More aspects regarding the system's efficiency and involving other BIM dimensions will be implemented. The following parameters are the first candidates to widen the tool's scope:

- Time (4D): Installation time (days);
- Cost (5D): Total cost (€/m$^2$);
- Management (7D): LCA (PEREN/PETOT).

Other relevant topics can be the implementation of the LOD level according to the starting point data availability from the EDS until the design output; the production process with shop drawings; and the management phase with the decommissioning of the building or its envelope.

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## References

1. Rousselot, M., Pollier, K.: Energy efficiency trends in buildings Odyssee-Mure. Policy Br. 1–4 (2018)
2. ESA 2010: Emissions of Greenhouse Gases and Air Pollutants from Final use of CPA08 Products—Input-Output Analysis (2017)
3. UN DESA Department of Economic and Social Affairs: World Population Prospects 2019 (2019)
4. Elkington, J.: Cannibals with Forks: The Triple Bottom Line of the 21st Century Business (1997)
5. Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., Fuller, G.: Sustainable Development Report 2019 (2019)
6. Salvalai, G., Sesana, M.M., Iannaccone, G.: Deep renovation of multi-storey multi-owner existing residential buildings: a pilot case study in Italy. Energy Build. **148**, 23–36 (2017)
7. Jacobs, P., Leidelmeijer, K., Borsboom, W., van Vliet, M.: Trans. Zero Energiesprong Energiesprong Platf. **31**, 32 (2015)
8. McKinsey Global Institute: Reinventing Construction: A Route To Higher Productivity (2017)
9. Sinclair, D., Tait, A., Carmichael, L.: RIBA Plan of Work 2020 Overview (2020)
10. Op 't Veld, P., Carrabs, M., van Oorschot, J.: More-Connect (2019)
11. Frank, L., Knut, E.L., Stephan, O., Yrsa, C.: TES EnergyFaçade—Prefabricated Timber Based Building System for Improving the Energy Efficiency of the Building Envelope, pp. 189 (2009)
12. Orsini, F., Marrone, P.: Approaches for a Low-Carbon Production of Building Materials: A Review (2019)
13. CNAPPC: Chi Ha Progettato L'Italia?—Ruolo dell'Architettura nella qualità del Paesaggio (2017)
14. Hammond, R., Nawari, N.O., Walters, B.: BIM in sustainable design: strategies for retrofitting/renovation. In: Proceedings of 2014 International Conference on Computer Civil Building Engineering, pp. 1969–1977 (2014)
15. Seghezzi, E., Masera, G., Cecconi, F.R.: Decision support for existing buildings: an LCC-based proposal for facade retrofitting technological choices. In: IOP Conference Series Earth Environment Science, pp. 296 (2019)
16. Spinelli, A.: NaturWall_Multifunctional Wood Façade in Existent Building Refurbishment (2012)
17. Ezcan, V., Isikdag, U., Goulding, J.S.: BIM and Off-Site Manufacturing: Recent Research and Opportunities (2013)
18. Scherer, R.J., Katranuschkov, P.: BIMification: How to create and use BIM for retrofitting. Adv. Eng. Inf. **38**, 54–66 (2018)
19. Salvalai, G., Iannaccone, G., Sesana, M.M., Pizzi, E., Sesana, M.M., Pizzi, E.: Outer facade retrofitting trough precast insulation panels: method and planning tool applied to an Italian residential building (2017)

20. Khaddaj, M., Srour, I.: Using BIM to retrofit existing buildings. Procedia Eng. **145**, 1526–1533 (2016)
21. Gholami, E., Kiviniemi, A., Kocaturk, T., Sharples, S.: Exploiting BIM in energy efficient domestic retrofit: evaluation of benefits and barriers. In: 2nd International Conference on Civil Building Engineering Informatics, pp. 1–8 (2015)
22. Focchi Facades: Open BIM RenoZEB. http://open-bim-renozeb-focchi-facades.cype.it/
23. Trimble: Tekla Structures. https://www.tekla.com/solutions/precast-fabricators/detailing
24. Xlam Dolomiti: BIM—Xlam Dolomiti. https://www.xlamdolomiti.it/en/free-bim-libraries-for-revit-and-autodesk
25. Cabrera, A.G., Ntimos, D., Purshouse, N., Gallagher, S.: IMPRESS BIM methodology and software tools (iBIMm) for façade retrofitting using prefabricated concrete panels. Int. J. 3-D Inf. Model. **6**, 57–84 (2018)
26. Horizon2020: BIM4EEB. https://www.bim4eeb-project.eu/
27. Lim, Y.W., Seghier, T.E., Harun, M.F., Ahmad, M.H., Samah, A.A., Majid, H.A.: Computational bim for green retrofitting of the existing building envelope WIT Trans. Built Environ. **192**, 33–44 (2019)
28. Abello, N.O., Tufani, N.: Scaling Up BIM for Resilience: Automated Designs to Retrofit Informal Housing, pp. 1–32
29. Jin, Q., Overend, M.: A prototype whole-life value optimization tool for façade design. J. Build. Perform. Simul. **7**, 217–232 (2014)
30. Tomasetti, C.-T.: Design Explorer. http://core.thorntontomasetti.com/design-explorer/
31. Giana, P.E., Schievano, M., Paleari, F., Seghezzi, E.: Introduzione al BIM. Protocolli di Modellazione e Gestione Informativa, Bologna (2019)
32. Kuma, K.: What Comes After Industrialized Society. KKAA Newsl. 32 (2020)
33. Alfieri, E., Seghezzi, E., Sauchelli, M., Di Giuda, G.M., Masera, G.: A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study. Archit. Eng. Des. Manag. **16**, 247–269 (2020)
34. Zambelli E.: Innovazione Edilizia in Giappone Modulo, pp. 700–706 (1989)
35. UNI: UNI 11337:2017 Edilizia e opere di ingegneria civile Gestione digitale dei processi informativi delle costruzioni (2017)
36. BSI: BSI (2013) PAS 1192-2:2013 Specification for Information Management for the Capital/Delivery Phase of Construction Projects using Building Information Modelling (2013)
37. BIMForum, American Institute of Architects: Level of development specification. Part I for Building Information Models (2019)
38. Colombo, I.G., Colombo, M., di Prisco, M., Galzerano, B., Verdolotti, L.: Lightweight TRC sandwich panels with sustainable diatomite-based core for energy retrofitting of existing buildings. Adv. Build. Energy Res. 1–22 (2019)
39. Cronhjort, Y., Nuikka, M., Hirsi, H.: TES Energy Facade Timber Based Element Systems for Improving the Energy Efficiency of the Building Envelope (2009)

# Neighbourhood Digital Modelling of Energy Consumption for Carbon Footprint Assessment

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**Abstract** Climate change is becoming a dominant concern for advanced countries. The Paris Agreement sets out a global framework for sustainable development performance configuring all climate action related policies. Fast control of CO2 emissions necessarily involves cities since they are responsible for 70 percent of greenhouse gas emissions. A common framework for urban policy impact assessment must be based on architectural design tools and common data repositories for standard digital building models. Many Neighbourhood Sustainability Assessment (NSA) tools have been developed but the growing availability of open data repositories for cities, together with big-data sources (provided through Internet of Things repositories), allow accurate neighbourhood simulations, or in other words, digital twins of neighbourhoods. These digital twins are excellent tools for policy impact assessment. This chapter provides a generic approach for a simple neighbourhood model developed from building physical parameters which meets relevant assessment requirements.

## 1 Introduction

City regeneration is becoming a key process through the city life which dominates the current urban policies in well-established cities and is considered as the basis for evaluating the sustainability of urban environments [1]. Urban regeneration policies alternate from neighbourhood evolution to structured redesign of citizen use, services aggregation and above all land economic value. Cities behave like living organisms and their evolution is shaped by human activities (with their associated processes), costs and urban policy. In order to understand these metabolic processes city officials, have to understand ever-increasing problems derived from human interaction. Topics like social disintegration, economic recession, environmental pollution, and urban function deterioration, are key for urban renewal and climate change issues to obtain a resilient result. These issues have received significant attention worldwide [2, 3].

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All EU countries are developing their urban agendas meeting United Nations Sustainable development goals (UN SDGs) following the European Green Deal principles. Cities play the most relevant role for achieving the Paris agreement objectives through UN SDG 11 but applying the term sustainability is a complex objective due to its multi layered nature [4]. Sustainable Cities have to aggregate a collection of unsustainable components into a neutral outcome [5]. Decoupling the interaction into its elementary parts is the key of urban policy. Neighbourhoods are the logical decoupled elements for solving the urban puzzle. Their size and coherence are best suited for addressing sustainable urban development [6]. It is also relevant to consider that their size matches an adequate project scale for including social co-design. However, an accurate approach requires a methodology based on a digital representation as in Building Integrated Modeling (BIM) [7]. Sustainable cities present different realities which can be balanced around carbon footprint evolution whose highest impact relates to energy consumption [8]. The final aim therefore targets Net Zero Energy buildings (NZEBs).

## 2 Literature Review

After a detailed bibliographical comparison of contextual and methodological procedures for building certification tools [8, 9], the building footprint has been proven as the leading criteria obtained through an LCA procedure (and its derivative LCC).

Although a full BIM deployment would solve most problems, it is already far from becoming a dominant reality [10]. Tools implementing generic approaches based on widespread equivalent data repositories, are sought in order to support sustainable policy design from performance evidence.

This chapter proposes an adaptive model framework, implemented in Valencia (Spain) at a neighbourhood scale, for an energy performance-based comparison of its residential buildings that is able to evaluate different renovations alternatives and their impact on the neighbourhood carbon footprint. The studied area is going to be renovated by the municipality of Valencia.

Energy performance of buildings can accurately estimate the most relevant part of their carbon footprint once the building physical parameters have been identified [11]. Although construction is always evolving over the course of time, the evaluation of relevant energy parameters for buildings have been performed by several instances [12, 13] through an informed analysis of the building stock through the perspective of time. Evolution of building typologies is due to the introduction of new materials and construction techniques, as well as through economical and raw materials fluctuations. In addition, architectonical innovations, social changes and cultural trends present repetitive solutions (or typologies) in homogeneous areas, easily recognizable in given periods, that can be categorized for their use as standard references.

Building energy performance also depends on the existing infrastructure for climate control (Heating, Ventilation and Air Conditioned, or HVAC systems) and the distribution system, as well as local conditions derived from green, blue and grey city infrastructures [14].

In conclusion, carbon foot-printing of buildings based on energy performance provides an efficient route to sustainability analysis parallel to ISO standardized LCA analysis [15]. This principle also facilitates SDG-based sustainability assessment by the matching carbon footprint, embedded energy, and city infrastructure indicators to SDG key performance indicators [16], delivering a building key performance indicators portfolio that can be applied at neighbourhood level. This approach facilitates the implementation of sustainable policy assessment in any city.

The consistent analysis performed on the current scientific literature on urban sustainability assessment demonstrates that some research gaps still exist [17], although the accuracy obtained from the simplified carbon footprint approach is enough and efficient. Specific studies performed for the Valencia region (Spain) [18] confirm the correlation between energy consumption at building level and the overall neighborhood carbon footprint.

## 3 Methodology

The proposed methodology for determining the carbon footprint starts with an evaluation on the energy profile based on the exhaustive analysis for different building typology energy consumptions presented on the TABULA Webtool [12] developed through the Episcope Eu project for main regions in Europe. Energy audit of the building. This audit collects fundamental information for the analysis of the building: architectural drawings to calculate the area and volume that is air-conditioned, number of users, schedules of use of the facilities, energy requirements of the users, activities that are performed in the building, and characteristics of the heating, ventilation, and air-conditioning system (HVAC).

Information for each building has to be completed after checking the corresponding building typology according to the construction date and applicable regulations.

In order to complete the neighbourhood model, each building has a record to be completed with the number of floors, window surfaces and roof structure after identifying each building through Google Maps and using Street View for visual evaluation.

The last step corresponds to the energy requirements simulation for climate control which corresponds to the most relevant energy consumption.

### 3.1 Reference Data

The reference data used for developing the proposed neighbourhood model require prior existence of cadastral information in an adequate graphical format. All relevant cities in the world have at least an orthophoto database for taxation purposes. However, one of the constituent parts of cadastral information systems are graphical data (vectorial format) on parcel boundaries also including data on ownership and other building related information. This information should be loaded to a GIS software platform for editing, leaving only shape, construction date and height information for each building. In this research we have used the free software QGIS.

### 3.2 Building Typologies

Several parameters have a direct influence on the energy performance of a building: construction period, building size, shading from other buildings, service installations type and age, together with energy saving measures already implemented. Building typologies allow us to group similar building patterns in terms of shape, materiality and performance to facilitate an approximate to their energy consumption evaluation.

In recent decades, there have been different approaches to building typological classifications in different European countries. The TABULA project has studied existing classifications in order to arrive at a common approach in the field of residential buildings [19]. In this model we have used the TABULA classification based on the Spanish cadaster data source and the use and management through a GIS tool.

Many studies have been carried out on this topic [20], starting from the knowledge of the condition of the existing building stock [21], applying statistical data analysis [22], collecting and organizing data [23] and identifying methodologies for assessing the building stock energy performance [24]. The public cadaster is an excellent source of information in Spain which has increased its use and exploitation for analysis and research thanks to Directive 2007/2/EC establishing an infrastructure for spatial information in the European Community (Inspire). The use of the Spanish cadaster database has allowed us to obtain data relating to: number of dwellings, period of construction, construction typology, number of floors, construction quality.

According to the review of Swan and Ugursal [25], two types of building stock energy models exist at large scale: top-down approaches consist in establishing a relationship between aggregated energy consumption and data such as housing description statistics or economic data; bottom-up estimation on energy consumptions of single or groups of buildings with different end-uses through a hierarchy of disaggregated input data and then extrapolate results for the entire building stock using some proxy indicators. Therefore, bottom-up techniques based on building-by-building methods represent potential methods of characterizing buildings according to geospatial building stock models [26]. These methods should be used considering the behaviour of occupants [25] that has a great impact on final energy consumption.

Tools such as Geographical Information Systems (GIS) facilitate the use of information associated with individual buildings and permit building-by-building analyses [26] and have been very useful in the method of work used.

### *3.3 Defining Building Typologies Models*

After getting the information from the cadastre and classifying the buildings, a statistical analysis has been done to find out what building would be the most representative for each typology. Following Tabula classification, we define three building typologies Single Family House (SFH), Terraced House (TH) and Multi Family House (MFH) from now on in this paper called VivUniAis, VivUniAdo and EdiPluri.

With the data of Table 1, the dimensions of each typology are settled. To complete the energy model, construction data taken from the Tabula Webtool database is used to define the envelope characteristics of each typology, considering the construction period Tabula follows for Spain, that is made specifically for Valencia region. As a result, 18 different simplified models are built to run the simulations, 3 typologies $\times$ 6 construction periods.

Tabula also defines 6 construction periods, so combining these six periods with the three building typologies, we configure the area of study as 18 building models as we can see in Table 2 (Fig. 1).

**Table 1** Building stock summary

| Variable | Number of buildings | Residential surface ($m^2$) | Average building area ($m^2$/building) | Number of floors |
|---|---|---|---|---|
| VivUniAis | 195 | 24,985 | 128.13 | 1.95 |
| VivUniAdo | 705 | 77,531 | 109.97 | 1.94 |
| EdiPluri | 504 | 480,963 | 954.29 | 4.25 |

**Table 2** Combination of construction periods and building types

| Construction period | VivUniAis | VivUniAdo | EdiPluri |
|---|---|---|---|
| Before 1900 | VivUniAisP01 | VivUniAdoP01 | EdiPluriP01 |
| 1901–1936 | VivUniAisP02 | VivUniAdoP02 | EdiPluriP02 |
| 1937–1959 | VivUniAisP03 | VivUniAdoP03 | EdiPluriP03 |
| 1960–1979 | VivUniAisP04 | VivUniAdoP04 | EdiPluriP04 |
| 1980–2006 | VivUniAisP05 | VivUniAdoP05 | EdiPluriP05 |
| After 2007 | VivUniAisP06 | VivUniAdoP06 | EdiPluriP06 |

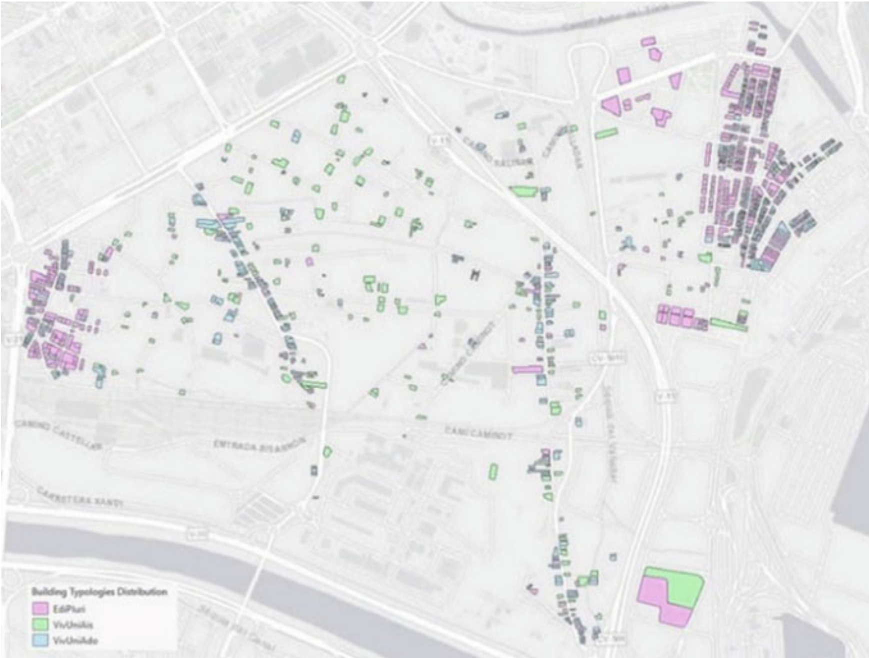


**Fig. 1** Modelled neighbourhood: la Fonteta-la Punta-Nazaret

## *3.4 Building the 17 Simplified Models (revisor2 dice de mover a la primera parte de resultados porque dice que se refiere al workflow del caso de estudio)*

With data gathered from Tabula Webtool and the cadastre, the models have been built with the help of SketchUp software to be later transferred to OpenStudio (OS). Since there are no VivUniP06 buildings in the area of study, the final number of models is 17. The workflow followed is explained in the Fig. 2.

The Occupancy Schedules used are according to the Spanish Technical Code for Construction, saving of energy. The loads for the simulations are:

- Interior thermal mass: 20 kJ/m$^2$; Occupancy: 20m$^2$/person
- Lighting: 4.4 W/m$^2$; Equipment: 4.4 W/m$^2$
- Air infiltration during night in summertime: 4 ACH
- Air infiltration during occupation: 0.2 ACH; Constant air infiltration: 0.2 ACH.

OS software uses the EnergyPlus (E+) engine to simulate the energy demand. E+ is free, open-source, and cross-platform. Both software, are developed and funded by the US Department of Energy (DOE) Building Technologies office (BTO).

The results obtained after the 17 simulations are in Table 3.

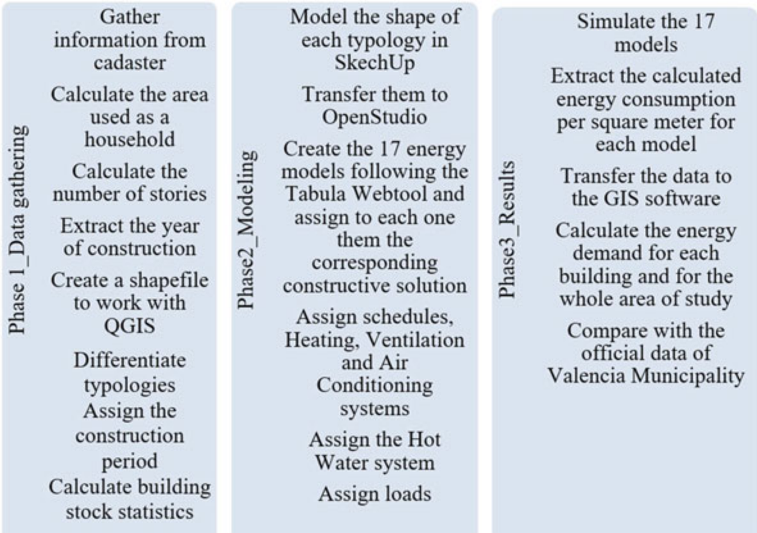


**Fig. 2** Workflow for neighbourhood energy consumption simulation

**Table 3** Results in kWh/m$^2$ of energy simulation with energy plus software

| Period/variable | VivUniAis | VivUniAdo | EdiPluri |
|---|---|---|---|
| P01 | 61.69 | 47.92 | 53.17 |
| P02 | 53.67 | 45.46 | 53.17 |
| P03 | 53.58 | 45.59 | 57.66 |
| P04 | 49.96 | 45.37 | 57.04 |
| P05 | 42.38 | 40.64 | 51.36 |
| P06 | – | 40.54 | 50.98 |

## 4 Results

The energy demand per square meter of each typology is deployed in the GIS model of the neighbourhood. The total demand for each building is then calculated as a simple multiplication of its energy demand (kWh/m$^2$) per its residential surface (m$^2$).

One correction is done after this calculation. According to the data gathered, there are some buildings that are unoccupied, so its energy demand is changed to zero.

The final energy demand for our area of study is 28,443.814, 4548 kWh/year household.

The energy demanded by residential houses and building in Valencia during 2019 is described in Table 4. There is no data for the energy demand of the studied area. It is assumed the energy demand per person is constant in Valencia. According to

**Table 4** Domestic energy consumption in Valencia 2019

| Domestic energy demand in Valencia 2019 | kWh |
|---|---|
| Electricity | 1,029,004,510.00 |
| Natural gas | 580,798,454.00 |
| Butane gas | 133,235,200.00 |
| Total | 1,743,038,164.00 |

the census of Valencia in 2019, the percentage of population of our area of study represents the 1.48% of the total inhabitants of Valencia Table 5.

The energy demand for the area of study is then 25,747,240 kWh which is lower than the simulated energy demand 28,443,814 kWh, so the simulated energy demand is 10.47% higher.

The energy demand breakdown Table 6 shows that 89% of the energy is consumed by EdiPluri building typology while the same typology represents the 91.92% of the area population. EdiPluriP04 uses about the 60% of the energy being the 64% of the population. VivUniAis demands 3.15% of the energy and accounts the 0.81% of the population. VivUniAdo practically represents the same consumption and population, 7.85 and 7.27%.

**Table 5** Percentage of inhabitants of the area of study in 2019

| | |
|---|---|
| Population of Valencia (census 2019) | 801,545 |
| Population of our area of study (census 2019) | 11,840 |
| Percentage (%) | 1.48 |
| Energy demand for studied area (Kwh) | 25,747,240 |

**Table 6** Energy consumption by building typology

| Period Variable | Simulated energy consumption (kWh/year) | | | Simulated energy consumption % of total consumption | | |
|---|---|---|---|---|---|---|
| | VivUniAis | VivUniAdo | EdiPluri | VivUniAis | VivUniAdo | EdiPluri |
| P01 | 155,089 | 173,662 | 50,405 | 0.55 | 0.61 | 0.18 |
| P02 | 351,431 | 611,437 | 389,789 | 1.24 | 2.15 | 1.37 |
| P03 | 158,650 | 854,402 | 925,328 | 0.56 | 3.00 | 3.25 |
| P04 | 93,026 | 296,085 | 16,739,928 | 0.33 | 1.04 | 58.85 |
| P05 | 137,565 | 207,548 | 3,966,276 | 0.48 | 0.73 | 13.94 |
| P06 | 0 | 90,202 | 3,242,991 | 0.00 | 0.32 | 11.40 |
| Total | 895,761 | 2,233,336 | 25,314,717 | 3.15 | 7.85 | 89.00 |

## 5 Discussion

The results presented in this paper introduce an efficient procedure for developing a fair approach to the carbon footprint evaluation of a building through an architectural analysis and energy consumption evaluation. Results from current literature analysis presented on the literature review [16–19] obtain results with similar accuracies which are difficult to implement without empirical data.

When applying the proposed digital model to a neighbourhood it is possible to simulate the performance after applying a given sustainability policy, and through this approach provide urban developers with a relevant decision-making tool.

The digital model developed can be automated and integrated on a GIS based platform for delivering good sustainability checks on future urban developments with limited resources.

A comprehensive sustainability analysis will require additional applications and evidence from parallel approaches based on artificial intelligence which, when combined with these results, will provide a complete digital twin at neighbourhood level.

A next step could also be to adapt the occupancy schedules types to the ages of the occupants of the buildings even though that the current methodology produce fairly good results.

## 6 Conclusions

Once the results obtained for "la Fonteta-la Punta-Nazaret" neighborhood in Valencia are expanded to alternative neighborhoods in other cities, the procedure will be finetuned and validated for its use as a reference.

The simulation techniques developed for energy use are valid, not only for climate control, but for other private and industrial applications separating the activity component from other fixed values corresponding to the building architectural conditions.

Statistical approaches using big-data monitoring results will definitely allow a smaller dependence on unevaluated variables.

The proposed approach can be readily used on Smart City platforms allowing cities (and companies) the possibility to develop a digital model of their assets to predict the LCA performance of refurbishment proposals.

The approach based on cadastral information allows the inclusion of future BIM projects which would facilitate the development of a complete and accurate digital model incorporating the history of the building and its maintenance. However, this future evolution will take very long to be considered at the neighbourhood level. Therefore, a refined evolution of the proposed methodology would allow a simple and solidly-based decision-making support for sustainable urban development. Model results match real performance with enough accuracy for forecasting a ranking of success of different policies.

## References


1. Peng, Y., Lai, Y., Li, X., Zhang, X.: An alternative model for measuring the sustainability of urban regeneration: the way forward. J. Clean. Prod. **109**, 76–83 (2015). https://doi.org/10.1016/j.jcle-pro.2015.06.143
2. Salat, S.: Cities and Forms, on Sustainable Urbanism. CSTB Urban Morphology Laboratory, Hermann Editeurs: Paris, France, Chapter 3, pp. 241–256 (2011)
3. Mavi, R.K., Gengatharen, D., Mavi, N.K., Hughes, R., Campbell, A., Yates, R.: Sustainability in construction projects: a systematic literature review. Sustainability **2021**, 13 (1932). https://doi.org/10.3390/su13041932
4. Kim, R., Lim, M.-K., Roh, S., Park, W.-J.: Analysis of the characteristics of environmental impacts according to the cut-off criteria applicable to the streamlined life cycle assessment (S-LCA) of apartment buildings in South Korea. Sustainability **13**, 2898 (2021). https://doi.org/10.3390/su13052898
5. Sharifi, A., Murayama, A.: A critical review of seven selected neighborhood sustainability assessment tools. Environ. Impact Assess. Rev. **38**, 73–87 (2013). https://doi.org/10.1016/j.eiar.2012.06.006
6. Bragança, L., Mateus, R., Koukkari, H.: Building sustainability assessment. Sustainability **2**, 2010–2023 (2010). https://doi.org/10.3390/su2072010
7. Bruce-Hyrkäs, T., Pasanen, P., Castro, R.: Overview of whole building life-cycle assessment for green building certification and ecodesign through industry surveys and interviews. Procedia CIRP **69**, 178–183 (2018). https://doi.org/10.1016/j.procir.2017.11.127
8. Homayouni, H., Dossick, C.S., Neff, G.: Three pathways to highly energy efficient buildings: assessing combinations of teaming and technology. J. Manag. Eng. **37**(2) (2021). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000883
9. Rehhausen, A., Hanusch, M., Fischer, T.B.: Multi-project-based strategic environmental assessment: practice in Germany. In: Handbook on Strategic Environmental Assessment (Political Science and Public Policy). Elgar on-line (2021). https://doi.org/10.4337/9781789909937
10. Obrecht, T.P., Röck, M., Hoxha, E., Passer, A.: BIM and LCA integration: a systematic literature review. Sustainability **12**, 5534 (2020). https://doi.org/10.3390/su12145534
11. Zangheri, P., Armani, R., Pietrobon, M., Pagliano, L.: Identification of cost-optimal and NZEB refurbishment levels for representative climates and building typologies across Europe. Energy Effic. **11**, 337–369 (2018). https://doi.org/10.1007/s12053-017-9566-8
12. TABULA: Webtool on EU Building Typologies. Available online: https://epi-scope.eu/building-typology/tabula-webtool/ (accessed on 4 April 2021)
13. EU Building Stock Observatory Datasets: Available online: https://data.europa.eu/eu-odp/en/data/dataset/building-stock-observatory (accessed on 4 April 2021)
14. Li, J., Wang, Y., Ni, Z., Chen, S., Xia, B.: An integrated strategy to improve the microclimate regulation of green-blue-grey infrastructures in specific urban forms. J. Clean. Prod. **271**, 122555 (2020). https://doi.org/10.1016/j.jclepro.2020.122555
15. Guinee, J.B.: Handbook on Life Cycle Assessment Operational Guide to the ISO Standards. Kluwer Academic Publishers, Amsterdam, The Netherlands (2002)
16. Wang, H., Chen, W.: Gaps between pre-2020 climate policies with NDC goals and long-term mitigation targets: analyses on major regions. Energy Procedia **158**, 3664–3669 (2019). https://doi.org/10.1016/j.egypro.2019.01.894
17. Piasecki, M.: Practical implementation of the indoor environmental quality model for the assessment of nearly zero energy single-family building. Buildings **9**, 214 (2019). https://doi.org/10.3390/buildings9100214

18. Escrivá-Escrivá, G., Álvarez-Bel, C., Peñalvo-López, E.: New indices to assess building energy efficiency at the use stage. Energy Build. **43**, 476–484 (2011). https://doi.org/10.1016/j.enbuild.2010.10.012
19. Ortega Madrigal, L., García-Prieto Ruiz, A., Serrano Lanzarote, B., Soto Francés, L.: Catálogo de tiplogía edificatoria residencial. España, Ámbito (2016)
20. Ballarini, I., Corgnati, S.P., Corrado, V.: Use of reference buildings to assess the energy saving potentials of the residential building stock: the experience of TABULA project. Energy Policy **68**, 273–284 (2014). https://doi.org/10.1016/j.enpol.2014.01.027
21. Ravetz, J.: State of the stock-What do we know about existing buildings and their future prospects? Energy Policy **36**(12), 4462–4470 (2008). https://doi.org/10.1016/j.en-pol.2008.09.026
22. Theodoridou, I., Papadopoulos, A.M., Hegger, M.: Statistical analysis of the Greek residential building stock. Energy Build. **43**(9), 2422–2428 (2011). https://doi.org/10.1016/j.enbuild.2011.05.034
23. Dascalaki, E.G., Droutsa, K., Gaglia, A.G., Kontoyiannidis, S., Balaras, C.A.: Data collection and analysis of the building stock and its energy performance—an example for Hellenic buildings. Energy Build. **42**(8), 1231–1237 (2010). https://doi.org/10.1016/j.enbuild.2010.02.014
24. Fracastoro, G.V., Serraino, M.: A methodology for assessing the energy performance of large scale building stocks and possible applications. Energy Build. **43**(4), 844–852 (2011). https://doi.org/10.1016/j.enbuild.2010.12.004
25. Swan, L.G., Ugursal, V.I.: Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. Renew. Sustain. Energy Rev. **13**(8), 1819–1835 (2009). https://doi.org/10.1016/j.rser.2008.09.03
26. García-Pérez, S., Sierra-Pérez, J., Boschmonart-Rives, J.: Environmental assessment at the urban level combining LCA-GIS methodologies: a case study of energy retrofits in the Barcelona metropolitan area. Build. Environ. **134**, 191– 204 (2018). https://doi.org/10.1016/j.buildenv.2018.01.041

# Multi-level Data Access Control in Positive Energy Districts

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**Abstract** Energy transition in the built environment requires collaborative action of interdependent actors coordinated on multiple levels of governance. Many of these actors operate in domains closely linked to a specific geographical or institutional scale, making it difficult to facilitate their collaboration. This is especially the case for positive energy districts (PED), an emergent intervention trend in the EU that requires these actors to operate on a scale with a competence vacuum in terms of governance. Actors from individual, household, building, community, city, and national scales need to be able to deliberate and work in a common discursive arena, each carrying their own goals, values, and information. In this paper, we re-imagine this discursive arena as an access-control framework to a multi-level PED database. We present a role-based model to manage interactions with data on PEDs. This includes the identification of actors expected in PED development, a specification of permission requirements based on their roles in PED, based on a PED in Austria developed under the syn.ikia Horizon project.

## 1 Introduction

The global transition towards decarbonized energy systems is increasingly characterized by a process of decentralization [1]. This creates a challenge in governance,

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as more numerous and more diverse actors gain stakes, competences, and responsibilities in transition [2]. Through decentralization, energy increasingly becomes a resource to be managed on multiple levels by interdependent actors, from households and local communities to global, international scales [3]. This means that national governments, enclosed with mechanisms ensuring their democratic legitimacy, are less relevant as an authority to provide accountability—simply because more and more decisions of consequence regarding energy happens outside centralized systems with governmental oversight [4]. If this challenge is not addressed, decisions influencing societal outcomes of the transition process will be less transparent, those responsible less accountable, weakening for example common following through on European goals like carbon neutrality or just transition [1].

This challenge is especially pertinent in the European context considering the trends to achieve transition through positive energy districts (PED) [5]. PEDs are beyond-building scale interventions targeting a net positive energy balance [6]. What is common for these projects, is that they introduce a formal or semi-formal institution between the building and the city scales, where a competence vacuum in governance currently exists [7]. In PED projects across the EU, these are either top-down, government-managed entities, aggregator businesses, or self-governing associations of multiple interdependent parties [8]. It is the latter case, where the issue of accountability could emerge. One study for example has shown, that strategic decisions to invest in public money in building energy refurbishment, renewable production, infrastructure or operational decisions to trade or allocate energy have major impact on individuals and households in and outside the PED, on the city, and on governmental efforts to enact energy transition [3].

New governance mechanisms need to be developed to address the accountability deficit in the multi-level governance of PEDs. In this paper, we propose to take an institutional technology perspective to propose a framework relying on Role-based Access Control (RBAC). The institutional technology perspective simply means that we explore governance capabilities inherent in technological—in this case computational—solutions. RBAC is a computer systems security model allocating permissions to authorized members on the basis of predefined roles [9]. In computer science, this model is widely used to provide differentiated access to shared resources in heterogeneous organizations, which is why it can be explored in multi-level energy governance as well. Thus, the main research question for this paper is: how can RBAC be used to ensure the accountability of PEDs in a multi-level energy governance context?

The rest of the paper is organized as follows: In Sect. 2, we review most relevant work in the area and show how multi-scale energy management currently lacks data access control solutions. Section 3 highlight the need for a privacy solution to protect data along multi-scale management of energy. Section 4 presents our contribution to support privacy-aware data access management along multi-scale management of energy. Finally, Sect. 5 concludes this paper.

## 2 Related Work

In this section, we review the most relevant existing research on data privacy in smart metering and Positive Energy District (PED). Several techniques have recently been proposed to ensure a privacy for smart meter users. Anonymization [10], aggregation [11], homomorphic encryption [12] and obfuscation [13] are some of the mechanisms that have been explored in the literature. In [14], the authors propose a technique to hide sensitive power consumption data. The proposed solution is based on a rechargeable battery which is connected to the household's power supply and modifies the energy consumption data by adding or subtracting noise in order to ensure privacy guarantees in the term of differential privacy. Moreover, they also consider different constraints on the rechargeable battery such as capacity and throughput.

The authors in paper [15], propose a data privacy-preserving energy management framework that protects the smart meter data privacy of consumers and minimizes the electricity bills. An online control algorithm is designed to protect the privacy-sensitive information of electricity. The proposed algorithm does not require to know the details of electricity statistics such as prices. However, the proposed solution is dependent on a rechargeable battery to protect the usage patterns of electricity consumer. Similarly, an online control algorithm to control the battery operations is presented in [10]. The proposed solution protects the data privacy of smart meter and reduce the electricity cost by using batteries. It cut down the electricity bill, without disclosing the statistics of the load requirement and the electricity prices. It has an advantage to protect the privacy of consumer's energy usage.

In [16, 17], authors ensure user's energy consumption data privacy by integrating renewable generation into energy management. The proposed solution is based on binary input and output loads to consider the energy management policies that achieve the trade-off between privacy and energy efficiency. If the battery has a higher capacity, then information leakage rate is lower. In [18], the authors provided a survey of approaches focusing on customer privacy protection in smart grids. It is important to protect the metering data from external attackers and to control how electricity suppliers or distribution system operators use this data. The results conclude that to guarantee privacy for the residents energy data should not be visible at all.

The electricity privacy issues (e.g. theft of electricity privacy data) in smart meter have been discussed in [19]. To overcome this issue, the authors proposed a Monte Carlo simulation-based approach to optimize the electricity cost and to ensure the electricity privacy protection in residential appliance demand resource energy management. The charge/discharge batteries within a fixed time slot are used to ensure electricity privacy protection. However, the battery cost is higher than the electricity bill cost. Table 1 summarizes advantages and limitations of existing work and relates to our identified research problem.

As a summary, existing solutions rely on rechargeable battery as an energy storage device to ensure data privacy in PEDs. Generally, a rechargeable battery requires a higher capacity to store the overall amount of energy data and throughput (the amount of energy that can be charged/retrieved within a given time), thus motivating research

**Table 1** Summary of related work analysis

| Refs. no | Challenge addressed | Approach | Advantages | Limitations |
|---|---|---|---|---|
| [15] | Ensure privacy of electricity consumer | Online control algorithm | It does not require prior knowledge of electricity statistics | Dependent on a rechargeable battery |
| [16, 17] | Ensure data privacy of user's energy consumption | Energy harvesting and rechargeable battery | Ensures user's energy data privacy | Require more privacy schemes; Privacy risk remain |
| [18] | Customer privacy protection in the smart grids | Customers calculate bills and ensure correctness via trusted computing | Ensures data privacy; Customer only shares final price | Need trusted third party or trusted platform to calculate bills; Lack of trust |
| [19] | Protect the electric privacy in residential appliance demand resource energy management | Monte Carlo simulation | Optimize the electricity cost; Ensure electric privacy | High battery cost |
| [10] | Ensure privacy of customer activities | Online control algorithm | Protect the privacy of consumer's energy usage | Does not work without rechargeable battery |
| [20] | Hide sensitive power consumption data | Storage device such as rechargeable battery and add noise to the data | Ensure data privacy | Requires rechargeable battery |

towards managing access to the data without any storage device. Our proposed solution enforces data security and access control without requiring such a rechargeable battery.

## 3 Motivating Scenario and Research Problem

To answer the research question, we characterize multi-level governance in PEDs as a use case for systems security design. We introduce a simplified scenario common in energy communities—pooled investment in energy assets—that highlights the challenges of database management in energy transition. The energy community model was chosen, as it involves the most decentralization of energy governance, in a form legally recognized in the EU—albeit not yet adopted by all member states [21]. Typically, energy communities formed on pre-existing social networks operate on mutual trust and make strategic decisions through direct negotiations [22]. However, to socially scale them from niche organizations, non-trusted new members, potential investors, and other stakeholders need to be involved [23]. The formal basis for their participation is increasingly some variation of performance-based contracting, and assignment of rules and responsibilities based on measurable performance indicators [24]. Performance-based contracting helps mitigating risk for involved parties by pegging their stakes to a performance that delivers value for them—for instance, a reduction of GHG emissions is valuable for a government, while a reduction of operational expenditures is valuable for investors. Investment in an energy asset, under performance-based contracts means that there has to be both a prediction, and a follow-up monitoring energy-related performance metrics. This translates to the need to collect and process all data ex ante and ex post that influences any performance corresponding to the stakes and objectives of all actors, which is why data security and privacy become relevant.

What is unique for energy transition is the structure of relationships among actors. Typically, potential stakeholders for an energy-related investment appear on multiple scales, each with their own goals and their own input data (Fig. 1). On the individual scale, occupants influence energy performance through their behavior, presence in the building, personal comfort needs, and seek reasonable energy expenditures while

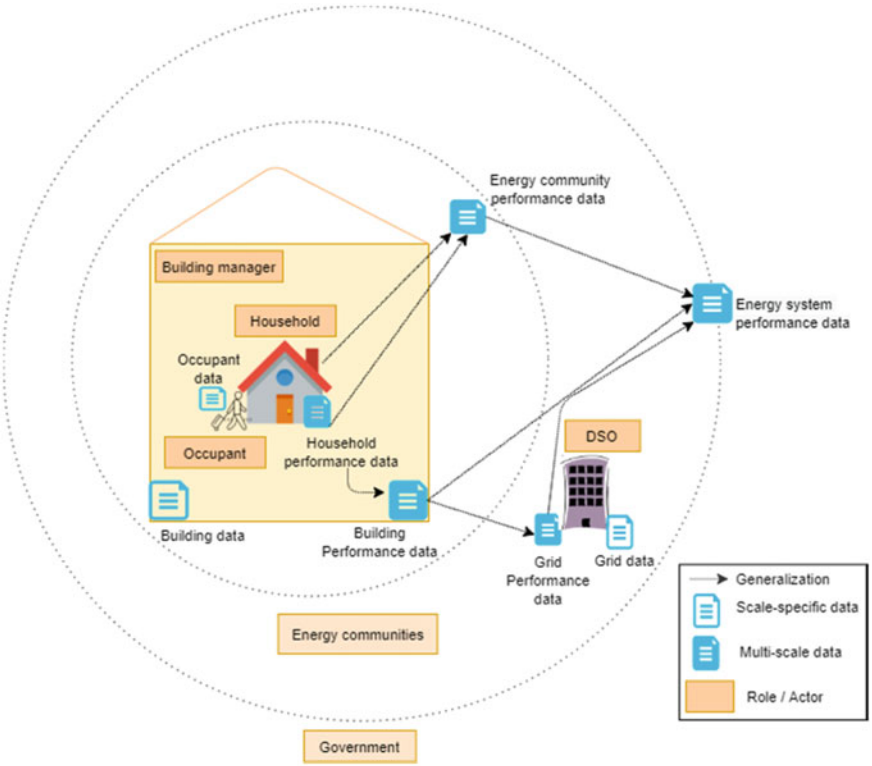


**Fig. 1** Overview of the one instance of each actor in the energy management scenario

maintaining a comfortable indoor environment. Multiple occupants form a household, that share the apartment, which is typically the unit for billing energy expenditures on the basis of their energy consumption. Households and other functional units in building are represented by building management, who seek to minimize costs while keeping dissatisfaction at reasonable levels. Multiple buildings in an energy community are connected to a microgrid, alongside energy production and storage capacities jointly owned by the community members. The community may operate in island-mode, completely independent of the energy market, but it is more common that they are connected to a larger grid. This grid is operated by a distribution service operator (DSO) that seeks to balance demand and supply to avoid grid congestion at any given time. Finally, public authorities may have two distinct roles in the investment: they provide regulatory oversight to make sure the new energy system complies to the law, and they incentivize projects with an environmental or social benefit.

In terms of data sharing, two kinds of data are expected: scale-specific, and multiscale data. Scale-specific refers to data that appears in the domain of a specific actor, while multiscale data can be (dis)aggregated across scales. For example, schedule of occupancy, appliances load, window-to-wall ratio, centralized storage capacity, network geometry, cap & trade policy are scale-specific data from individual to government scales. Energy consumption and GHG inventories on the other hand are data aggregated from individuals to national scale. The range of both types of data depends on the traded performances, i.e. the metrics upon which performance-based contracts are written on.

The goals are represented as key performance indicators, while the key metrics describe the most critical input data to calculate the KPIs.

In this simplified scenario, an energy community decides to invest in the deep energy retrofitting of their building stock, which the local government decides to financially support. Deep energy retrofit is a systemic approach to energy retrofitting, which considers multiple, interdependent interventions covering HVAC system, building envelope, building operation, on-site renewables, and other solutions to deliver multiple, energy- and non-energy benefits [25]. The scenario can be broken down to a planning and follow-up phase. During planning, community members (households) decide on how to allocate their investment funds to reduce their energy costs, while the local government prescribes a minimum share of on-site renewable energy production in exchange for support. This brings in intermittent, decentralized energy production to the local grid, which has to be balanced by a DSO. As such, the energy community makes a separate agreement to shift loads to production peaks to minimize the feed-in of energy into the grid. Note that in reality, both the energy community and the government have more objectives due to the multiple benefits of energy investment, the indicators are merely chosen for simplicity. The performance indicators and the metrics they are mainly derived from in the context of the investment are summarized in Table 2.

To make these traded relationships possible, several personal, and sensitive data must be either fed into a modelling engine (in planning phase) or monitored (in follow-up phase). These data-sharing challenges can be summarized as follows:

**Table 2** Overview of the data model of decision-making, derived from actor goals

| Actor | Key performance indicator | Key metrics |
|---|---|---|
| Occupant | Operational expenditures | Final energy consumption |
| Household | Operational expenditures | Final energy consumption |
| Building | Operational expenditures | Final energy consumption |
| Community | Internal rate of return | Savings on operational expenditures, investment size |
| DSO | Supply cover factor | Self-consumed on site production, total energy produced on site |
| Government | Renewable energy ratio | Total primary energy consumption, total energy produced on site from renewable sources |

1. Continuous personal data on occupant behavior is required to accurately calculate energy consumption on any scale, and to diagnose occupancy-related performance issues.
2. Sensitive demographic data, home appliances, and lighting loads are required to be audited once before investment and whenever they change in the follow-up phase to calculate energy consumption on any scale. The latter two are at the discretion of the household, while the former is personal.
3. Building management is a trusted third party that manages metered data, and information on the building systems. Building managers should be accountable to households, but they must follow professional standards in handling building data, meaning scale-specific data should be accessible for households.
4. Energy community is an organization pooling competences and responsibilities of households. Their collective, negotiated decision-making defines the rules of data management, but these should be accountable to each household, meaning scale-specific data should be accessible for households.
5. The community and the DSO and the community and the government are in bilateral relationships, where the community has compliance reporting responsibilities. Both the DSO and the government may challenge the reporting, to which an arbitration mechanism must exist.

Our scenario highlights the need for access management to privacy-sensitive data, while at the same time allowing actors on different scales to use that data for their activities—meaning for example that DSOs should be able to monitor energy production in energy communities to some extent. However, our multi-scale energy management scenario highlights that actors need to protect their privacy-sensitive data from unauthorized access. There is a need to design a solution that enforces security on data and guarantee that it is not possible to access all energy data and customer statistics from it. Therefore, based on our scenario, our solution must provide fine-grained access control as data can be accessed according to the identified role. In the following, we identified the following scientific locks (SL) that rise from our scenario and the goals of the actors discussed above:

**SL1: Fine-grained access control**: actors' actions on energy data should be managed using access control models. The proposed solution should ensure data privacy and protect privacy-sensitive data from unauthorized access.

**SL2: Data security**: data must be prevented from unauthorized access through encryption mechanisms. The proposed framework must ensure that data must not be available to unauthorized users.

To answer these scientific locks, we propose a solution that combines relevant technologies in a single framework. We provide an overview our proposed framework with the help of our motivating scenario.

## 4 Conceptual Framework

In this paper, we propose a privacy-aware data management framework to support multi-scale energy management. This framework combines RBAC with multiple types of encryption mechanisms as depicted in Fig. 2.

### *4.1 RBAC Component*

First, our framework answers SL1 using a RBAC model to provide authorized access to the data. The RBAC model is comprised of following parameters: user, role, and permission. In a RBAC model users are actors collaborating on energy management/investment. Roles are fixed sets of permissions regulating access to the data. A permission is an authorization to access different levels of data within the specific scenario. For multi-level energy governance, the following users, roles, resources and permissions are proposed.

- **Users**: In our framework, users are the actors corresponding to multiple levels of energy management. Specifically, occupant, household, building manager, community manager, DSO, and government.
- **Roles**: Roles are defined based on the interactions user must have with the data to perform their duties.

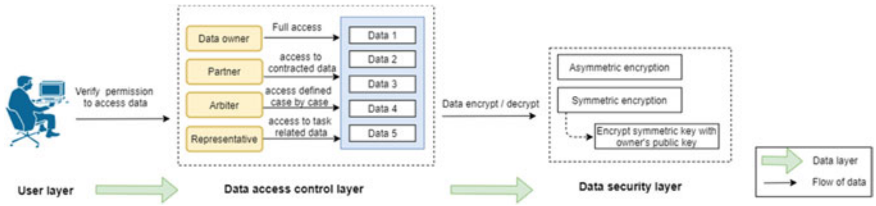


**Fig. 2** Overview of our conceptual framework

- *Data owner*: Each user is an owner to the data originating on their level. For instance, an occupant owns thermal comfort preferences (e.g. 19–24 °C on weekdays between 6 a.m. and 9 a.m.), or a DSO owns data on overall grid balance (e.g. + 10.8 kWh energy surplus on day of interest).
- *Partner*: partners have limited access to data that is specified in the contract regulating the partnership. Partners access data specifically to hold each other accountable and to monitor contractual obligations. The DSO and the government are both partners to the energy community. The government can, for example access data to check whether the community complies to its green energy targets (e.g. 50% of consumption met by local renewable sources on day of interest).
- *Arbiter*: the arbiter role defines a trusted third party for the purpose of conflict resolution between contracted partners. They can decide the scope of their data access on a case-by-case basis, if the scope is justifiably needed for arbitration. Thus, the parties in conflict should be able to see what the arbiter accessed, and why in order to contest it. The arbiter has access as long as its mandate dictates. For example, a civil court could access household-level energy consumption (e.g. 24.0 kWh in hour of interest) if the DSO contests the validity of an aggregated energy consumption reported by the community.
- *Representative*: On some levels there are no autonomous entities, because they represent a collective of lower-level actors. Specifically, building managers and managers of energy communities are appointed by households and carry out the collective decisions of multiple households. As such, they assume a representative role when accessing energy-related data, which means they can access data from lower levels that is necessary for them to carry out their tasks. However, a representative access must always be anonymous, and disaggregated only to the extent their task demands. For example, a building manager can access schedules of occupants (e.g. 80% probability of being at home in hour of interest) to calculate day-ahead energy demand for the whole building.

- **Resources**: resources in this scenario refer to the data generated on each level. In this sense, we define occupant data (e.g. schedules, and comfort preferences), household data (e.g. home appliance performance data), building data (e.g. thermal properties of the building constructions), community data (e.g. total energy produced per day), and grid data (e.g. daily grid balance).
- **Permissions**: permissions are restrictions assigned to each role to interact with resources, i.e. with data on different levels. For example, a DSO user, under the role of partner, can access hourly energy production data (0.35 kWh in hour of interest) of the energy community if it is stated in their contract.
- **Rules and policie**s: rules and policies are in place to control access to data by defining how the RBAC assigns roles to users. In the case of the data owner, this assignment is an authentication of the existence of the data owner role for that specific user, and a verification of permission to access owned data. For other roles, there is an additional step to specify permissions using an access policy, which is unique for each role.

- *Partner access policy*: the partner permissions are specified in the contract approved all engaged parties. For example, in our scenario, a government invests in an energy community if it maintains a quota for producing renewable energy. Then, the access policy adds renewable energy production to the list of permissions of the government.
- *Arbiter access policy*: an arbiter specifies its own permissions if an arbitration process is initiated. For example, the government suspects the energy community overestimates their renewable energy production and a court is involved to investigate. To do so, they decide to need detailed technical data on production equipment, as well as household-level consumption data. The access policy is then adding these requests to the list of permissions to the court, for a limited time period.
- *Representative access policy*: representative permissions are specified by the task they carry out, as given by the collective decisions of the actors they represent. For example, if households in an energy community decide to expand their production capacities to meet their energy demand in peak hours, the community manager would have to know what the peak demand is. The access policy adds peak demand to the list of permissions, as parsed from the community decision.

## *4.2 Encryption Mechanisms*

Second, we address SL2 by using multiple types of encryption mechanisms to enforce security on the data. Our proposed framework design is flexible to allow actors to choose either asymmetric or symmetric encryption method for each data write/read operation. Asymmetric encryption method is comprised of the public and private key pair. A public key is available publicly to encrypt the data, while the private key is only accessible to the key's owner for corresponding data decryption. In our scenario, an actor as a data owner chooses the asymmetric encryption method, then energy data will be encrypted with the data owner's public key. Later, the data owner can access/decrypt this data using the corresponding private key. This can be used for example to ensure that only household can access to their own data.

On the other hand, symmetric key is based on a single key for encryption and decryption. In our scenario, the data owner chooses the symmetric method to allow other actors to read this data upon request. Data owner will encrypt the data by using a symmetric key which will again be encrypted by using the data requester's public key. This way only the data requester can access it later for decryption. This can be used for example to share building-level, or community-level energy performance data with the households.

## 5 Discussion and Conclusion

In this paper, we illustrate the need for privacy-aware data access control in multi-scale energy management scenario that presents the challenges of this application domain, before discussing related scientific locks. We propose a framework that relies on a combination of role-based access control model and multiple types of encryption mechanisms that enable only authorized actors to access their data. We described advantages and limitations of existing work to highlight the research gap. The limitation of existing work is rechargeable battery that requires higher throughput and capacity to store the energy data.

To the best of our knowledge, our research is the first work that integrates this combination of technologies with PEDs and ensures data security and access control without requiring such a rechargeable battery.

One serious shortcoming of the proposed framework is reliance on a trusted third party to adjudicate conflicts regarding the data. While this limitation may be addressed by combining other technologies once data enters the system (see the following paragraph for future work), tamper-proofing on the sensor, or input side is still necessary to fully eliminate third party involvement. Also, the presented concept is based on the premise of data-based regulation of dynamic relationships, in the form of performance-based contracts. It is thus assumed to be relevant for smart grids, where the maturity of the information system allows and the degree of decentralization necessitates this degree of regulation. While the scenario presented describes a smart power grid, the advent of fifth generation district heating, distributed geothermal energy, and heat pumps does suggest direction towards smart thermal grids [26], where the same framework is applicable.

In future work, we will explore different options for decentralized data management such as blockchain or distributed hash table. Further work can be extended to different access control model e.g. attribute-based access control model, rule-based access control model, mandatory-access control model. Further work can compare what are the advantages and disadvantages of access control model as thy are being developed continuously. Our framework has TTP as an arbiter and we can eliminate it by using decentralized database such as blockchain, and we have a plan to work on it for our next paper. Cost action can help by providing case study and projects for validation of the concept and further development of the framework in real life scenario.

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## References


1. International Energy Agency I World Energy Outlook (2018)
2. Goldthau, A.: Rethinking the governance of energy infrastructure: scale, decentralization and polycentrism. Energy Res. Soc. Sci. **1**, 134–140 (2014). https://doi.org/10.1016/j.erss.2014.02.009
3. Brisbois, M.C.: Decentralised energy, decentralised accountability? Lessons on how to govern decentralised electricity transitions from multi-level natural resource governance. Glob. Trans. **2**, 16–25 (2020). https://doi.org/10.1016/j.glt.2020.01.001
4. van Kersbergen, K., van Waarden, F.: “Governance” as a bridge between disciplines: cross-disciplinary inspiration regarding shifts in governance and problems of governability, accountability and legitimacy. Eur. J. Polit. Res. **43**, 143–171 (2004). https://doi.org/10.1111/j.1475-6765.2004.00149.x
5. European Commission: The Strategic Energy Technology Plan—At the Heart of Energy Research and Innovation in Euro. Luxembourg (2018)
6. Bossi, S., Gollner, C., Theierling, S.: Towards 100 positive energy districts in Europe: preliminary data analysis of 61 European cases. Energies **13**, 6083 (2020). https://doi.org/10.3390/en13226083
7. Bukovszki, V., Balázs, R., Mafé, C., Reith, A.: Six lessons learned by considering social sustainability in plus-energy neighbourhoods. In: Waltjen, T. (ed.) In the Neighbourhood. Vienna Congress on Sustainable Building, pp. 26–28. IBO Verlag, Vienna (2021)
8. Gollner, C., Hinterberger, R., Bossi, S., et al.: Europe Towards Positive Energy Districts—A Compilation of Projects Towards Sustainable Urbanization and the Energy Transition (2020)
9. Kashmar, N., Adda, M., Atieh, M.: From access control models to access control metamodels: a survey. In: Lecture Notes in Networks and Systems, pp. 892–892. Springer, Berlin (2020)
10. Yang, L., Chen, X., Zhang, J., Poor, H.V.: Optimal privacy-preserving energy management for smart meters. In: Proceedings—IEEE INFOCOM. Institute of Electrical and Electronics Engineers Inc., pp. 513–521 (2014)
11. Efthymiou, C., Kalogridis, G.: Smart Grid Privacy via Anonymization of Smart Metering Data, pp. 238–243. Institute of Electrical and Electronics Engineers (IEEE) (2010)
12. Bohli, J.M., Sorge, C., Ugus, O.: A privacy model for smart metering. In: 2010 IEEE International Conference on Communications Workshops, ICC 2010 (2010)
13. Garcia, F.D., Jacobs, B.: Privacy-friendly energy-metering via homomorphic encryption. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 226–238. Springer, Berlin, Heidelberg (2011)
14. Kim, Y., Ngai, E.C.H., Srivastava, M.B.: Cooperative state estimation for preserving privacy of user behaviors in smart grid. In: 2011 IEEE International Conference on Smart Grid Communications, pp. 178–183. SmartGridComm 2011 (2011)
15. Yang, L., Chen, X., Zhang, J., Poor, H.V.: Cost-effective and privacy-preserving energy management for smart meters. IEEE Trans. Smart Grid **6**, 486–495 (2015). https://doi.org/10.1109/TSG.2014.2343611
16. Tan, O., Gunduz, D., Poor, H.V.: Increasing smart meter privacy through energy harvesting and storage devices. IEEE J. Sel. Areas Commun. **31**, 1331–1341 (2013). https://doi.org/10.1109/JSAC.2013.130715
17. Koo, J., Lin, X., Bagchi, S.: PRIVATUS: wallet-friendly privacy protection for smart meters. In: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 343–360. Springer, Berlin, Heidelberg (2012)
18. Finster, S., Baumgart, I.: Privacy-aware smart metering: a survey. IEEE Commun. Surv. Tutor. **17**, 1088–1101 (2015). https://doi.org/10.1109/COMST.2015.2425958
19. Chen, Z., Wu, L.: Residential appliance DR energy management with electric privacy protection by online stochastic optimization. IEEE Trans. Smart Grid **4**, 1861–1869 (2013). https://doi.org/10.1109/TSG.2013.2256803

20. Backes, M., Meiser, S.: Differentially private smart metering with battery recharging. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 194–212. Springer, Berlin (2014)
21. Lowitzsch, J., Hoicka, C.E., van Tulder, F.J.: Renewable energy communities under the 2019 European clean energy package—governance model for the energy clusters of the future? Renew. Sustain. Energy Rev. 122 (2020). https://doi.org/10.1016/j.rser.2019.109489
22. Moroni, S., Alberti, V., Antoniucci, V., Bisello, A.: Energy communities in the transition to a low-carbon future: a taxonomical approach and some policy dilemmas. J. Environ. Manage. **236**, 45–53 (2019). https://doi.org/10.1016/j.jenvman.2019.01.095
23. Bukovszki, V., Magyari, Á., Braun, M.K., et al.: Energy modelling as a trigger for energy communities: a joint socio-technical perspective. Energies **13**, 2274 (2020). https://doi.org/10.3390/en13092274
24. Marino, A., Bertoldi, P., Rezessy, S., Boza-Kiss, B.: A snapshot of the European energy service market in 2010 and policy recommendations to foster a further market development. Energy Policy **39**, 6190–6198 (2011). https://doi.org/10.1016/j.enpol.2011.07.019
25. Lohse, R., Zhivov, A.: Deep Energy Retrofit Guide for Public Buildings. Springer International Publishing, Cham (2019)
26. Stănişteanu, C.: Smart thermal grids—a review. Sci. Bull. Electr. Eng. Faculty (2017). https://doi.org/10.1515/sbeef-2016-0030

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