Journal of Building Engineering 45 (2022) 103485

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

A parallel computing simulation-based multi-objective optimization framework for economic analysis of building energy retrofit: A case study in Iran

Mehdi Tavakolan, Ph.D., Farzad Mostafazadeh *, Saeed Jalilzadeh Eirdmousa, Amir Safari, Kaveh Mirzaei

Dept. of Construction Engineering and Management, School of Civil Engineering, Faculty of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran

A R T I C L E I N F O

Keywords:
Building energy retrofit
Multi-objective optimization
Parallel computing
Energy efficiency
Genetic algorithm
Energy pricing policy

A B S T R A C T

The building sector represents a large share of rising global energy demand. Improving energy efficiency in existing building stock is a crucial strategy. Adopting the best energy retrofitting strategy in a specific building is a challenging task due to a plethora of possible combinations of retrofit measures and mutually contrasting objective functions. In addition, peculiar conditions of Iran, such as extremely subsidized energy prices, and step utility tariffs, escalate the challenges of building energy retrofit. Accordingly, the current study presents a simulation-based multi-objective optimization framework characterized by parallel processing structure and results-saving archive. The framework is implemented by integrating MATLAB® as an optimization engine with EnergyPlus as a dynamic energy simulator to minimize primary energy consumption and discounted payback period while maximizing the net present value. The algorithm explores a vast domain of possible solutions including, building envelope, cooling and heating systems, and renewable energy sources. The framework is applied to a single-family residence located in Iran. Three different scenarios are examined with reference to prospective energy pricing policies to evaluate their effect on the attractiveness of energy retrofit projects. For each scenario, final solutions are selected from respective Pareto fronts according to cost-optimality and energy-efficiency criteria and considering budget constraints. The results indicate that even though significant reductions in primary energy consumption can be achieved, implementing energy retrofit under the current energy pricing policy in Iran would not yield economic benefits. However, the elimination of subsidies along with offering incentives for building energy retrofits presents promising outcomes.

Nomenclature

Symbols

c_i^j	cost of implementing the *i*th type of decision variable with the *j*th alternative measure
COP	coefficient of performance
dEC	present value of saving electricity ($)
dEC_1	difference in electricity cost in the first year between the base case and retrofitted building ($)
dGC	present value of saving natural gas ($)
dGC_1	difference in natural gas cost in the first year between the base case and retrofitted building ($)
DPP	discounted payback period (year)
EER	energy efficiency ratio
i	discount rate
ie	inflation rate of energy price
I	total number of retrofitting measures types
IC	investment cost ($)
J	total number of potential options for retrofitting measure of *i*th type

* Corresponding author.
E-mail addresses: mtavakolan@ut.ac.ir (M. Tavakolan), farzadmostafazade@ut.ac.ir (F. Mostafazadeh), saeed.jalilzadeh@ut.ac.ir (S. Jalilzadeh Eirdmousa), safari.amir@ut.ac.ir (A. Safari), kaveh.mirzaei@ut.ac.ir (K. Mirzaei).

https://doi.org/10.1016/j.jobe.2021.103485
Received 15 August 2021; Received in revised form 4 October 2021; Accepted 16 October 2021
Available online 28 October 2021
2352-7102/

k_i^j	binary number for implementing measure
n	project service time (year)
PEC	primary energy consumption (kWh)
PEC_0	primary energy consumption of baseline building (kWh)
r	difference between the discount rate and the inflation rate
RE	present value of renewable energy production income ($)
RE_1	potential renewable energy production income in the first year ($)
R_t	net cash flow at time t
SHGC	Solar heat gain coefficient
t	time of the cash flow
x	vector of decision variables
X	feasible set of decision vectors
η	efficiency of heating system

Acronyms

DHW	domestic hot water
GSHP	ground source heat pump
HVAC	heating, ventilation, and air conditioning
LCC	life cycle cost
NPV	net present value
NSGA-II	non-dominated sorting genetic algorithm-II
PV	photovoltaic
TVM	time value of money

1. Introduction

The increasing global energy demand over the past decades and the limitation of non-renewable energy resources have led to numerous problems such as global warming escalation, air pollution, and energy market instability. Consequently, countries have focused on improving energy efficiency to tackle this critical issue. The U.S. Energy Information Administration (EIA) projects the energy consumption of the world to rise by nearly 50% between 2018 and 2050 [1]. The bulk of this growth stems from countries that are not in the Organization for Economic Cooperation and Development (OECD), such as Iran. A study by Moshiri et al. [2] forecasted that total energy demand in Iran will double by 2030, growing on average 2.8% per year under the Business-As-Usual scenario. The energy intensity index (measured in terms of primary energy per GDP) of Iran is one of the highest in the world, increasing from 0.145 to 0.173 toe/1000 USD between 2000 and 2017. However, during the same period, the energy intensity in the world decreased from 0.158 to 0.119 toe/1000 USD [3]. The high energy intensity index of Iran can generally be attributed to behavioral patterns of occupants, sub-standard facilities, and most importantly, excessive energy subsidies provided by the government. As shown in Fig. 1, in 2018, Iran ranked 1st in terms of energy subsidies in the world [4]. These subsidies are intended to reduce the energy price for end-users; however, they have been inherently contributing to increased energy consumption in different sectors such as buildings.

Buildings are responsible for roughly 40% of global energy consumption [5]. Therefore, pursuing energy efficiency in the building sector can positively impact the environment and economy [6]. Nowadays, in the design and construction of new buildings, efforts are being made to optimize operational energy consumption by implementing green building principles. However, existing building stock is obsolete and has high energy consumption. On the other hand, the replacement rate of existing buildings with new buildings is about 1–3% per year [7]. Hence, in order to reduce global energy consumption and promote sustainability in a timely manner, it is necessary to reduce energy consumption in existing buildings. Energy retrofit is the operational or physical changes in a building itself, occupants behavior, or equipment that enhances building energy performance [8], which is considered the most cost-effective and feasible solution to reduce energy use intensity (EUI) levels in building stock [9].

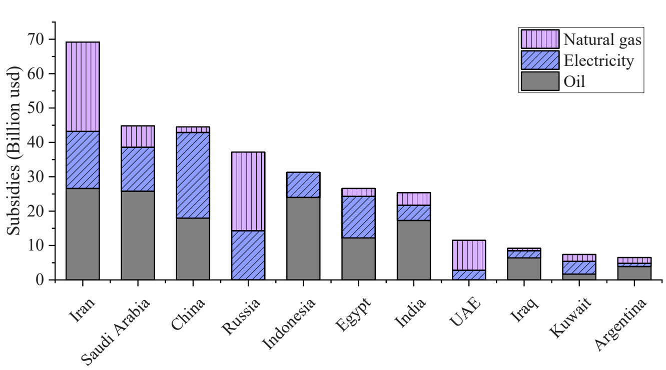

Fig. 1. Value of fossil-fuel subsidies by fuel, 2018.

The main challenge in building energy retrofitting is finding the best combination of energy efficiency measures among a wide range of available strategies. To propose an optimum solution, the project team should provide stakeholders with a detailed economic evaluation of the project. Therefore, a framework that can facilitate energy efficiency calculations and provide investors with clear insight into the economic benefits of energy retrofit projects can be worthwhile [10].

Furthermore, energy retrofitting measures are not independent but rather interact, meaning implementing one measure might significantly affect another one [8]. Therefore, to estimate the result of implementing an energy retrofit package, it is not accurate to sum up the effect of individual measures linearly. Consequently, building energy simulation must be performed to factor in the interaction of the various energy efficiency measures.

Additionally, a tremendous number of possible combinations of energy efficiency measures practically renders an exhaustive search coupled with whole building simulation unfeasible. To be more specific, given the time required to simulate building energy performance of a particular combination of measures, a detailed evaluation of all possible solutions is not computationally viable. Accordingly, to tackle this challenge, optimization algorithms such as genetic algorithms can be adopted to find optimal solutions promptly [11–13].

Finally, it is highlighted that energy retrofitting projects are a trade-off between the initial investment and the benefits obtained from improving buildings energy performance [14]. These benefits can be categorized into environmental, economic, and social benefits [8]. Implementing an energy efficiency measure can conversely affect the abovementioned targets. Therefore, to achieve a satisfactory trade-off among contradictory objectives, a multi-objective optimization framework should be implemented [15,16].

2. Literature review

The importance of energy efficiency in different aspects of society has encouraged researchers to pay immense attention to this issue and conduct extensive research in this area. The following lines review the existing literature in the field of energy efficiency.

2.1. Decision-making model

In an energy efficiency decision-making process, there can be numerous combinations of potential energy efficiency measures depending on the number of decision variables. Decision-making models can be classified into three approaches: scenario-based, exhaustive search, and optimization algorithms [17,18]. In the scenario-based approach, only limited combinations of energy efficiency measures are considered. This approach's advantage is that it requires less computational time, but it necessarily would not result in the best possible combination [19,20].

Another approach is an exhaustive search that explores all possible solutions [21]. However, the main disadvantage of this approach is that integrating the search process with energy simulation would require tremendous computational time; thus, only limited options for each decision variable can be explored. Therefore, several studies have adopted heuristic algorithms such as the Genetic Algorithm (GA) to solve the optimization problem faster and more efficiently [11,17,22–34]. Applying the proper optimization method depends on the search approach and the factors that are involved.

Different objective functions can be considered for a building retrofits project. These objective functions can be generally categorized into three groups: economic, environmental, and social. Diakaki et al. [35] developed a multi-objective decision-making model using Mixed-integer programming for minimizing energy consumption, initial investment cost, and annual CO2 emissions. Kusiak et al. [36] modeled a heating, cooling, and ventilation system in the office building and optimized the HVAC systems using the multi-objective particle swarm optimization algorithm for reducing energy consumption and increasing thermal comfort. Kerdan et al. [37] developed a model for optimization using the NSGA (non-dominated sorting genetic algorithm) II. In this model, the net present value, energy consumption, and the thermal comfort of a building's occupants are considered as objective functions.

In this research, a multi-objective optimization coupled with an energy simulation framework characterized by parallel processing and result saving archive is implemented to reach optimum results expeditiously.

2.2. Energy performance assessment

The purpose of building energy simulation is to analyze the baseline model and have a reliable assessment of the benefits of different retrofitting decisions [38,39]. Simulation of building energy performance can be carried out through two general methods: static methods, also known as mathematical methods, and dynamic methods, using simulation software [8]. Murray et al. [40] presented a degree-days simulation as a static method coupled with a genetic algorithm to achieve optimal retrofit solutions. Rosti et al. [41] determined optimal insulation thickness of exterior walls in different climate zones using a mathematical method for building energy performance simulation.

Dynamic modeling considers different parameters and factors affecting the performance of buildings and their interactions. Nevertheless, performing dynamic energy simulations is more time-consuming than static modeling. Mauro et al. [42] presented a simulation-based optimization model using EnergyPlus [43] as a simulation engine to investigate the cost optimality of energy retrofitting a representative building sample. Ferrara et al. [44] used TRNSYS for energy simulation and GenOpt and MATLAB [45] for the optimization process. Fesanghary et al. [46] presented a model to reduce the life cycle cost of building and carbon dioxide emissions using EnergyPlus for simulation and the Harmony Search algorithm (HS) for optimization.

In this research, EnergyPlus is used as a simulation engine for multi-objective optimization, and DesignBuilder [47] is used as a graphical user interface (GUI) to create a baseline building model.

2.3. Economic evaluation

For an accurate economic evaluation of energy retrofit projects, the life cycle cost analysis (LCCA) methods should be used [48]. The net present value method, which calculates the difference between the present value of the cash inflow and outflow, has been employed in several studies. Kumbaroglu and Madlener [49] presented a method to identify optimal solutions by maximizing the net present value in a case study office building located in Germany. Ruparathna et al. [50] presented a new method to calculate the life cycle cost based on the fuzzy set theory.

Another useful metric in economic decision-making is the payback period, which is the time required for a project to recover its investment cost in terms of profits or savings [51]. Wang et al. [9] proposed a multi-objective optimization using a differential evolution (DE) algorithm to minimize energy consumption and the payback period and maximize NPV. Malatji et al. [10] proposed a multi-objective optimization model to minimize energy consumption and the payback period.

In this research, to determine the economic viability of the energy retrofit projects, net present value and discounted payback period are incorporated into a simulation-based multi-objective optimization framework.

2.4. Energy efficiency studies in Iran

A large number of existing buildings in Iran that do not comply with energy efficiency codes [52] have raised serious concerns over the future of the energy market, which indicates the need for further research on improving the energy efficiency. It is highlighted that most of the studies in the field of multi-objective optimization for building retrofit have been applied to case studies in Europe, America, and East Asia, where energy prices are relatively high. However, their results are not applicable to countries such as Iran. Mirzaei et al. [27] developed a multi-objective optimization framework by coupling EnergyPlus and NSGA-II through jEPlus software to minimize energy consumption, life cycle cost, and thermal discomfort of a residential building in Iran. Tahsildoost and Zomorodian [53] conducted an experimental study that retrofitted two typical school buildings in Iran, by prioritizing scenarios based on energy simulation. Balali et al. [54] aimed to identify and prioritize energy reduction measures in existing and historic buildings in Iran by conducting experts interviews. Javid et al. [55] proposed a multi-objective optimization framework to minimize the economic costs and global warming potential (GWP) impacts of two educational buildings in Iran. Table 1 summarizes some of the previous studies concerning building energy efficiency.

2.5. Contributions and aim of the current study

Achieving the robust assessment of energy retrofit measures is a complex process due to a huge number of possible combinations of energy efficiency measures and also mutually opposed objective functions. The existing literature proposes simulation-based optimization algorithms to achieve higher robustness in comparison to the exhaustive searches by performing a smart search in a reasonable time. However, even simulation-based optimization algorithms require investigating a large number of options to guarantee convergence. Thus, the total optimization time is still significant. As a consequence, applying the simulation-based approaches detailed in the existing literature to different building categories is not practical due to the computational burden. To tackle this issue, parallel processing can be used instead of traditional optimization methods. The current study proposes a simulation-based multi-objective optimization framework characterized by parallel processing capability that enables performing simultaneous simulations. Additionally, a result-saving archive is integrated into the framework, which further reduces the required computational burden by preventing the repetition of simulations. The framework enables taking full advantage of high-tech multi-processors, as opposed to traditional simulation-based approaches, thereby allowing enhanced robust assessment of energy retrofit projects by exploring a wider domain of solutions expeditiously.

Furthermore, building energy retrofit projects in Iran face additional challenges due to the country's peculiar characteristics, notably highly subsidized energy prices, step utility tariffs. Despite the significant contribution of previous studies, to the best of our knowledge, there is no study that (1) provides a comprehensive framework for analyzing

Table 1
Summary of literature concerning building energy optimization.

Ref	Year	Optimization Tool	Method	Objective functions	Decision Variables
[35]	2010	Lingo	Mixed-integer combinatorial optimization problem	- Min CO2 emission - Min Initial Investment Cost - Min Energy Consumption	Envelope characteristics (wall, roof, and window), HVAC systems
[56]	2012	GenOpt, MATLAB	Tchebycheff programming	- Min CO2 Emission - Min Initial Investment Cost - Max Thermal Comfort	Envelope characteristics
[57]	2011	EnergyPlus, MATLAB	Regression Analysis	- Min Payback Period	Envelope characteristics (wall, roof, and window), HVAC systems
[10]	2013	EnergyPlus, MATLAB	GA	- Min Payback Period - Min Energy Consumption	Envelope characteristics (wall, roof, and window), HVAC systems
[8]	2017	EnergyPlus, MATLAB	GA	- Min Energy Consumption - Min LCC	Envelope characteristics (wall, roof, and window), HVAC systems, lighting systems
[9]	2014	TRNSYS, GenOpt	Differential Evaluation	- Max NPV - Min Energy Consumption	Envelope characteristics (wall, roof, and window), HVAC systems, lighting systems
[49]	2012	Monte Carlo	–	- Min LCC	Envelope characteristics (wall, roof, and window), HVAC systems
[58]	2014	LCA	Mixed-integer linear programming	- Min LCC - Min Environmental Impacts	Envelope characteristics (wall, roof, and window)
[20]	2017	EnergyPlus	–	- Min Energy Consumption	Envelope characteristics (wall, roof, and window)
[59]	2017	LIDER	–	- Min Heating and Cooling Consumption - Max Thermal Comfort	Envelope characteristics (wall, roof, and window), HVAC systems
[50]	2017	LCA	Fuzzy based approach	- Min LCC	Envelope characteristics (roof), HVAC systems
[60]	2017	EnergyPlus	NSGA-II	- Min Energy Consumption	Windows size, insulation thickness
[61]	2016	LCA, EnergyPlus, Sensitivity Analysis	–	- Min LCC - Min Environmental Impacts	Envelope characteristics (wall, roof, and window)
[40]	2014	Degree-days simulation	GA	- Min Energy Costs - Min CO2 Emission - Min Payback Period	Envelope characteristics (wall, roof, and window), HVAC systems
[62]	2013	EnergyPlus, Monte Carlo	GA	- Min Payback Period - Min GHG Emission	Envelope characteristics (wall, roof, and window), HVAC systems
[63]	2016	Decision Support System	GA	- Min Energy Consumption	Envelope characteristics (wall, roof, and window), HVAC systems, lighting systems
[64]	2015	EnergyPlus, MATLAB	Sensitivity Analysis	- Min Heating and Cooling Energy Consumption - Max Thermal Comfort	Envelope characteristics (wall, roof, and window), HVAC systems
[42]	2017	Monte Carlo	Sensitivity Analysis	- Min LCC - Min Energy Consumption	Envelope characteristics (wall, roof, and window), HVAC systems, renewable energy

economic outcomes of building energy retrofits based on a simulation-based multi-objective approach that is capable of addressing peculiar economic conditions of Iran and other similar countries (2) Investigates the impact of a possible change in governmental energy pricing policies on the results of an energy efficiency project.

This study aims to develop a comprehensive simulation-based multi-objective optimization framework to address the economic and environmental aspects of energy retrofit projects. The algorithm investigates a large domain of possible energy efficiency solutions, including heating and cooling systems, building envelope, and renewable energy sources, to minimize primary energy consumption and discounted payback period while maximizing the net present value. These objective economic functions are selected to maintain the balance between total earnings by the end of building service life and the time required to achieve a break-even point, providing investors with clear insight into potential economic outcomes. Additionally, the framework is tailored to function under the peculiar economic characteristics of Iran and is capable of calculating economic objective functions with step utility tariffs. The framework features a parallel processing structure as well as a result-saving archive that dramatically enhances the efficiency of the optimization algorithm.

The proposed framework is applied to a single-family residence in Iran. Three different scenarios are investigated with reference to the current state of energy pricing policies and possible changes enhancing the viability of energy retrofit projects. In the first scenario, the optimization is performed by considering the current state of energy pricing policies of Iran, characterized by highly subsidized energy prices and step utility tariffs. The second scenario investigates the prospect of the elimination of energy subsidies and rising energy prices to match global rates. In the third scenario, the impacts of offering assumptive low-interest loans as an economic incentive for building energy retrofit are evaluated.

To put it briefly, the salient original contributions of the present study to the body of knowledge reside in the following:

- Application of parallel computing and result-saving archive to address the prohibitive computational burden of simulation-based optimization of building energy retrofit leading to enhanced robustness.
- Developing an economic framework based on the discounted payback period and net present value methods, tailored to function under peculiar economic conditions of Iran (step utility pricing and high subsidies).
- Evaluation of current and potential energy pricing policies and the impact of eliminating subsidies on building performance optimization, which provides new information to Iranian policymakers regarding modification of current policies to encourage investment in building energy retrofit projects.
- Application of the framework to a real residential building and providing precious guidelines for energy retrofit projects in Iran with reference to energy efficiency and cost-effectiveness. It also can be valuable in countries similar to Iran with low energy prices.
- All of the above considered together.

This study consolidates and expands previous research by providing an efficient framework for economic analysis of energy retrofit projects, particularly for buildings located in Iran. The outcomes of the investigated scenarios could support the country's macro-level management

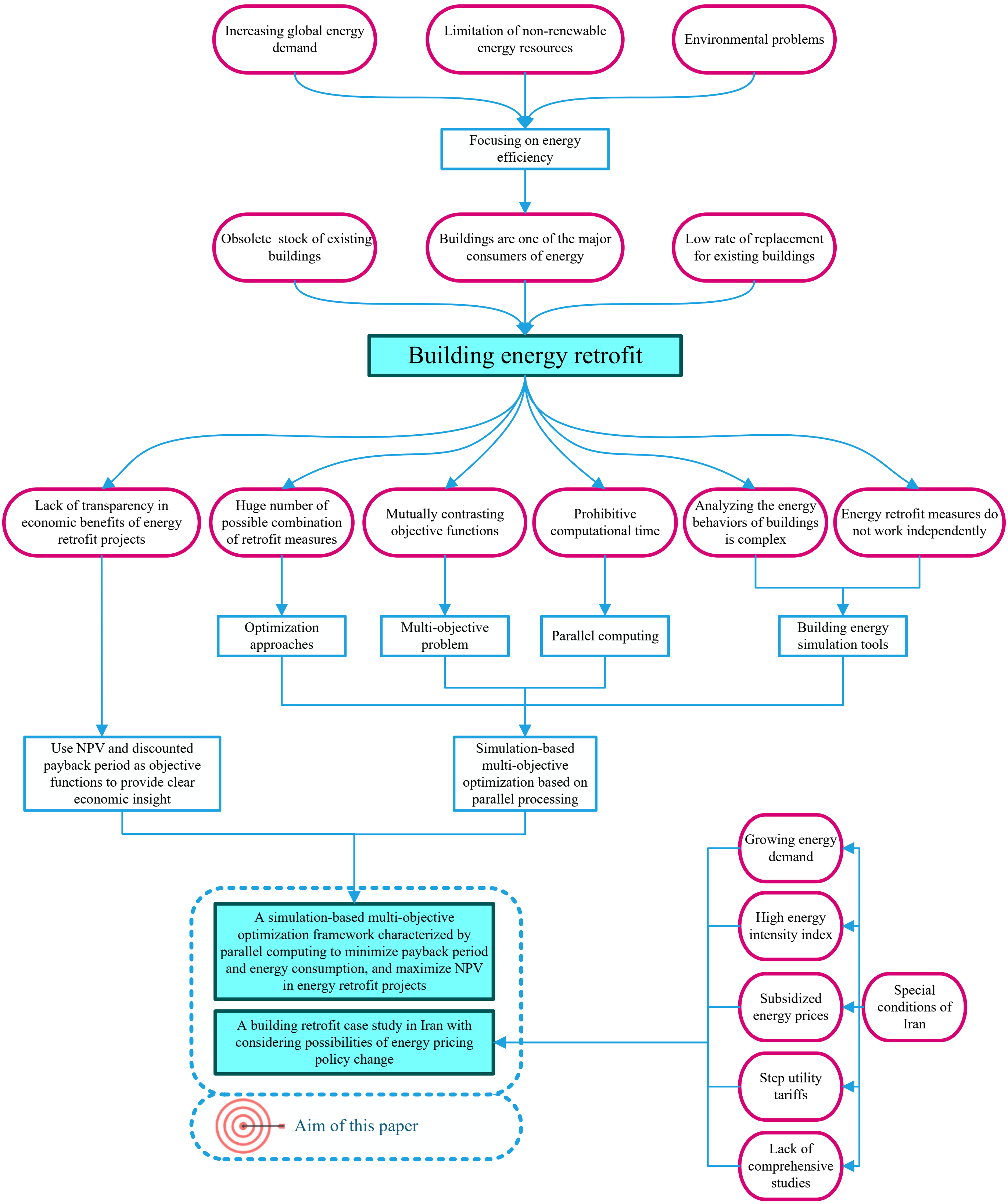

Fig. 2. Problem statement and aim of the study.

and private entrepreneurs in an informed decision-making process. Fig. 2 demonstrates the problem statement and the approach taken to solve challenges in this paper.

3. Methodology

In this study, a parallel computing simulation-based multi-objective optimization model is developed by coupling MATLAB [45] and

EnergyPlus [43] to optimize building energy retrofit projects. The methodology adopted in this paper consists of five stages: The first stage defines the baseline building model by incorporating energy auditing data in EnergyPlus software to perform a whole building energy simulation. The second stage introduces the decision variables and creates a parametric model. In the third stage, the objective functions are discussed and formulated. The fourth stage performs a multi-objective optimization using the Non-Dominated Sorting Genetic Algorithm (NSGA-II) under MATLAB environment. The optimization algorithm written under MATLAB environment continuously improves the building model in EnergyPlus until a set of Pareto-optimal solutions is found. Finally, the optimal combination of building energy efficiency measures will be selected at the fifth stage. The proposed framework for building energy retrofit is shown in Fig. 3, which is similar to the one developed by the same authors in Ref. [27]. This methodology is further described in the following sections.

3.1. Step 1. Building energy auditing and simulating the existing building

Each building has unique specifications; therefore, the first step in building energy retrofit projects is to assess the existing building's status and obtain the information needed for further evaluation. The evaluation of building energy performance requires accurate data. This data can be classified as follows: building layout and general data, occupancy data, construction data, lighting system specifications, and HVAC systems specifications.

Collected data, usually during an energy audit, are employed to develop a building baseline model. In this study, the existing building is modeled using EnergyPlus software, which is a free, open-source, and cross-platform whole building energy simulation software. Although EnergyPlus lacks a built-in graphical user interface (GUI), DesignBuilder is used in this study as a GUI. The energy simulation results are then compared with the actual energy consumption data obtained from energy bills to validate the model. If there is a discrepancy in the results, the model must be modified. This process continues until the model is calibrated with acceptable accuracy. On the other hand, energy performance results provide the opportunity to identify the element with high energy waste and consequently the high potential for improvement. This information is beneficial in the next step for defining decision variables.

3.2. Step 2. Identifying decision variables

In the context of optimization, decision variables are controllable parameters of the system. Decision variables are selected based on building energy performance, climatic conditions, stakeholders' criteria, and market availability. Major categories for improving building energy efficiency are building envelope elements, HVAC systems, and renewable energy sources. Once potential energy efficiency measures (EEMs) are identified and categorized, each category is defined as a parameter in the energy simulation model. The structure of decision variables in the proposed framework is in the form of a genetic algorithm's chromosome.

3.3. Step 3. Objective functions

Building energy retrofit projects should include economic and environmental goals for moving toward a sustainable future. In this study, minimizing primary energy consumption (PEC) is considered as an environmental objective, and maximizing net present value and minimizing discounted payback period are chosen as economic objective functions.

3.3.1. Environmental objective function

In the presented framework, in order to assess the environmental aspect of building energy retrofits, primary energy consumption (PEC) is used, which is the preferred metric according to EPBD recast [65]. PEC is calculated by converting the net electricity and natural gas demands to primary energy consumption using primary energy factors [66]. More in detail, monthly energy demands are derived from dynamic energy simulations performed by EnergyPlus software. It is highlighted that in the proposed framework, rooftop PV panels are considered as a retrofitting measure. The generated energy is deducted from the amount of energy consumption resulting in decreased net grid energy demand.

3.3.2. Economic objective function

The investment in energy retrofit projects is made to implement EEMs, consequently reducing energy consumption and resulting in decreased operating costs. The difference between the operating costs of the base case and the proposed retrofitted building during the building service time translates into the return on the investment. Thus, it is crucial to conduct an economic analysis before investing in energy retrofit projects.

For the economic evaluation, concepts of net present value and discounted payback period (DPP) are used in this study. The net present value (NPV) method evaluates the project in a specific time frame. The project is economically justified if the savings exceed the capital investment, taking into account the time value of money (TVM). Higher NPV means the project will be more profitable. Nevertheless, the disadvantage of the NPV method is that it only focuses on the net profit made at the end of the project life cycle, and it does not factor in how fast the return on investment occurs.

In this regard, in the presented framework, along with NPV, DPP is considered as the second economic objective. While the NPV evaluates the financial profit of projects at the end of the life cycle, the DPP indicates when the savings offset the project's initial costs. Moreover, calculating NPV and DPP makes it possible to compare different retrofitting strategies effectively. The proposed framework provides investors with a clear insight into the economic outcomes of implementing various EEMs and facilitates selecting EEMs that guarantee the best balance between a shorter payback period and a higher net present value. The following lines elucidate the calculations for NPV and DPP methods.

3.3.2.1. Net present value (NPV). NPV can be framed as the difference between the present value of cash outflows and cash inflows over a specific time frame. In other words, in the NPV method, all project cash flows are discounted to the present time and then added up. If the NPV of a project is positive, the project is profitable. NPV can be calculated as follows:

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{1}$$

Where i is the discount rate, t is the time of the cash flow, R_t is net cash flow at time t, and N is the total number of time periods [67].

In energy retrofit projects, cash inflows are achieved as a result of the implementation of EEMs, which are calculated in terms of the utility costs reduction compared to the base case and income from renewable energy production. Thus, the NPV of an energy retrofit project can be calculated as follows:

$$NPV = -IC + dEC + dGC + RE \tag{2}$$

Where IC is the investment cost, dEC and dGC are the present value of saving in electricity and natural gas bills during building service time, and RE is the present value of renewable energy production income. In Equation (2), cash outflow (IC) is negative. Cash inflows, including incomes achieved due to lower electricity and gas bills and renewable energy production, are positive. The following sections explain how to calculate each of the above terms.

3.3.2.2. Investment cost (IC). The investment cost of an energy retrofit

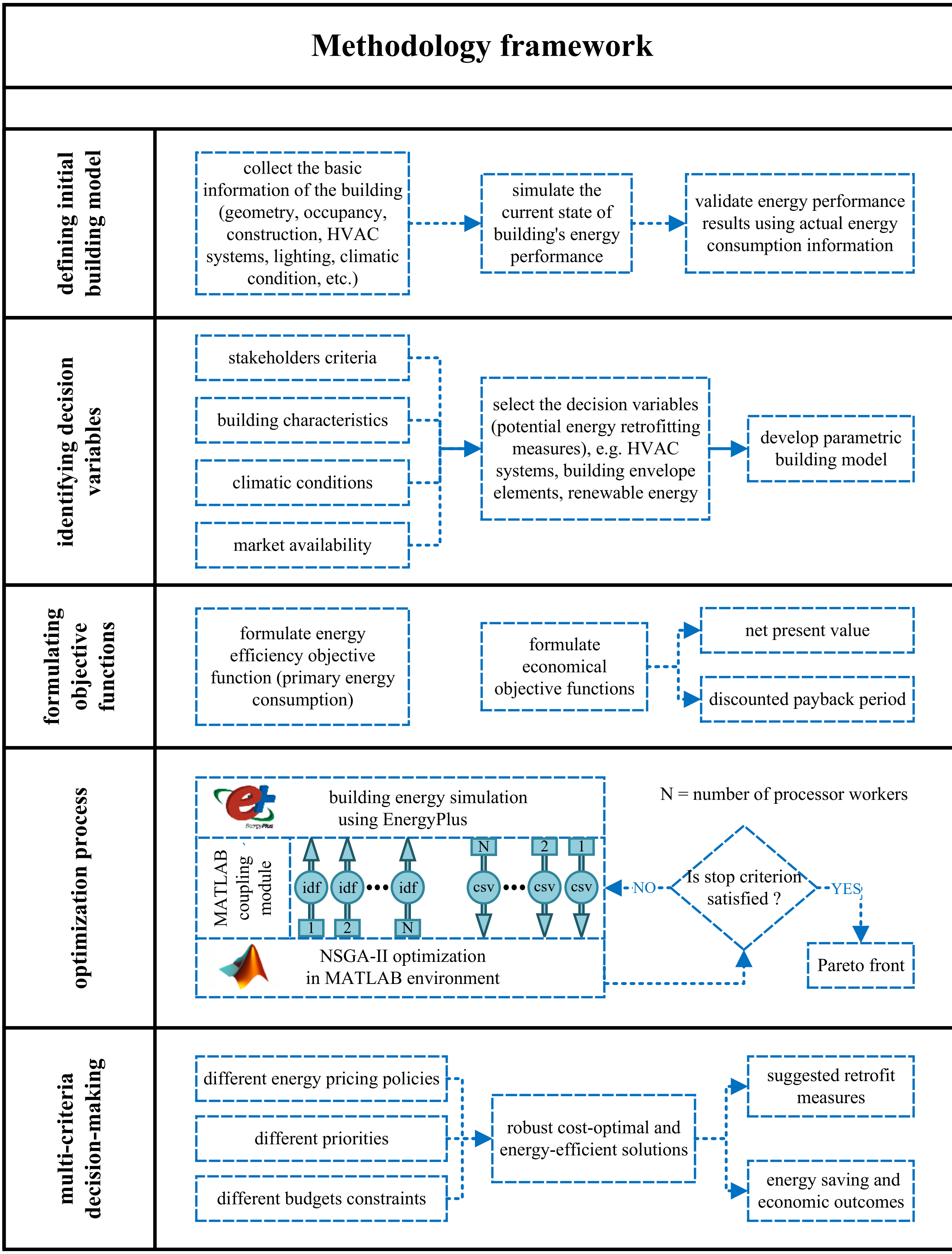

Fig. 3. Methodology framework.

project can be calculated as follows:

$$IC = \sum_{i=0}^{I} \sum_{j=0}^{J} c_i^j . k_i^j \tag{3}$$

where c_i^j is the cost of implementing the *i*th type of decision variable with the *j*th alternative measure. k_i^j is a binary number, which is equal to 1 if measure (*i*, *j*) is used, and 0 if measure (*i*, *j*) is not used. *I* represents the total types of EEMs, and *J* is the total number of potential options for EEMs of *i*th type.

3.3.2.3. Present value of electricity, natural gas, and renewable energy. The present value of electricity and gas consumption cost and income of renewable energy production during the building service time can be calculated as follows:

$$r = \left(\frac{i - ie}{1 + ie}\right) \tag{4}$$

$$\text{dEC} = \text{dEC}_1 * \frac{(1+r)^n - 1}{r * (1+r)^n} \tag{5}$$

$$\text{dGC} = dGC_1 * \frac{(1+r)^n - 1}{r * (1+r)^n} \tag{6}$$

$$\text{RE} = RE_1 * \frac{(1+r)^n - 1}{r * (1+r)^n} \tag{7}$$

where dEC_1 is the difference between the electricity cost of the base case in the first year and that of the proposed retrofitted building. dGC_1 is the difference between the natural gas cost in the first year for the base case and that of the proposed retrofitted building. RE_1 is the potential renewable energy production income in the first year. *i* is the discount rate, and *ie* is the inflation rate of energy price, and n is the project service time. *r* represents the difference between the discount rate and the inflation rate of energy price.

The discount rate is a decisive component of the life cycle cost assessment. When calculating the NPV of the energy retrofit projects, instead of using only a discount rate, the difference between discount rate and energy price inflation can be used, resulting in more reliable outcomes. Due to the exhaustion of non-renewable energy resources and increasing global energy demand, energy prices are on a long-term upward trend. The absence of an indicator for energy price inflation leads to a decrease in the attractiveness of energy retrofit projects. It should be noted that the discount rate and energy price inflation rate may fluctuate over buildings service time. However, due to inherent complexities and uncertainties of predicting future values of discount rate and energy price inflation, these terms are assumed to be constant in this study.

3.3.2.4. Discounted payback period (DPP). The payback period expresses the time required to recoup the initial outlay of investment through the generated cash inflows [68]. There are two approaches in calculating the payback period:

- Simple payback period (SPP)
- Discounted payback period (DPP)

If the periodic cash inflows from the project are assumed even, the simple payback period can be calculated as follows [68]:

$$SPP = \frac{Initial\ investment}{Expected\ cash\ inflow\ per\ period} \tag{8}$$

There are both benefits and drawbacks to the SPP method. The SPP is easy to understand and apply and provides insight into the expected investment return time. Nevertheless, one chief drawback associated with this method is that it does not account for the TVM. In fact, in the calculation of the SPP, energy price inflation and discount rate are ignored. Consequently, despite providing relatively good results for countries with stable economic conditions, this method may not present the true picture in countries with volatile economic status, as is the case of this study.

The DPP is a modified version of the SPP, which shows how long it takes to break even from investment cost by discounting expected cash flows and considering the TVM. The discounted payback period (DPP) of an energy retrofit project can be calculated by equating the NPV to zero value in equation (3):

$$DPP = \frac{\log\left(\frac{dEC + dGC + RE}{dEC + dGC + RE - \left(\frac{i - ie}{1 + ie}\right) * IC}\right)}{\log\left(1 + \frac{i - ie}{1 + ie}\right)} \tag{9}$$

In this approach, in order to prevent overestimation of the payback period, the difference between the discount rate and inflation rate of energy price is used to take into account the TVM. The proposed framework provides investors with a valuable metric for evaluating the economic viability of energy retrofit projects and comparing different alternatives and presents a clear insight into the relationship between investment costs and economic returns.

3.4. Step 4. Multi-objective optimization

Once defined objective functions, multi-objective optimization can be framed as follows:

$$[\text{Minimize}]\ F_1(x) = PEC \tag{10}$$

$$[\text{Maximize}]\ F_2(x) = NPV \tag{11}$$

$$[\text{Minimize}]\ F_3(x) = DPP \tag{12}$$

Subject to:

$x\ \varepsilon\ X$

$$F_1(x) \le PEC_0 \tag{13}$$

$$F_3(x) \le n\ (\text{project service time}) \tag{14}$$

$$IC(x) \le \text{Available budget} \tag{15}$$

Where n is expected project service time, PEC_0 is the primary energy consumption of baseline building in the first year, x is the vector of decision variables which represents different retrofit scenarios, and X is the feasible set of decision vectors. Notably, the optimization problem is subjected to three constraints. In particular, since an effective energy retrofit strategy must not produce a worsening of energy efficiency, all solutions that cause an increase in PEC compared to the base case configuration are excluded. Moreover, since the investor expects to achieve economic benefits within the project's service time, solutions with higher payback than project service time are deemed economically unjustified. Furthermore, high investment costs and insufficient financial resources are barriers to implement energy retrofit projects [69–73]. Therefore, the available budget is considered a constraint.

The formulated problem is solved by implementing a simulation-based multi-objective optimization process to select the optimum EEMs (or values that the decision variables should assume) that maximize NPV and minimize DPP and PEC. The Genetic algorithm has been used in this paper to provide a reasonable trade-off between reliability and computational time, which has also been used in many previous studies in the process of building energy optimization [8,15,17,27]. The proposed simulation-based multi-objective optimization process is outlined in the flowchart of Fig. 4, which consists of the following major parts:

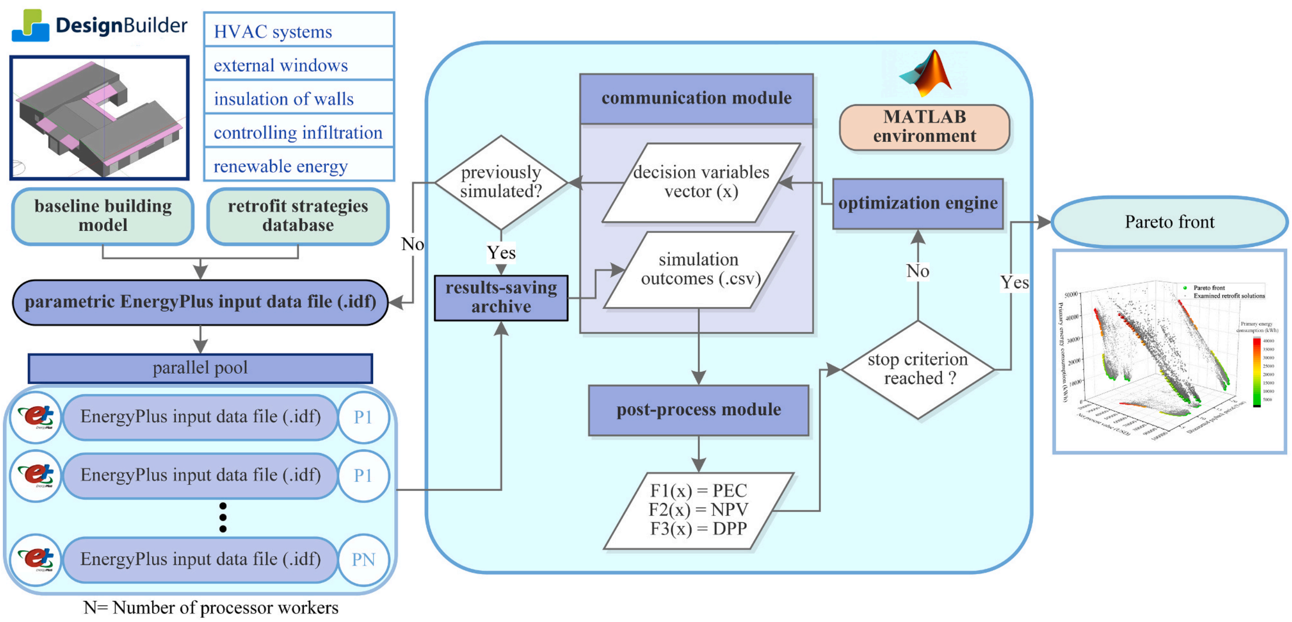

Fig. 4. Optimization process.

- NSGA-II code acts as the optimization engine and enables utilizing parallel computing.
- Parametric EnergyPlus input data file (.idf)
- Communication module that has two main functions:
  - o Creating specific EnergyPlus files (.idf) for any vector of decision variables (x) using the parametric EnergyPlus model.
  - o Automatically running simulations for aforementioned (.idf) files and reading results from (.csv) file.
- Post-process module that uses simulations outcomes for:
  - o Calculating natural gas and electricity costs based on step utility tariff policy in Iran.
  - o Calculating PEC, NPV, and DPP using formulas discussed in previous sections.

More in detail, NSGA-II is employed as an optimization algorithm written under MATLAB environment. In addition, EnergyPlus is used as a dynamic energy simulation engine. Chosen software are capable of working with text-based inputs/outputs that enable communication between the environments.

Furthermore, MATLAB is able to run codes designed for parallel computing that allows taking advantage of computers equipped with multicore processors to solve data-intensive problems. Parallel computing enables breaking down a time-consuming problem into smaller parts which are distributed among a pool of workers executing the assigned tasks independently and concurrently. The overall outcomes are combined at the end of the process. In this study, parallel computing significantly reduced the required computational time for performing the simulation-based multi-objective optimization process by using a typical quad-core, eight-thread processor.

NSGA-II is an elitist multi-objective genetic algorithm inspired by the Darwinian principle of evolution [74], which is widely regarded as one of the most effective evolutionary algorithms [75]. NSGA-II carries out an iterative process of fitness-based creation, crossover, mutation, and selection to improve a population of individuals or the so-called chromosomes. In fact, these chromosomes are string representations of solutions of the optimization problem. In particular, possible building configurations or retrofit strategies are encoded by means of the vector of decision variables (x) using a bit-string format. NSGA-II tends to select individuals with better fitness values (values of objective functions) as well as individuals that result in higher average crowding distance, ensuring the diversity of the population. In order to assess each individual, the NSGA-II optimization algorithm written under MATLAB environment requires simulation of each building retrofit model corresponding to an energy retrofit strategy. Thus, a communication platform is required to connect MATLAB optimization code and the EnergyPlus simulation engine. To this end, a parametric EnergyPlus model is developed using the energy retrofit strategies database and baseline building model, and whenever the optimization algorithm needs to assess an individual of the population, the communication module converts the aforementioned parametric model of EnergyPlus to a specific building model corresponding with the decision variable vector (x) and reads the simulation outcomes. The post-process module, which contains a cost calculation algorithm based on step utility tariff policy in Iran, calculates values of objective functions (PEC, NPV, and DPP) with reference to each individual of population and returns these values to the optimization algorithm.

Additionally, in order to reduce computational time, an algorithm for storing the results of each EnergyPlus simulation with a unique key is used. To be more specific, during the optimization, if a previously evaluated case emerges again in the process, the algorithm accesses the archived simulation results using the unique key; hence the simulation is not performed again.

As the optimization process iterates, the NSGA-II continuatively improves the building models until the stop criterion is met, which here is a predefined maximum number of iterations (denoted as generations in the context of the genetic algorithm). Finally, since the optimization algorithm addresses contrasting objective functions, the ultimate result is a set of non-dominated solutions called the Pareto front.

3.5. Step 5. Multi-criteria decision-making

Each point on the Pareto front is a potential solution for the optimization problem. All Pareto optimal solutions are acceptable without subjective preference information. Hence, there is a need for a multi-criteria decision-making method to select the optimum solution from the Pareto front to satisfy mutually contrasting criteria. In this study, three scenarios corresponding to different energy pricing policies are presented. Four final solutions for each scenario are proposed based on different priorities (cost-effectiveness and energy efficiency) and budget constraints.

The detailed methodology ensures a reliable investigation of the solutions to optimize objective functions and determine the best combination of EEMs using parallel processing and result saving archive in the optimization procedure. In the following sections, the proposed framework's capabilities are demonstrated for the case study building.

4. Case study

4.1. Characteristic of the case study building

The case study building is a single-family residence with an area of 240 m^2, which was built in 1970. The building is located in Tehran (capital of Iran) metropolitan area with a population of approximately 16 million, which is climatically similar to large parts of Iran, the Middle East, and central Asia. It is highlighted that more than 50% of the existing buildings in Iran were constructed before 1999 [76]. Most of these buildings were built without energy saving codes and are not equipped with thermal insulation resulting in high energy demands. Notably, this building is an obsolete building characterized by a reinforced concrete structure and brick walls with no insulations that is representative of a large portion of Iran's building stock. The average monthly temperatures are shown in Fig. 5 [77]. Required information for the building energy simulation is gathered through conducting surveys and a building walkthrough. Fig. 6 demonstrates the schematic view of the investigated building. The building's plan is U-shaped, which causes the building to be divided into three main sectors. In the northern sector, there is a living room and a kitchen, the central sector consists of a dining room and a restroom, and the southern sector comprises a bathroom and three bedrooms. All of these spaces are air-conditioned.

The exterior walls have a composite structure with a total thickness of 30 cm, interior plastering, and no thermal insulation (U-value = 0.875 W/m2K). The building has a pitched roof with a U-value of 0.385 W/m^2K. Windows are single-glazed glass (U-value = 5.829 W/m^2K) with steel frames. The heating system's terminal units are hot-water radiators supplied by an obsolete natural gas boiler with an efficiency of 65%. The building cooling system includes two split air conditioner systems, with an energy efficiency ratio (EER) of 2.1. The energy for this building is supplied through natural gas and grid electricity. The cooling system, lighting system, and electrical appliances such as refrigerators and televisions consume electricity. Natural gas is used for space heating, domestic hot water (DHW), and cooking stove. Building's main characteristics are summarized in Table 2.

4.2. Comparison of simulation results with actual building energy consumption

Once the case study building is modeled in DesignBuilder software and the simulation results are obtained, it is necessary to compare the

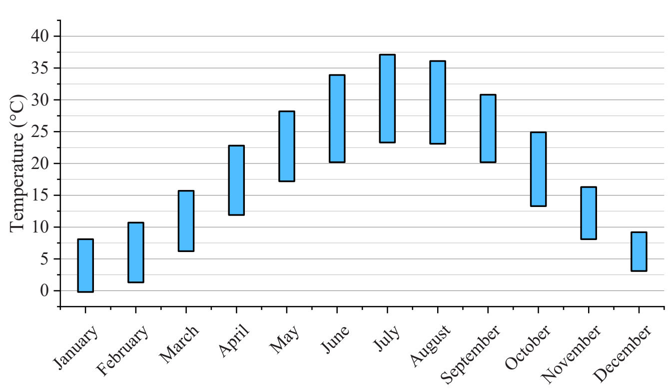

Fig. 5. Average monthly temperatures in Tehran.

simulation results with actual building performance to validate the simulation. The actual energy consumption and simulation results are not necessarily the same due to the inherent uncertainties in an energy simulation process. Two of the salient uncertainties in this area are the weather conditions and the building occupants' behavior. For example, in the EnergyPlus simulation, the cooling system stays on until the specified setpoint is met. However, the system is operated manually and might be off at certain hours of the day for reasons such as residents' adaptation to the heat and saving energy. Moreover, other uncertainties such as user occupancy pattern, building physical condition, and difference in empirical and measured parameters in EnergyPlus simulation influence the difference between actual energy consumption and simulation results [50,78].

The average annual electricity and natural gas consumption respectively are 5510 kWh and 43,153 kWh, gathered from building bills from 2017 to 2019. Fig. 7 and 8 compare the results of building energy simulation with the actual consumption. The simulation results are not significantly different from the actual consumption (less than 11% discrepancy for electricity and 7% for natural gas), which indicates that the simulation results are acceptable.

4.3. Energy efficiency measures (EEMs)

After conducting market research and holding a focus group with key stakeholders, the following set of strategies were developed. These measures are parametrically defined in EnergyPlus and MATLAB environment as decision variables and are used in the simulation-based multi-objective optimization process. These proposed EEMs are summarized in Table 3.

More in detail, in order to propose solutions for optimizing the energy performance of the building, it is crucial to have a benchmark for building energy performance. The building envelope is rated poor based on the average performance criteria. Therefore, providing solutions to prevent energy loss through surfaces and air infiltration can improve its performance. The application of thermal insulation in the building envelope serves to diminish heat transfer through the envelope. Different types of proposed insulation material and thickness are presented in Table 4. Besides, external windows significantly impact building energy performance since they enable natural lighting and heat transfer between indoor and outdoor spaces. Different considered options for windows are shown in Table 5.

Air infiltration is one of the main reasons for energy loss in the building. The purpose of building sealing is to prevent unplanned air infiltration, which is influenced by the number and size of air leakage paths. Improving airtightness is considered a decision variable in the optimization process that reduces the air infiltration rate from 0.9 to 0.3 Air Change per Hour (ac/h) using air barrier strips. Based on the market research, the cost is estimated to be $1250 for the whole building. Moreover, Table 6 shows the characteristics of the different options for the cooling and heating systems.

Furthermore, renewable energy sources, namely PV panels, can diminish buildings' dependency on grid electricity and reduce carbon footprint. As shown in Fig. 9, Iran has a high photovoltaic power potential [79]. To encourage building owners to equip buildings with PV panels, the Iranian government purchases electricity generated in the building at a higher price than the grid electricity price. Table 7 shows the specifications and costs of different options for installing photovoltaic panels (PV) on the south wing of the building's pitched roof.

As previously discussed, an archive for storing simulation results is integrated into the developed framework. As the optimization algorithm proceeds and approaches the optimal solutions, the probability of repeating cases increases. Consequently, the above-mentioned algorithm saves significant processing time. Fig. 10 demonstrates the processing time of each generation of the genetic algorithm using a computer with an Intel Core i7 2.60 GHz, 6 MB cache processor. As it is clear, with the progress of the algorithm, the processing time of each

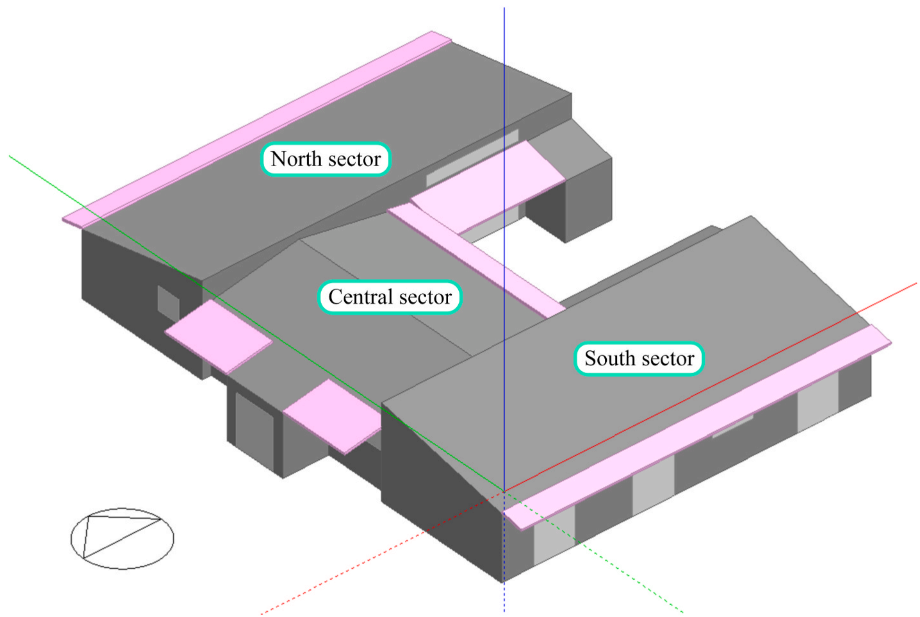

Fig. 6. The case study building.

Table 2
Characterization of the baseline building.

Location	Coordinates	Floor Area	U-Value (W/m²K)			Heating cooling Systems	Lighting system	Infiltration Rate
			External Walls	Pitched Roof	Single-glazed windows			
Tehran, Iran	35.6892°N, 51.3890° E	240m²	0.875	0.385	5.829	Natural-gas boiler (η = 0.65) Duct Split (ERR = 2.1)	High efficiency LED	0.9 ACH
Heating degree days (baseline 18 °C)				1673		Heating setpoint	21 °C	
Cooling degree days (baseline 22 °C)				1031		Cooling setpoint	27 °C	

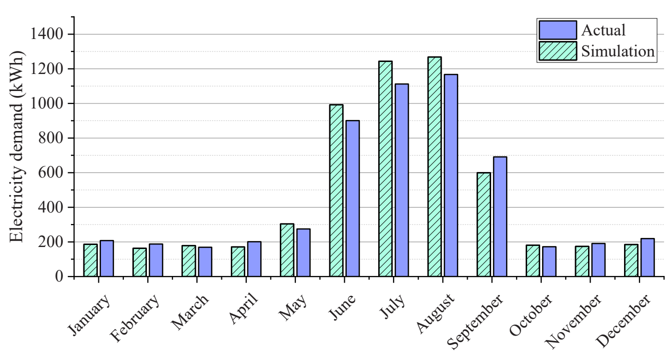

Fig. 7. Comparison of actual monthly electric demand with simulation results.

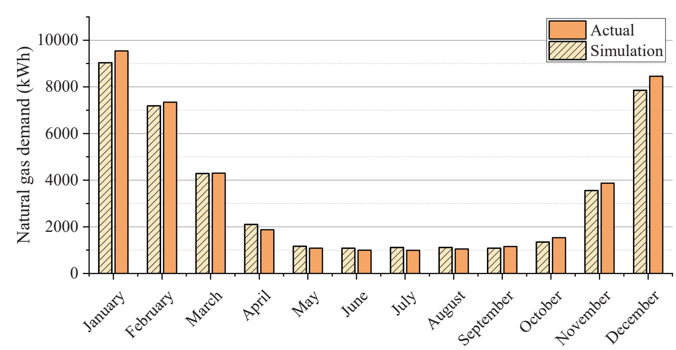

Fig. 8. Comparison of actual monthly natural gas energy demand with simulation results.

generation is gradually reduced from about 500 s to 200 s, which indicates the benefit of using this algorithm.

The population size of the genetic algorithm is set equal to 60. The mutation rate and crossover rate are set to 0.7 and 0.4, respectively, based on previous studies to achieve reliable results in a reasonable computational time [80–82]. The population continues to evolve until the stop criterion is satisfied. (The number of generations reaches 100). The computational time with parallel computing was 9 h. The total number of possible combinations of energy efficiency measures in the case study is 5,120, 216, 064,000. Evaluation of this number of cases required years of processing. Achieving the optimal solutions within just 9 h demonstrates the capability of the proposed framework to search the decision space intelligently.

4.4. Energy pricing policies in Iran

The government of Iran allocates substantial financial resources as energy subsidies in residential buildings. However, the subsidies are different for each building, determined by the energy consumption levels. The energy price rate is increased with the amount of use. Consequently, the share of government subsidies in energy prices decreases. The purpose of this policy, which is referred to as step utility tariff, is to modify the behavior of building occupants and encourage energy conservation. However, the last defined step of utility tariffs (the highest energy rate) is still significantly cheaper than global energy prices.

Table 3
Characterization of investigated energy efficiency measures (EEMs).

Decision Variables	Investigated options	Number of discrete options
Wall insulation	Material: glass wool; mineral wool; polystyrene Thickness (mm): 0 (base case); 30; 50; 75; 100	8
Roof insulation	Material: glass wool; mineral wool; polystyrene Thickness (mm): 0 (base case); 30; 50; 75; 100	8
Improving airtightness	No; Yes	2
Windows glazing	Glass material: clear; bronze; reflex Glass thickness (mm): 0 (base case); 4; 6; 10 Gas: air; argon	19
Heating system	Boiler (η): 0.65 (base case); 0.850; 0.95 Heat pomp (COP): 3.2; 4.6	5
Cooling system	EER: 2.1 (base case); 3.2; 3.3; 3.5; 5	5
Photovoltaic panels (PV)	Area (m^2): 0; 10; 20; 30; 40	5

Table 4
Characterization of thermal insulation.

Name	Material	Thickness (mm)	Conductivity (W/m-K)	Cost ($/$m^2$)
g-50	Glass Wool	50	0.038	7.8
g-75	Glass Wool	75	0.038	8.8
m-30	Mineral Wool	30	0.040	5.6
m-50	Mineral Wool	50	0.040	6.6
m-75	Mineral Wool	75	0.040	8.1
p-50	Polystyrene	50	0.042	5.1
p-100	Polystyrene	100	0.042	5.7

In the following section, three different scenarios are examined according to the current state of energy pricing policies in Iran and the possible changes that the government can implement to increase the attractiveness of energy retrofit projects. These scenarios are as follows:

- Simulation with reference to subsidized energy prices (the current state of affairs)
- Simulation with reference to global energy prices (elimination of energy subsidies)
- Simulation with reference to global energy prices and offering incentives for energy retrofits

In the first scenario, the case study building is evaluated by considering the current state of affairs, assuming that the energy pricing policies remain unchanged. The second scenario investigates the prospect of increasing the economic viability of energy retrofit projects by elimination of energy subsidies and raising energy prices to match global rates. Clearly, higher energy prices would yield a substantial financial resource for the government that could be redirected to boost the energy efficiency of buildings by providing low-interest loans as economic incentives for energy retrofits, which is the subject of the third scenario.

The simulation-based multi-objective optimization process is implemented for each scenario due to the fact that changing energy prices and the presence of incentives change the obtained Pareto front and optimal solutions. In practice, building energy retrofit projects face budget constraints. Therefore, in each scenario, the optimal solutions are evaluated with or without budget constraints. Finally, for each scenario, a cost-optimal solution and an energy-efficient solution are selected from the Pareto front and assessed for limited and unlimited budget conditions. In this study, the cost-optimality criterion is defined by a lower payback period, and energy efficiency is defined by lower primary energy consumption.

Table 5
Windows type.

Name	Glass thickness (mm)	Gas Type	Glass Type	U-Value (W/m^2K)	SHGC	Cost ($/$m^2$)
4-air-clr	4	Air	clear	2.96	0.76	75.0
6-air-clr	6	Air	clear	2.92	0.76	82.4
10-air-clr	10	Air	clear	2.86	0.76	92.4
4-arg-clr	4	Argon	clear	2.77	0.76	76.0
6-arg-clr	6	Argon	clear	2.73	0.76	83.4
10-arg-clr	10	Argon	clear	2.68	0.76	93.4
4-air-br	4	Air	bronze	2.71	0.62	77.4
6-air-br	6	Air	bronze	2.68	0.62	85.0
10-air-br	10	Air	bronze	2.64	0.62	90.0
4-arg-br	4	Argon	bronze	2.70	0.62	78.8
6-arg-br	6	Argon	bronze	2.65	0.62	86.2
10-arg-br	10	Argon	bronze	2.61	0.62	91.2
4-air-ref	4	Air	reflex	2.67	0.43	78.8
6-air-ref	6	Air	reflex	2.54	0.43	86.2
10-air-ref	10	Air	reflex	2.42	0.43	96.2
4-arg-ref	4	Argon	reflex	2.44	0.43	80.0
6-arg-ref	6	Argon	reflex	2.28	0.43	87.4
10-arg-ref	10	Argon	reflex	2.16	0.43	97.4

Table 6
Specification of investigated HVAC system.

HVAC systems			
Heating system	Cost ($)	Cooling system	Cost ($)
Base case- existing natural gas Boiler (η = 0.65)	500 (maintenance)	Base case - split (EER = 2.1)	438 (maintenance)
New Natural gas boiler (η = 0.85)	1500	Split air conditioner system (EER = 3.2)	2750
Condensing gas boiler (η = 0.95)	2700	Split air conditioner system + Inventor (EER = 3.32)	3000
Air Source heat pump (COP = 3.2)	7250	Air-cooled chiller (EER = 3.5)	3750
Ground source heat pump (COP = 4.6)	15,625	Water-cooled chiller (EER = 5)	6250

5. Results and discussion

The outputs of each scenario, including the Pareto front, the options selected for the decision variables, and the values of the objective functions and their assessment, are elaborated in the following sections:

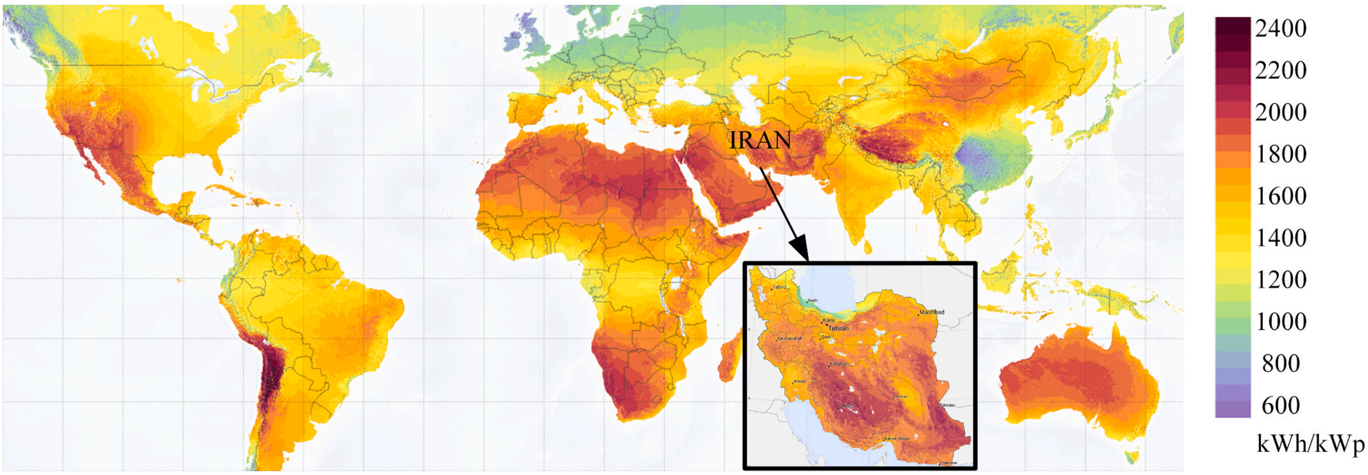

Fig. 9. Photovoltaic power potential in the world.

Table 7
Characterization of investigated photovoltaic panels (PV).

Name	Area (m^2)	Price ($)
SA-10	10	2250
SA-20	20	4250
SA-30	30	6000
SA-40	40	7500

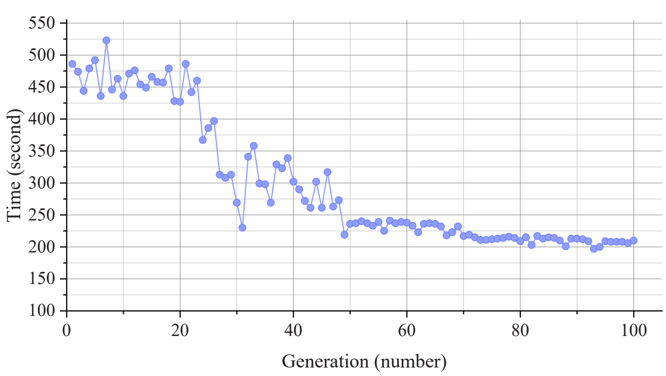

Fig. 10. Run time of each generation.

5.1. Scenario 1. Subsidized energy prices

In this scenario, by considering the current state of utility pricing policies (step utility tariffs), the three-dimensional (3D) Pareto front obtained from performing the simulation-based multi-objective optimization is shown in Fig. 11, including 57 optimal solutions. Moreover, the Pareto front is shown in Fig. 12 in bi-dimensional (2D) format, indicating that DPP and energy consumption are inversely related, meaning that energy-efficient solutions require a higher investment cost, leading to an extended payback period.

Additionally, the suggested EEMs for Pareto-optimal solutions are further analyzed. Roof insulation is not considered an economical solution because it is not selected in options with a shorter payback period. However, in more energy-efficient solutions, roof insulation is frequently suggested (51% of Pareto solutions). Likewise, the results indicate that the cooling system should remain unchanged if the economic aspect is the priority, whereas in 40% of more energy-efficient options using new cooling systems are proposed. Similarly, renewing the heating system is suggested for 68% of energy-efficient solutions. Some solutions are both energy-efficient and economical. Notably, equipping the building with PV panels has been selected as an energy production source in all solutions. This strategy is cost-effective because the government buys electricity generated from PV panels in buildings at a higher price than the selling price of grid electricity. This policy promotes investment in renewable energy production and moves towards sustainable development goals. Moreover, wall insulation and replacement of windows have been recurred in most solutions (96% of cases) due to lack of thermal insulation of the walls and the use of single glazed windows in the case study building, leading to a considerable amount of energy loss. It is worth mentioning that the reason that wall insulation is more prevalent than roof insulation could stem from the fact that walls are characterized by lower U values in comparison with roofs. Airtightness improvement is repeated in 80% of cases indicating that a significant amount of energy loss stems from infiltration, which can be prevented at a reasonable cost.

Without considering any budget limitations, two final solutions are selected. The optimal solution in terms of cost optimality has an energy consumption of 32,859 kWh/year, which indicates a 46.8% reduction compared to the base case. The DPP is 13.01 years, and the NPV is $37,261. This strategy requires $ 10,569 as IC. Regarding the suggested EEMs, for insulating northern and southern walls, polystyrene with a thickness of 100 mm (P-100) is selected. Double-glazed windows with a thickness of 4 mm and argon-filling gas and reflex coating (4-arg-ref) are proposed for the south sector, and for windows in the central sector, double-glazed ones with a thickness of 4 mm and air-filling and reflex coating (4-air-ref) are chosen. PV panels with an area of 40 m^2 are selected. For other decision variables, no change to the base case is suggested. The optimal solution in terms of energy efficiency is expected to reduce energy consumption by 96.8% with a primary energy consumption of 1945 kWh/year. This solution requires a budget of $ 35,804, with a DPP of 31.9 years and an NPV of $14905.

By considering a limitation on the budget (70$/$m^2$), the optimal solution in terms of energy efficiency is expected to reduce PEC by 85% (9171 kWh/year). This option requires an IC of $16835, with a DPP of 17.27 years and an NPV of $37297. The cost-optimal solution (solution with the shortest payback period) requires a low investment cost. Consequently, it is not affected by the budget limitation and is the same as the unlimited budget state. The selected EEMs, values of the objective functions, and required investment cost for each final solution are reported in Table 8.

5.2. Scenario 2. Global energy prices (elimination of energy subsidies)

In this scenario, it is assumed that the government increases the utility prices to the global levels by the elimination of energy subsidies. Accordingly, the simulation-based multi-objective optimization process

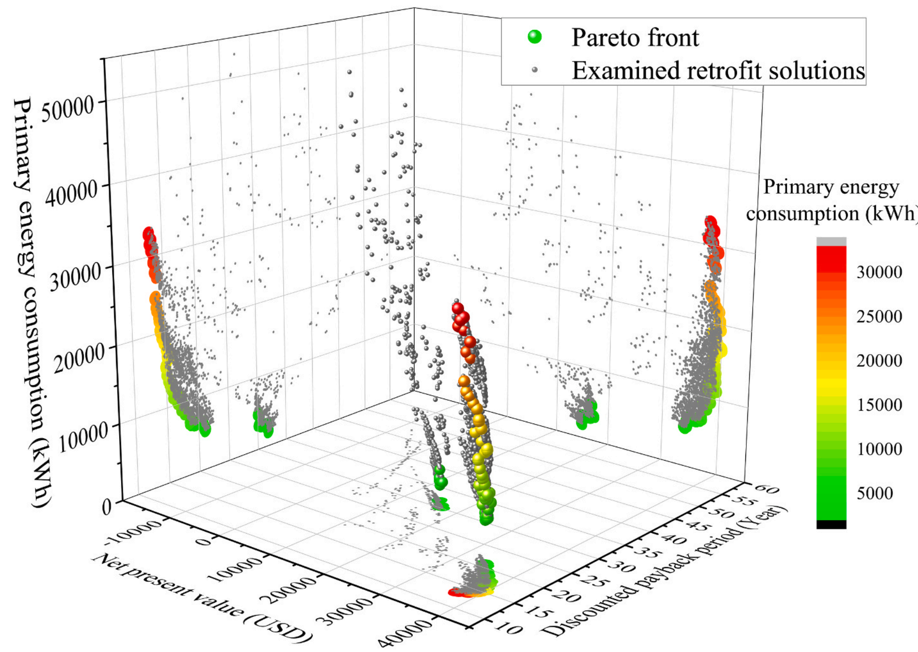

Fig. 11. 3D Pareto front for scenario 1: Subsidized energy prices.

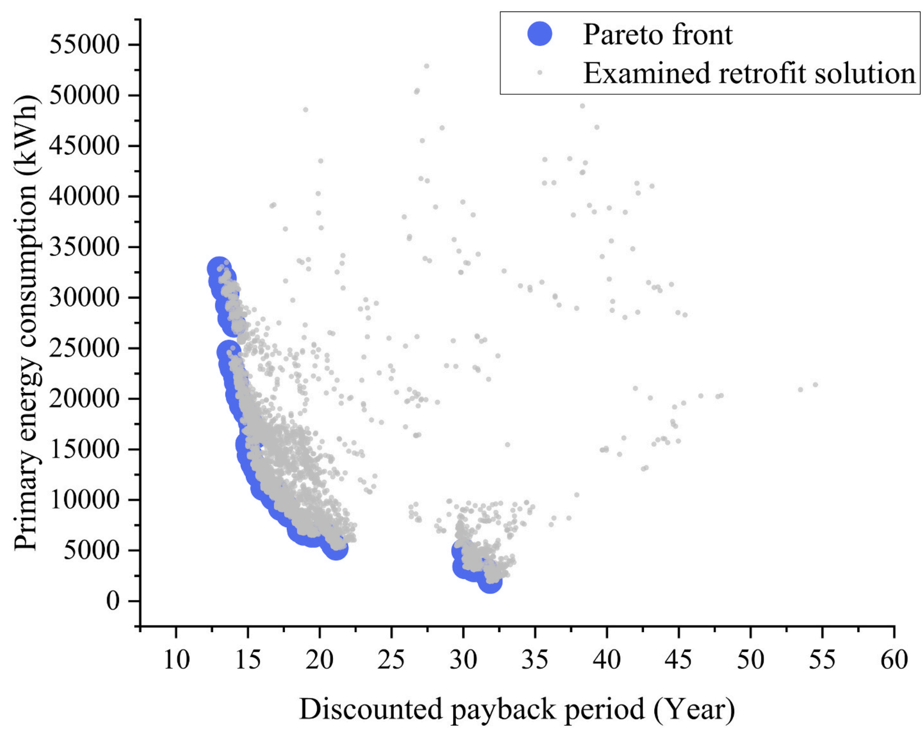

Fig. 12. 2D Pareto front for scenario 1: Subsidized energy prices.

is re-implemented. The three-dimensional (3D) and bi-dimensional (2D) Pareto front shown in Fig. 13 and 14, including 53 optimal solutions.

The following provides an elaboration on obtained optimal EEMs. Roof insulation is suggested in energy-efficient EEMs (35% of optimal cases); however, it is not proved to be a cost-effective solution. In 41.5% of more energy-efficient options using new cooling systems is recommended. Equipping the building with PV panels and replacing windows have been suggested in most solutions (79% for PV panels and 83% for windows). Furthermore, using a new heating system, wall insulation, and airtightness is suggested in the entire Pareto front solutions, indicating that they have both economic and energy-saving benefits. The selected options for wall and roof insulation, windows replacement, and cooling system did not change significantly compared to the Pareto front of the first scenario. Meanwhile, changing the heating system has been selected in all options (100% of cases compared to 68% in the first scenario), which can be attributed to the fact that increased natural gas prices could justify upgrading heating systems. Conversely, installing PV panels in this scenario is not suggested in the entire solutions (80% compared to 100% of cases in the first scenario). The reason is that, unlike the previous scenario in which the government buys electricity

Table 8
Suggested energy efficiency measures (EEMs) and value of objective functions for scenario 1: Subsidized energy prices.

Budget	Solution	Decision variables							IC ($)	Objective functions		
		Wall insulation (South, Middle, North)	Windows glazing (South, Middle, North)	Roof insulation (South, Middle, North)	Airtightness improvement	Cooling system	Heating system	PV (m^2)		PEC (kWh)	NPV ($)	DPP (year)
Unlimited	Cost-optimal	p-100 / p-100	4-arg-ref / 4-arg-ref	/ / /	/	/	/	40	10,569	32,859	37,261	13.0
	Energy-efficient	p-100 p-100 p-100	6-arg-clr 4-arg-ref 10-arg-br	p-100 p-100 p-100	Yes	Water-cooled chiller	GSHP	40	35,805	1945	14,906	31.9
Limited	Cost-optimal	p-100 / p-100	4-arg-ref / 4-arg-ref	/ / /	/	/	/	40	10,569	32,859	37,261	13.0
	Energy-efficient	p-100 p-100 p-100	4-air-br 4-arg-ref 4-air-ref	p-100 p-100 p-100	Yes	Split air conditioner	New boiler	40	17,302	9817	38,231	17.3

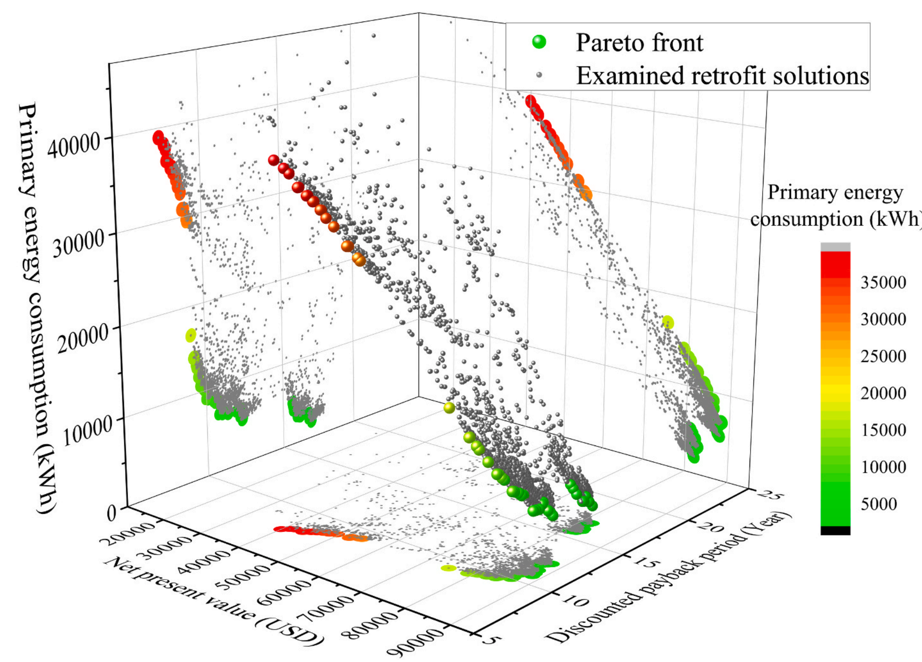

Fig. 13. 3D Pareto front for scenario 2: Global energy prices.

produced by PV panels at a higher price than the price of electricity bills, in this scenario, due to the elimination of subsidies, the government buys the produced electricity at its market price. As a result, the Pareto front options move towards more energy-conserving methods rather than electricity production by PV panels.

Without considering budget constraints, the cost-optimal solution has resulted in a PEC of 39,006 kWh/year. The DPP is 7.61 years (5.4 years reduction in comparison with scenario 1), and the NPV for the project is $ 39,934. This solution requires $ 5459 as IC. The energy-efficient solution has an anticipated PEC of 1936 kWh/year. The DPP is 16.97 years, and the NPV is $ 82,064, and the required capital is $ 35,891.

By considering a limitation on the budget (70$/m^2), the energy-efficient solution is expected to reduce PEC by 85.5% (8954 kWh/year) with a DPP of 10.16 years and the NPV of $ 86,083, requiring IC of $ 17,135. Imposing budget constraints does not alter the selected cost-effective solution compared to the unlimited budget state due to the low required IC. The selected EEMs, values of the objective functions, and required IC for each final solution are reported in Table 9.

5.3. Scenario 3. Global energy prices and presence of public incentives

As shown in previous sections, the obtained solutions in scenario 2 were more attractive in comparison with scenario 1, particularly in terms of the lower payback period. However, increasing the energy prices and eliminating subsidies could lead to dissatisfaction in society and exerts economic pressure primarily on low-income households who might not be able to provide the required budget for undertaking an energy retrofit project. In order to curb the adverse effects of this potential issue, in the third scenario, it is assumed that the government offers a low-interest loan as an incentive for the initiation of energy retrofit projects. It is assumed that the government provides 60% of the investment cost of the project as a loan with an interest rate of 8%, which is roughly half of the current inflation rate in Iran. Homeowners repay the loan to the government in 8 years. The advantage of this proposal is threefold:

- It would tackle the project financing problem by reducing the required investment cost.

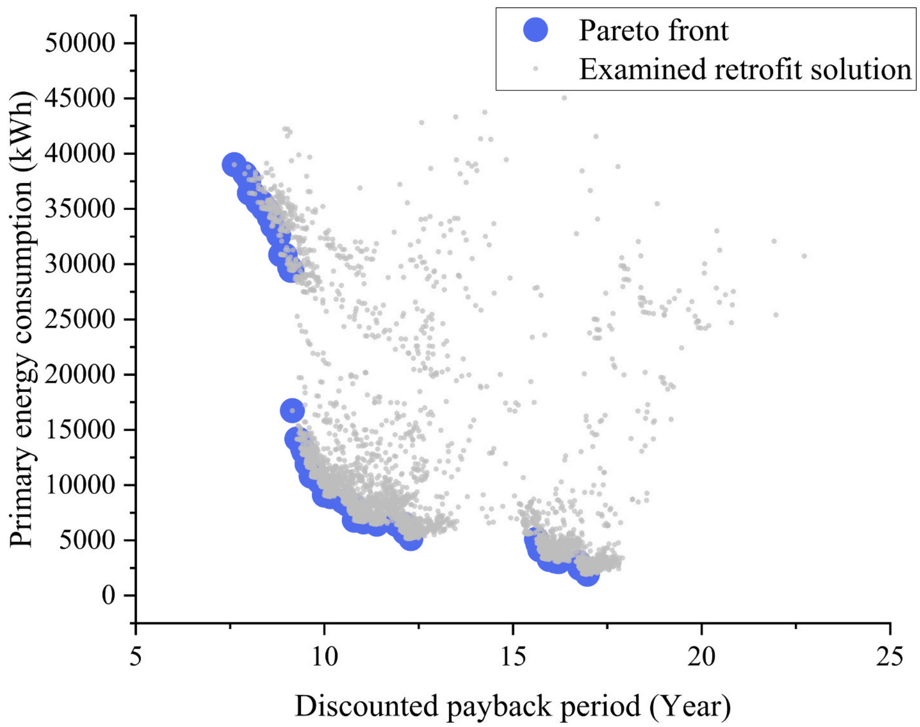

Fig. 14. 2D Pareto front for scenario 2: Global energy prices.

Table 9
Suggested energy efficiency measures (EEMs) and value of objective functions for scenario 2: Global energy prices.

Budget	Solution	Decision variables							IC ($)	Objective functions		
		Wall insulation (South, Middle, North)	Windows glazing (South, Middle, North)	Roof insulation (South, Middle, North)	Airtightness improvement	Cooling system	Heating system	PV (m^2)		PEC (kWh)	NPV ($)	DPP (year)
Unlimited	Cost-optimal	p-100 p-100 p-100	/ 4-arg-ref /	p-100 / /	Yes	/	New Boiler	40	5459	39,006	39,934	7.6
	Energy-efficient	p-100 p-100 p-100	10-arg-clr 4-arg-ref 10-arg-br	p-100 p-100 p-100	Yes	Water-cooled chiller	GSHP	40	35,891	1936	82,064	17.0
Limited	Cost-optimal	p-100 p-100 p-100	/ 4-arg-ref /	p-100 / /	Yes	/	New boiler	/	5459	39,006	39,934	7.6
	Energy-efficient	p-100 p-100 p-100	10-arg-clr 10-arg-ref 10-arg-ref	p-100 p-100 p-100	Yes	/	Condensing boiler	40	17,135	8954	86,083	10.2

- It is likely to diminish social dissatisfaction stemmed from rising energy prices.
- The relatively low interest rate of this loan boosts the economic attractiveness of the energy retrofit projects.

Similar to the previous scenarios, the optimization process is performed again resulting in 54 Pareto-optimal solutions (see Fig. 15 and 16).

Regarding proposed EEMs in Pareto optimal solutions, roof insulation appears in 37% of solutions with higher energy efficiency. Similarly, 33.3% of more energy-efficient options using new cooling systems are suggested. On the other hand, using a new heating system, wall insulation, and airtightness improvement is suggested in all Pareto front solutions, highlighting both economic and energy-saving benefits of these measures. Using PV panels and replacing windows have been presented in most solutions (81.4% for PV panels and 70.3% for windows).

The cost-optimal solution has resulted in 41,205 kWh/year PEC without budget limitations, which indicates a 33.38% reduction compared to the base case. The DPP is 5.77 years (1.8 years reduction compared to scenario 2 and 7.2 years compared to scenario 1). It is highlighted that the presence of incentives exerts a less pivotal effect on the economic viability of the project compared to the elimination of energy subsidies. The NPV and IC are $ 37,498 and $ 4506, respectively. The energy-efficient solution is expected to reduce PEC by 96.88% (1925 kWh/year). This solution requires a budget of $ 35,948, with a DPP of 14.31 years, and the NPV is $88799.

With a limited budget (70 $/m^2$), the energy-efficient solution is anticipated to decrease PEC by 85.22% (9140 kWh/year). This option requires a budget of $ 16,771, with a DPP of 8.3 years and the NPV of the project is $ 89,248. Similar to scenario 2, owing to the fact that the budget constraint does not affect the cost-optimal cases, the cost-effective solution is the same as the unlimited budget. The selected EEMs, values of the objective functions, and required IC for each final

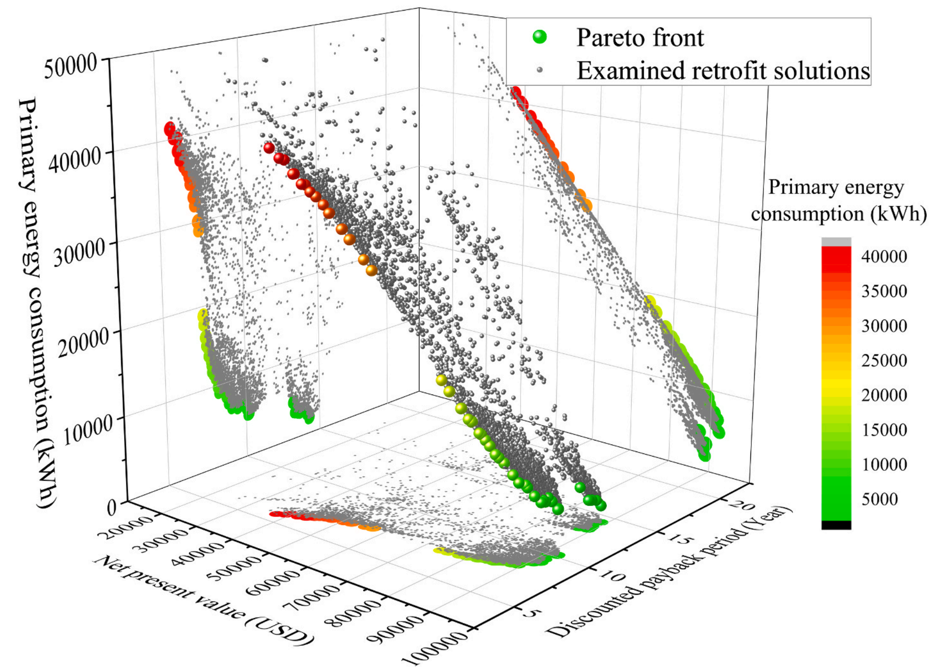

Fig. 15. 3D Pareto front for scenario 3: Global energy prices and presence of incentives.

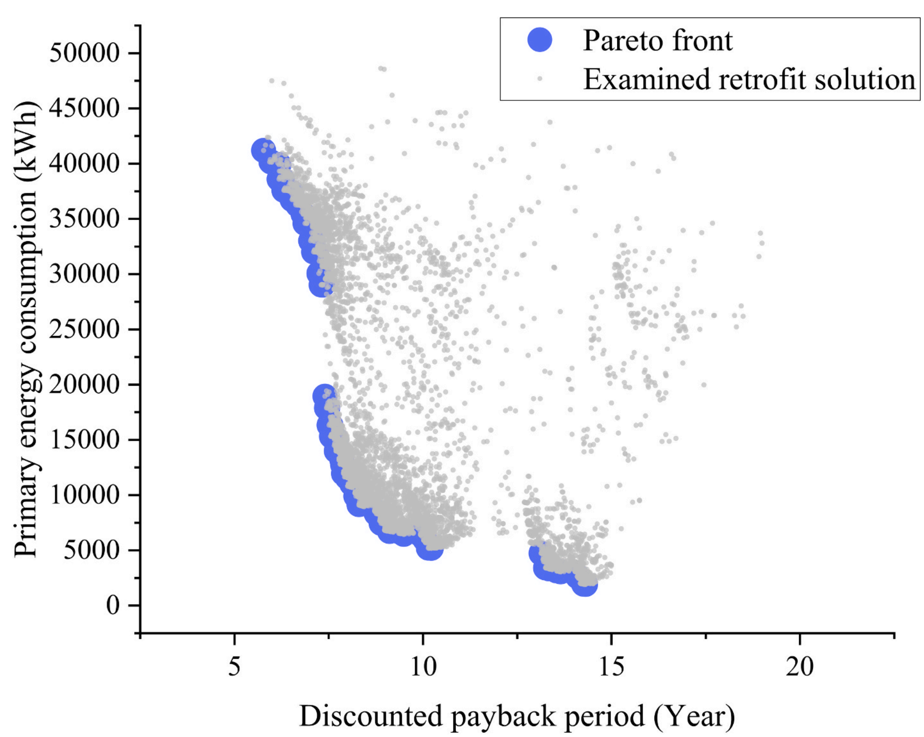

Fig. 16. 2D Pareto front for scenario 3: Global energy prices and presence of incentives.

solution are reported in Table 10.

5.4. Comparison of scenarios and guideline

In this section, the results of each scenario, the values of the objective functions, and the selected solutions are compared. The range of the objective functions in each scenario is reported in Table 11 for all Pareto front solutions. There is a noticeable difference in the DPP in each scenario. The DPPs of scenario 1 are not economically justifiable. Thus, with current energy pricing policies, energy retrofit projects are not profitable and unlikely to be implemented. Whereas, in scenario 2, the DPP is significantly reduced by eliminating government subsidies (about a 55% reduction in the DPP), making the energy retrofits project more attractive than scenario 1. Comparing the results of the two scenarios highlights the importance of energy policies for addressing the challenging aspects of energy retrofit projects. If the government is planning for the decarbonization of the building sector, there is a need for an evaluation of the energy pricing policies and the possibility of

Table 10
Suggested energy efficiency measures (EEMs) and value of objective functions for scenario 3: Global energy prices and presence of incentives.

		Decision variables								Objective functions		
Budget	Solution	Wall insulation (South, Middle, North)	Windows glazing (South, Middle, North)	Roof insulation (South, Middle, North)	Airtightness improvement	Cooling system	Heating system	PV (m^2)	IC ($)	PEC (kWh)	NPV ($)	DPP (year)
Unlimited	Cost-optimal	p-100 p-100 p-100	/ / /	/ / /	Yes	/	New boiler	/	4506	41,205	37,498	5.77
	Energy-efficient	p-100 p-100 p-100	10-arg-clr 10-arg-ref 10-arg-br	p-100 p-100 p-100	Yes	Water-cooled chiller	GSHP	40	35,948	1925	88,799	14.31
Limited	Cost-optimal	p-100 p-100 p-100	/ / /	/ / /	Yes	/	New boiler	/	4506	41,205	37,498	5.77
	Energy-efficient	p-100 p-100 p-100	4-arg-clr 4-air-ref 4-arg-ref	p-100 p-100 p-100	Yes	/	Condensing boiler	40	16,771	9140	89,248	8.3

Table 11
Range of the objective functions for different scenarios in all Pareto front solutions.

	PEC (kWh/year)		DPP (year)		NPV ($)	
	Max	Min	Max	Min	Max	Min
Scenario 1	32,859	1945	31.9	13	39,981	14,866
Scenario 2	39,006	1936	17	7.6	88,207	39,934
Scenario 3	41,205	1925	14.31	5.77	92,154	37,498

supportive incentives for retrofit projects. It is worth mentioning that higher energy costs would be a burden for the vulnerable communities (economically challenged groups). In this study, it is assumed that energy subsidies are eliminated, and every household has to pay the same prices. However, it is recommended that the government should consider different scenarios for ramping up the energy price. In scenario 3, the DPP decreases due to reduced investment costs by offering low-interest loans as an economic incentive. However, compared to removing energy subsidies, the presence of incentives does not dramatically affect obtained solutions. Consequently, it is suggested that the government should primarily focus on eliminating subsidies rather than providing incentives for energy retrofit projects. The three-dimensional (3D) Pareto fronts of the three scenarios are shown in Fig. 17, which elucidates the effect of eliminating subsidies and offering incentives on obtained solutions.

Table 12 summarizes the range of objective functions and optimal solutions for different available budget levels. For the first scenario, polystyrene with a thickness of 100 mm (P-100) for wall insulation, double-glazed windows with 4 mm glasses, and argon-filling gas and reflex coating (4-arg-ref), improving airtightness and PV panels are suggested in the majority of solutions. With a highly limited budget (first level), the heating and cooling system remains unchanged. However, in the second budget level, in addition to the EEMs mentioned above, polystyrene with a thickness of 100 mm (P-100) for roof insulation and condensing gas boiler for heating system and split air conditioner for cooling system are selected. More energy-efficient systems (water-cooled chiller for cooling and ground source heat pump for heating) are proposed in the third budget level.

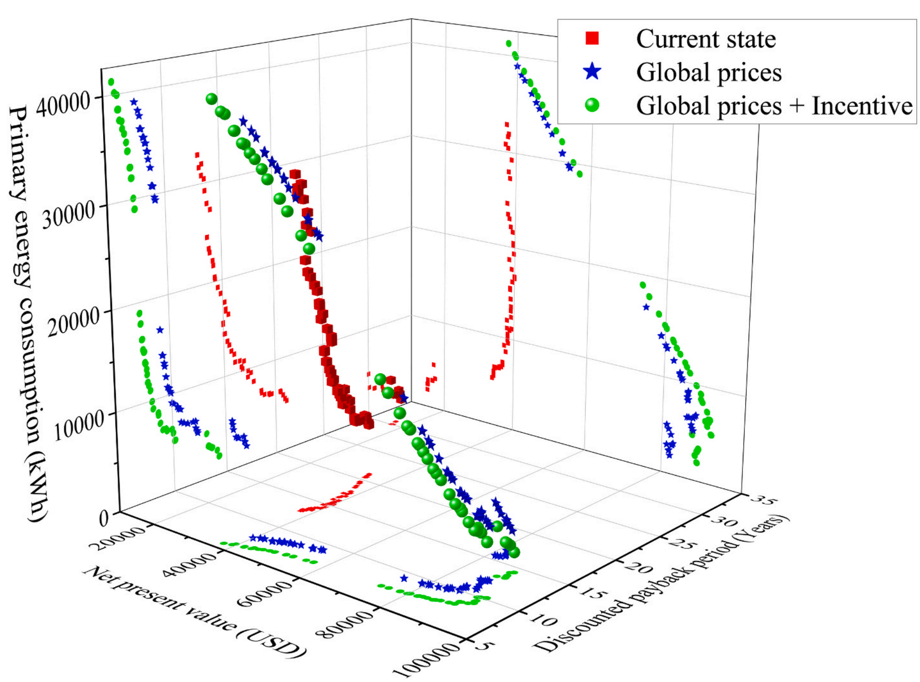

Fig. 17. Comparison of obtained Pareto fronts in three scenarios.

Table 12
Suggested energy efficiency measure and range of objective functions for different scenarios and budget ranges.

Scenario	Budget ($)	Decision variables							Objective functions		
		Wall insulation	Windows glazing	Roof insulation	Airtightness improvement	Cooling system	Heating system	PV (m^2)	PEC (kWh)	NPV ($)	DPP (year)
1	5000 to 15,000	p-100	4-arg-ref	/	Yes	/	/	40	32,000 to 12,000	37,000 to 39,000	13.1 to 15.7
	15,000 to 25,000	p-100	4-arg-ref	p-100	Yes	Split air conditioner	Condensing boiler	40	12,000 to 5000	39,000 to 34,000	15.7 to 21.1
	25,000 to 35,000	p-100	4-arg-ref	p-100	Yes	Water-cooled chiller	GSHP	40	5000 to 2000	34,000 to 15,000	21.1 to 31.8
2	5000 to 15,000	p-100	4-arg-ref	/	Yes	/	New boiler	0	39,000 to 13,000	40,000 to 81,000	7.6 to 9.5
	15,000 to 25,000	p-100	4-arg-ref	p-100	Yes	Split air conditioner	Condensing boiler	40	13,000 to 5000	81,000 to 88,000	9.5 to 12.3
	25,000 to 35,000	p-100	4-arg-ref	p-100	Yes	Water-cooled chiller	GSHP	40	5000 to 2000	88,000 to 89,000	12.3 to 16.9
3	5000 to 15,000	p-100	4-arg-ref	/	Yes	/	New boiler	40	41,000 to 12,000	37,000 to 85,000	5.7 to 7.9
	15,000 to 25,000	p-100	4-arg-ref	p-100	Yes	Water-cooled chiller	Condensing boiler	40	12,000 to 5000	85,000 to 92,000	7.9 to 10.2
	25,000 to 35,000	p-100	4-arg-ref	p-100	Yes	Water-cooled chiller	GSHP	40	5000 to 2000	88,000 to 92,000	10.2 to 14.3

Implementing the developed simulation-based multi-objective optimization in existing buildings requires high expertise and knowledge. However, most building owners and investors do not have the required specialties to use this approach. Therefore, developing a guideline helps investors and homeowners to select energy retrofit strategies and attain a general perception of the approximate results of performing an energy retrofit project on their buildings.

According to Section 4.1, the case study building is representative of a large share of Iran's building stock; hence the general results of this study can be used as a guideline for implementing energy retrofit in similar buildings. As detailed in Table 12, with budget constraints, wall insulation, windows replacement, improving airtightness, and PV panel installation are of high priority. With the increase in available budget, in addition to the above EEMs, roof insulation, upgrading heating, and cooling systems are suggested as EEMs. In the case of an unlimited budget, more expensive heating and cooling systems with high efficiency are recommended.

6. Conclusion

This paper proposes a simulation-based multi-objective optimization framework for building energy retrofits to enhance energy efficiency and maximize economic benefits. The methodology framework consists of 5 steps:

- Step 1: Baseline building model is defined in EnergyPlus software to perform dynamic energy simulations based on energy auditing data.
- Step 2: A parametric building model is developed using decision variables that address key factors pertaining to energy efficiency, including heating and cooling systems, the building envelope elements, and renewable energy sources.
- Step 3: Objective functions of maximizing net present value and minimizing primary energy consumption, and discounted payback period are defined.
- Step 4: A simulation-based multi-objective optimization process based on the integration of EnergyPlus as a dynamic energy simulator and MATLAB as an optimization engine is performed.
- Step 5: A multi-criteria decision-making is conducted to select final solutions from the Pareto front.

A result-saving code is incorporated into the optimization algorithm, which stores simulation results in an archive to be used if required in future iterations to avoid repetition. It was observed that the probability of repeating previously assessed solutions increases by generation. In the optimizations process, the result-saving algorithm managed to gradually reduce the required computational time of each iteration by about 60%. In addition, the optimization process is coded to work in parallel mode. Parallel processing enables performing multiple simulations simultaneously (corresponding to the number of processor cores), significantly reducing computational time.

As a case study, the framework is applied to a single-family residence built in the 1970s in Tehran, Iran. It is highlighted that the framework is tailored to function under Iran's unique economic characteristics. To this end, the ability to calculate energy costs with the step utility tariff policy is incorporated into the framework. Additionally, the framework employs discounted payback period as an objective function which is a useful tool for risk assessment and mitigation, particularly in countries with volatile economic conditions. Notably, results indicate that net present value and primary energy consumption are not necessarily inversely related, as opposed to the relationship between primary energy consumption and discounted payback period. Employing discounted payback period and net present value together maintains the balance between total earnings by the end of building service life and the required time for the project to achieve a break-even point and also provides investors with clear insight into potential economic outcomes.

The impact of possible energy pricing policies on the viability of energy retrofit projects in Iran is examined under three different scenarios. In the first scenario, the current status of energy pricing in Iran, characterized by high subsidize and step utility tariffs, is considered. The idea behind step utility tariff is to encourage residents to curb their energy consumption by applying higher tariffs to high-consumption users. Nevertheless, with the prices being highly subsidized, the energy price is significantly lower than global rates, rendering the step utility policy almost ineffective. This is elucidated in the result of the first scenario, which suggests that although a substantial amount of energy saving can be achieved, widely participation of private investors in building energy retrofitting is highly unlikely due to economic disadvantage (with DPP between 13 years for the cost-effective solution to 32 years for the energy-efficient solution). Thus, it is imperative that to improve the bleak outlook of investment in building energy efficiency, the government must reform energy pricing policies. Accordingly, the second scenario investigated the prospect of rising energy prices to match global rates, which resulted in promising outcomes (with DPP between 7.6 years for the cost-effective solution to 17 years for the energy-efficient solution). Escalating prices, however, could lead to social dissatisfaction, particularly among economically challenged societies. As a solution, the government could redirect financial resources obtained from increased energy prices to provide low-interest loans for building energy retrofit, which is investigated in the third scenario. This strategy could offset the pressure stemming from energy pricing escalation and also provide further impetus for energy retrofitting by funding a portion of the required investment cost. Additionally, offering low-interest loans resulted in further improvement of outcomes in the third scenario (with DPP between 5.8 years for the cost-effective solution to 14.3 years for the energy-efficient solutions).

Overall, and with the existing market condition, wall insulation, windows replacement, improving airtightness, and PV panel installation are cost-effective solutions. However, with an unlimited budget and prioritizing the energy-efficiency, in addition to these EEMs, roof insulation and upgrading heating and cooling systems are also proposed. One notable point in proposed EEMs is the widespread selection of PV panels. High solar radiation, which is one of defining characteristics of Iran's climate, along with the government's pledge to buy exported electricity to the grid at higher rates compared to the selling price of grid electricity, is the main contributing factor to the attractiveness of PV panels. Finally, the findings indicate that the proposed framework enables effective evaluation of potential retrofit solutions, provides insight into outcomes of different scenarios, supports macro-level management and private entrepreneurs in an informed decision-making process, and ultimately facilitates the development of more environmentally friendly building stock in Iran.

7. Limitations and future work

It is worth mentioning that some limitations need to be acknowledged, which set the stage for future studies. First, although the outcomes of this study can serve as a general guideline in similar buildings, generalizing the results to buildings with different functionality, construction technology, and climate would not be reliable. Hence, further research is required to develop a comprehensive guideline by applying the proposed framework to different climatic zones and building categories. Second, since most construction and energy sectors professionals lack the required knowledge and expertise in energy simulation, optimization, and programming to implement the proposed framework, transforming the framework into a user-friendly tool would simplify the process and ensure widespread adaption of this method. Third, outcomes of energy retrofit projects are subjected to several uncertainties, including global warming, variation in energy prices, and human behavior throughout the building life cycle, which lies beyond the scope of this study. Future research could focus on uncertainty and sensitivity analysis which can increase the reliability of results. Ultimately, the present framework is characterized by parallel processing and a result-saving archive, enabling higher computational capabilities compared to conventional methods. Consequently, it paves the way for more time-intensive studies such as designing new sustainable buildings with more design variables and complex case studies.

CRediT authorship contribution statement

Mehdi Tavakolan: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Farzad Mostafazadeh:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Saeed Jalilzadeh Eirdmousa:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Amir Safari:** Conceptualization, Data curation, Methodology, Resources, Writing – original draft. **Kaveh Mirzaei:** Conceptualization, Data curation, Methodology, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] n.d. International energy outlook 2020 https://www.eia.gov/outlooks/ieo/. (Accessed 17 July 2021).
[2] S. Moshiri, F. Atabi, M. Hassan Panjehshahi, S. Lechtenböehmer, Long run energy demand in Iran: a scenario analysis, Int. J. Energy Sect. Manag. 6 (2012) 120–144, https://doi.org/10.1108/17506221211216571.
[3] (n.d.) Energy intensity – sdg7: data and projections – analysis - IEA, https://www.iea.org/reports/sdg7-data-and-projections/energy-intensity. (Accessed 17 July 2021).
[4] (n.d.) Energy subsidies – topics - IEA, https://www.iea.org/topics/energy-subsidies. (Accessed 17 July 2021).
[5] (n.d.) Energy outlook 2018 | news and insights | home, https://www.bp.com/en/global/corporate/news-and-insights/press-releases/energy-outlook-2018.html. (Accessed 17 July 2021).
[6] Y. Zhu, S. Saeidi, T. Rizzuto, A. Roetzel, R. Kooima, Potential and challenges of immersive virtual environments for occupant energy behavior modeling and validation: a literature review, J. Build. Eng. 19 (2018) 302–319, https://doi.org/10.1016/j.jobe.2018.05.017.
[7] S. Barlow, D. Fiala, Occupant comfort in UK offices—how adaptive comfort theories might influence future low energy office refurbishment strategies, Energy Build. 39 (2007) 837–846, https://doi.org/10.1016/j.enbuild.2007.02.002.
[8] A. Jafari, V. Valentin, An optimization framework for building energy retrofits decision-making, Build. Environ. 115 (2017) 118–129, https://doi.org/10.1016/j.buildenv.2017.01.020.
[9] B. Wang, X. Xia, J. Zhang, A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings, Energy Build. 77 (2014) 227–235, https://doi.org/10.1016/J.ENBUILD.2014.03.025.
[10] E.M. Malatji, J. Zhang, X. Xia, A multiple objective optimisation model for building energy efficiency investment decision, Energy Build. 61 (2013) 81–87, https://doi.org/10.1016/J.ENBUILD.2013.01.042.
[11] F.P. Chantrelle, H. Lahmidi, W. Keilholz, M. El Mankibi, P. Michel, Development of a multicriteria tool for optimizing the renovation of buildings, Appl. Energy 88 (2011) 1386–1394, https://doi.org/10.1016/J.APENERGY.2010.10.002.
[12] N. Brito, KarlHöfler, DavidVenus JuliaMaydl, O. Morck, I. Østergaard, K. Thomsen, J. Rose, S. Jensen, HenkKaan ManuelaAlmeida, M. Ferreira, NunoBaptista RuiFragoso, Åke Blomsterberg, BlaisePérisset StéphaneCitherlet, Shining Examples of Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation, Annex 56, 2014.
[13] V. Lapinskiene, V. Martinaitis, The framework of an optimization model for building envelope, Procedia Eng 57 (2013) 670–677, https://doi.org/10.1016/J.PROENG.2013.04.085.
[14] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: methodology and state-of-the-art, Energy Build. 55 (2012) 889–902, https://doi.org/10.1016/J.ENBUILD.2012.08.018.
[15] A.T. Nguyen, S. Reiter, P. Rigo, A review on simulation-based optimization methods applied to building performance analysis, Appl. Energy 113 (2014) 1043–1058, https://doi.org/10.1016/J.APENERGY.2013.08.061.
[16] M. Hamdy, A. Hasan, K. Siren, Optimum design of a house and its HVAC systems using simulation-based optimisation, Int. J. Low Carbon Technol. 5 (2010) 120–124, https://doi.org/10.1093/ijlct/ctq010.
[17] S.A. Sharif, A. Hammad, Simulation-based multi-objective optimization of institutional building renovation considering energy consumption, life-cycle cost and life-cycle assessment, J. Build. Eng. 21 (2019) 429–445, https://doi.org/10.1016/J.JOBE.2018.11.006.
[18] F. Ascione, N. Bianco, R.F. De Masi, G.M. Mauro, G.P. Vanoli, Design of the building envelope: a novel multi-objective approach for the optimization of energy performance and thermal comfort, Sustain. Times 7 (2015), https://doi.org/10.3390/su70810809.
[19] E. Di Giuseppe, M. Iannaccone, M. Telloni, M. D'Orazio, C. Di Perna, Probabilistic life cycle costing of existing buildings retrofit interventions towards nZE target: methodology and application example, Energy Build. 144 (2017) 416–432, https://doi.org/10.1016/J.ENBUILD.2017.03.055.
[20] I. El-Darwish, M. Gomaa, Retrofitting strategy for building envelopes to achieve energy efficiency, Alexandria Eng. J. 56 (2017) 579–589, https://doi.org/10.1016/J.AEJ.2017.05.011.
[21] T. Ashrafian, A.Z. Yilmaz, S.P. Corgnati, N. Moazzen, Methodology to define cost-optimal level of architectural measures for energy efficient retrofits of existing detached residential buildings in Turkey, Energy Build. 120 (2016) 58–77, https://doi.org/10.1016/J.ENBUILD.2016.03.074.
[22] Z. Yong, Y. Li-juan, Z. Qian, S. Xiao-yan, Multi-objective optimization of building energy performance using a particle swarm optimizer with less control parameters, J. Build. Eng. 32 (2020) 101505, https://doi.org/10.1016/J.JOBE.2020.101505.
[23] X. Wang, X. Mao, H. Khodaei, A multi-objective home energy management system based on internet of things and optimization algorithms, J. Build. Eng. 33 (2021) 101603, https://doi.org/10.1016/J.JOBE.2020.101603.

[24] Y. Wang, C. Wei, Design optimization of office building envelope based on quantum genetic algorithm for energy conservation, J. Build. Eng. 35 (2021) 102048, https://doi.org/10.1016/J.JOBE.2020.102048.
[25] B. Liu, D. Rodriguez, Application of multi-objective optimization model to assess the energy efficiency measures for the cases of Spain, J. Build. Eng. 38 (2021) 102144, https://doi.org/10.1016/J.JOBE.2020.102144.
[26] Y. Sun, X. Luo, X. Liu, Optimization of a university timetable considering building energy efficiency: an approach based on the building controls virtual test bed platform using a genetic algorithm, J. Build. Eng. 35 (2021) 102095, https://doi.org/10.1016/J.JOBE.2020.102095.
[27] K. Mirzaei, A. Safari, S. Jalilzadeh, F. Mostafazadeh, M. Tavakolan, M. Safari, Environmental, social, and economic benefits of buildings energy retrofit projects: a case study in Iran's construction industry, Constr. Res. Congr. (2020) 693–701, https://doi.org/10.1061/9780784482858.075.
[28] N. Delgarm, B. Sajadi, F. Kowsary, S. Delgarm, Multi-objective optimization of the building energy performance: a simulation-based approach by means of particle swarm optimization (PSO), Appl. Energy 170 (2016) 293–303, https://doi.org/10.1016/J.APENERGY.2016.02.141.
[29] S. Chang, D. Castro-Lacouture, Y. Yamagata, Decision support for retrofitting building envelopes using multi-objective optimization under uncertainties, J. Build. Eng. 32 (2020) 101413, https://doi.org/10.1016/j.jobe.2020.101413.
[30] F. Ascione, N. Bianco, T. Iovane, G.M. Mauro, D.F. Napolitano, A. Ruggiano, L. Viscido, A real industrial building: modeling, calibration and Pareto optimization of energy retrofit, J. Build. Eng. 29 (2020) 101186, https://doi.org/10.1016/j.jobe.2020.101186.
[31] A.A.S. Bahdad, S.F.S. Fadzil, H.O. Onubi, S.A. Ben Lasod, Sensitivity analysis linked to multi-objective optimization for adjustments of light-shelves design parameters in response to visual comfort and thermal energy performance, J. Build. Eng. (2021) 102996, https://doi.org/10.1016/J.JOBE.2021.102996.
[32] U. Acar, O. Kaska, N. Tokgoz, Multi-objective optimization of building envelope components at the preliminary design stage for residential buildings in Turkey, J. Build. Eng. 42 (2021) 102499, https://doi.org/10.1016/J.JOBE.2021.102499.
[33] M. Ghaderian, F. Veysi, Multi-objective optimization of energy efficiency and thermal comfort in an existing office building using NSGA-II with fitness approximation: a case study, J. Build. Eng. 41 (2021) 102440, https://doi.org/10.1016/J.JOBE.2021.102440.
[34] Y. Dong, C. Sun, Y. Han, Q. Liu, Intelligent optimization: a novel framework to automatize multi-objective optimization of building daylighting and energy performances, J. Build. Eng. 43 (2021) 102804, https://doi.org/10.1016/J.JOBE.2021.102804.
[35] C. Diakaki, E. Grigoroudis, N. Kabelis, D. Kolokotsa, K. Kalaitzakis, G. Stavrakakis, A multi-objective decision model for the improvement of energy efficiency in buildings, Energy 35 (2010) 5483–5496, https://doi.org/10.1016/J.ENERGY.2010.05.012.
[36] A. Kusiak, G. Xu, F. Tang, Optimization of an HVAC system with a strength multi-objective particle-swarm algorithm, Energy 36 (2011) 5935–5943, https://doi.org/10.1016/J.ENERGY.2011.08.024.
[37] I. García Kerdan, R. Raslan, P. Ruyssevelt, D. Morillón Gálvez, A comparison of an energy/economic-based against an exergoeconomic-based multi-objective optimisation for low carbon building energy design, Energy 128 (2017) 244–263, https://doi.org/10.1016/J.ENERGY.2017.03.142.
[38] P. de Wilde, Building performance analysis, Build. Perform. Anal. (2018), https://doi.org/10.1002/9781119341901.
[39] S. Stevanović, Optimization of passive solar design strategies: a review, Renew. Sustain. Energy Rev. 25 (2013) 177–196, https://doi.org/10.1016/J.RSER.2013.04.028.
[40] S. Murray, B. Walsh, D. Kelliher, D. O' Sullivan, Multi-variable optimization of thermal energy efficiency retrofitting of buildings using static modelling and genetic algorithms - a case study, Build. Environ. 75 (2014), https://doi.org/10.1016/j.buildenv.2014.01.011.
[41] B. Rosti, A. Omidvar, N. Monghasemi, Optimal insulation thickness of common classic and modern exterior walls in different climate zones of Iran, J. Build. Eng. 27 (2020) 100954, https://doi.org/10.1016/J.JOBE.2019.100954.
[42] G.M. Mauro, M. Hamdy, G.P. Vanoli, N. Bianco, J.L.M. Hensen, A new methodology for investigating the cost-optimality of energy retrofitting a building category, Energy Build. 107 (2015) 456–478, https://doi.org/10.1016/J.ENBUILD.2015.08.044.
[43] (n.d.) EnergyPlus | EnergyPlus, https://energyplus.net/. (Accessed 17 July 2021).
[44] M. Ferrara, E. Fabrizio, J. Virgone, M. Filippi, A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings, Energy Build. 84 (2014) 442–457, https://doi.org/10.1016/J.ENBUILD.2014.08.031.
[45] (n.d.) MATLAB runtime - MATLAB compiler - MATLAB, https://www.mathworks.com/products/compiler/matlab-runtime.html. (Accessed 17 July 2021).
[46] M. Fesanghary, S. Asadi, Z.W. Geem, Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm, Build. Environ. 49 (2012) 245–250, https://doi.org/10.1016/J.BUILDENV.2011.09.030.
[47] (n.d.) DesignBuilder software ltd - home, https://designbuilder.co.uk/. (Accessed 17 July 2021).
[48] S.I. Gustafsson, Optimisation and simulation of building energy systems, Appl. Therm. Eng. 20 (2000) 1731–1741, https://doi.org/10.1016/S1359-4311(00)00004-1.
[49] G. Kumbaroglu, R. Madlener, Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy Build. 49 (2012) 327–334, https://doi.org/10.1016/J.ENBUILD.2012.02.022.
[50] R. Ruparathna, K. Hewage, R. Sadiq, Economic evaluation of building energy retrofits: a fuzzy based approach, Energy Build. 139 (2017) 395–406, https://doi.org/10.1016/J.ENBUILD.2017.01.031.
[51] C. Zhang, M. Hu, B. Laclau, T. Garnesson, X. Yang, A. Tukker, Energy-carbon-investment payback analysis of prefabricated envelope-cladding system for building energy renovation: cases in Spain, The Netherlands, and Sweden, Renew. Sustain. Energy Rev. 145 (2021) 111077, https://doi.org/10.1016/J.RSER.2021.111077.
[52] S. Ahmadi, A.H. Fakehi, A. Vakili, M. Moeini-Aghtaie, An optimization model for the long-term energy planning based on useful energy, economic and environmental pollution reduction in residential sector: a case of Iran, J. Build. Eng. 30 (2020) 101247, https://doi.org/10.1016/J.JOBE.2020.101247.
[53] M. Tahsildoost, Z.S. Zomorodian, Energy retrofit techniques: an experimental study of two typical school buildings in Tehran, Energy Build. 104 (2015) 65–72, https://doi.org/10.1016/J.ENBUILD.2015.06.079.
[54] A. Balali, A. Hakimelahi, A. Valipour, Identification and prioritization of passive energy consumption optimization measures in the building industry: an Iranian case study, J. Build. Eng. 30 (2020) 101239, https://doi.org/10.1016/J.JOBE.2020.101239.
[55] A.S. Javid, F. Aramoun, M. Bararzadeh, A. Avami, Multi objective planning for sustainable retrofit of educational buildings, J. Build. Eng. 24 (2019) 100759, https://doi.org/10.1016/J.JOBE.2019.100759.
[56] E. Asadi, M.G. da Silva, C.H. Antunes, L. Dias, A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB, Build. Environ. 56 (2012) 370–378, https://doi.org/10.1016/J.BUILDENV.2012.04.005.
[57] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, A screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings, Energy Build. 43 (2011) 614–620, https://doi.org/10.1016/J.ENBUILD.2010.11.002.
[58] E. Antipova, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, L. Jiménez, Multi-objective optimization coupled with life cycle assessment for retrofitting buildings, Energy Build. 82 (2014) 92–99, https://doi.org/10.1016/J.ENBUILD.2014.07.001.
[59] O. Irulegi, A. Ruiz-Pardo, A. Serra, J.M. Salmerón, R. Vega, Retrofit strategies towards net zero energy educational buildings: a case study at the university of the Basque country, Energy Build. 144 (2017) 387–400, https://doi.org/10.1016/J.ENBUILD.2017.03.030.
[60] F. Ascione, N. Bianco, R.F. De Masi, G.M. Mauro, G.P. Vanoli, Energy retrofit of educational buildings: transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance, Energy Build. 144 (2017) 303–319, https://doi.org/10.1016/J.ENBUILD.2017.03.056.
[61] O. Pombo, K. Allacker, B. Rivela, J. Neila, Sustainability assessment of energy saving measures: a multi-criteria approach for residential buildings retrofitting—a case study of the Spanish housing stock, Energy Build. 116 (2016) 384–394, https://doi.org/10.1016/J.ENBUILD.2016.01.019.
[62] G. Gourlis, I. Kovacic, Building Information Modelling for analysis of energy efficient industrial buildings – a case study, Renew. Sustain. Energy Rev. 68 (2017) 953–963, https://doi.org/10.1016/J.RSER.2016.02.009.
[63] A.M. Rysanek, R. Choudhary, Optimum building energy retrofits under technical and economic uncertainty, Energy Build. 57 (2013) 324–337, https://doi.org/10.1016/J.ENBUILD.2012.10.027.
[64] D. Duah, M. Syal, Intelligent decision support system for home energy retrofit adoption, Int. J. Sustain. Built Environ. 5 (2016) 620–634, https://doi.org/10.1016/J.IJSBE.2016.05.003.
[65] (n.d.) L_2018156EN.01007501.xml, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L0844&rid=7. (Accessed 17 July 2021).
[66] F. Maamari, M. Andersen, J. de Boer, W.L. Carroll, D. Dumortier, P. Greenup, Experimental validation of simulation methods for bi-directional transmission properties at the daylighting performance level, Energy Build. 38 (2006) 878–889, https://doi.org/10.1016/J.ENBUILD.2006.03.008.
[67] J. Swan, Mainly functions, Pract. Financ. Model. (2016) 157–205, https://doi.org/10.1016/B978-0-08-100587-3.00006-3.
[68] J.J. Wild, K.W. Shaw, B. Chiappetta, Financial and Managerial Accounting, Information for Decision, 2018.
[69] K. Palmer, M. Walls, H. Gordon, T. Gerarden, Assessing the energy-efficiency information gap: results from a survey of home energy auditors, Energy Effic 6 (2013) 271–292, https://doi.org/10.1007/s12053-012-9178-2.
[70] M. Achtnicht, R. Madlener, Factors influencing German house owners' preferences on energy retrofits, Energy Pol. 68 (2014) 254–263, https://doi.org/10.1016/J.ENPOL.2014.01.006.
[71] S. Banfi, M. Farsi, M. Filippini, M. Jakob, Willingness to pay for energy-saving measures in residential buildings, Energy Econ. 30 (2008) 503–516, https://doi.org/10.1016/J.ENECO.2006.06.001.
[72] M. Achtnicht, Do environmental benefits matter? Evidence from a choice experiment among house owners in Germany, Ecol. Econ. 70 (2011) 2191–2200, https://doi.org/10.1016/J.ECOLECON.2011.06.026.
[73] M.G. Bjørneboe, S. Svendsen, A. Heller, Initiatives for the energy renovation of single-family houses in Denmark evaluated on the basis of barriers and motivators, Energy Build. 167 (2018) 347–358, https://doi.org/10.1016/J.ENBUILD.2017.11.065.
[74] K. Deb, in: L. Wang, A.H.C. Ng, K. Deb (Eds.), Multi-objective Optimisation Using Evolutionary Algorithms: an Introduction BT - Multi-Objective Evolutionary Optimisation for Product Design and Manufacturing, Springer London, London, 2011, pp. 3–34, https://doi.org/10.1007/978-0-85729-652-8_1.

[75] E. Zitzler, K. Deb, L. Thiele, Comparison of multiobjective evolutionary algorithms: empirical results, Evol. Comput. 8 (2000) 173–195, https://doi.org/10.1162/106365600568202.
[76] (n.d.) Statistical center of Iran > population and housing censuses > census 2016 - general results, https://www.amar.org.ir/english/Population-and-Housing-Censuses/Census-2016-General-Results. (Accessed 1 October 2021).
[77] (n.d.) I.R.OF Iran meteorological organization, https://www.irimo.ir/eng/index.php. (Accessed 30 September 2021).
[78] Y. Ding, Y. Shen, J. Wang, X. Shi, Uncertainty sources and calculation approaches for building energy simulation models, Energy Procedia 78 (2015) 2566–2571, https://doi.org/10.1016/J.EGYPRO.2015.11.283.
[79] (n.d.) Global solar atlas, https://globalsolaratlas.info/map. (Accessed 17 July 2021).
[80] A. Karatas, K. El-Rayes, Optimizing tradeoffs among housing sustainability objectives, Autom. ConStruct. 53 (2015) 83–94, https://doi.org/10.1016/j.autcon.2015.02.010.
[81] Y.F. Li, M. Xie, T.N. Goh, A study of project selection and feature weighting for analogy based software cost estimation, J. Syst. Software 82 (2009) 241–252, https://doi.org/10.1016/J.JSS.2008.06.001.
[82] Y.F. Li, S.H. Ng, M. Xie, T.N. Goh, A systematic comparison of metamodeling techniques for simulation optimization in Decision Support Systems, Appl. Soft Comput. 10 (2010) 1257–1273, https://doi.org/10.1016/J.ASOC.2009.11.034.