Building performance simulation in architectural design

Jon Wedersøe Strunge

Søren Jensen Rådgivende Ingeniører A/S

Copenhagen, Denmark, jws@sj.dk

Abstract

Building physics is key when designing architecture of high comfort and energy efficiency quality, but knowledge hereof is rarely utilized and integral when opportunities for influence is present. Rapid development of new tools in digital modelling has potential to change existing design processes. The paper contributes to existing limited research on whether such tools can be adopted into design practice. Experiences on implementing the BPS open source interface Honeybee in a Danish practice demonstrates increased holistic project qualities. Together with a performed positive BESTest validation of the interface, barriers for a more widespread introduction of such a tool in the industry is delimited. Through reflection on an innovation model grounded in learning theory and design thinking, it is suggested that by engaging designers in this mindset enables an influential role of such tools.

Keywords: Parametric design, Honeybee, validation, case studies, design thinking

1. Introduction

Today building designers are faced with many value interests driven by societal changes. Demands on energy efficiency leads to efficient installation design, use of renewable energy and efficient envelope design. With this aesthetic, economic values and an increased focus on health with its broad physiological effects of the indoor environment constitutes a multiplicity of design factors that individualizes the building project as a prototype distinguished from serial consumer of industrial mass production [1]. Market statistics show that today most companies are struggling with innovating [3]. 10% of new prototypes succeed, the top reason for failing being that there is no market need [4], that they are not made for the users. In the design of buildings of high sustainable quality, it is crucial integrate a specialist of buildings physics to develop, test and implement ideas when opportunities to influence the design is present. High performance systems and components added on retrospectively cannot overcome the handicaps imposed by the poor initial design decisions [1].

1.1 Innovation in building design as a interdisciplinarity learning process

Through 60 years of preceding research on design methodologies, there has been several suggestions on how to formalize design approaches in contexts in which professionals of different professional backgrounds collaborates. Starting from 1st and 2nd generation [3], to later e.g. performance based [5] and recent discourse attempts to provide an integrated view of design as a problem-solving process that involves players from multiple disciplines [1, 3]. There is not much knowledge on whether the suggestions are adopted in design practices, the notion is that it is not common [6]. A reason might be that methodologies structured as processes with series of rigid tasks might be too idealized, or they interpret wrong what designers need [7] to support today’s conditions.

The notion that innovation requires putting together professionals from diverse backgrounds is not new. Neither is the process of design thinking that concerns the understanding of the design problem that creates most user value. A recent view is that companies exhibits a barrier in not understanding of the fundamental principles hereof [3]. It proposes a generic innovation model grounded in models of how people learn. The model has evolved through two streams of thought: design and learning. It stands out by acknowledging that professionals each learn and communicate in distinctive ways. When all humans are faced with a complex problem however, the same learning process with four thinking steps occurs: reflective observation, abstract conceptualization, active experimentation ending in concrete experience, in with each people of diverse backgrounds will work distinctively. The approach embeds this into design thinking and describes an innovation process in four steps: reflecting on design brief to find problems, conceptualizing selected problems, finding solutions and from that gain new experiences to select solutions. Through iterative learning cycles new problems are found and the understanding of the complex problem is increased [3]. Reflection on this, it is opportune that in active experimentation designers each apply their culturally preferred method, whereas reflecting, conceptualizing and finding the right solution done as a collective process can lead to achieve an “eureka” experience and finding of the right solution that included the aspects of building physics.

Prototypes that do not have adequate answers in heuristics can benefit from BPS. The functionality of traditional decoupled third-party building performance simulation tools (BPS) tools, such as IES-VE [11], is limited to the later design phases as a notable number of steps is needed when geometry, zoning etc. undergoes changes. Rapid development of new tools in digital modelling design theories and processes are undergoing reformulation into new ways of working [8]. Parametric Design Thinking concerns an understanding of structures of complex design knowledge, through establishing relationships between properties within a system. In this way, more alternative solutions can be explored by changing the parameters of the logical relationships. Designers can return in any stage and revise parameters or rules to modify their design or pursue a different one. This allows them methodologically to keep the design process open and flexible, that provides an explorative mechanism for transformation and generation of variation and thus supporting the generic innovation model.

1.2 Scope

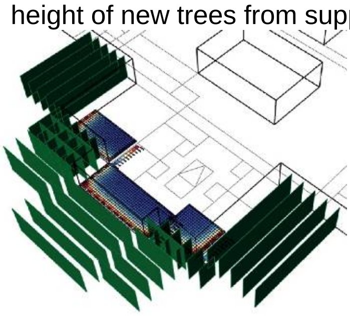
Given the rapid development of digital modelling tools it has become important to understand the role of parametric tools on design [8]. The aim of this paper is to supplement the understanding of the role and opportunities of emerging parametric BPS in the creation of building of high architectural, energy efficiency and comfort quality. How fit is the tool Honeybee (HB), in learning about the building physics of an idea in the context of interdisciplinary early stage prototyping. This is investigated through three case studies from a Danish practice. Furthermore, a BESTest validation of HB is presented as the open source interfaces has not yet been officially validated using a standard, which potentially holds a barrier for its widespread among advanced users due to reluctance in trusting the outputs.

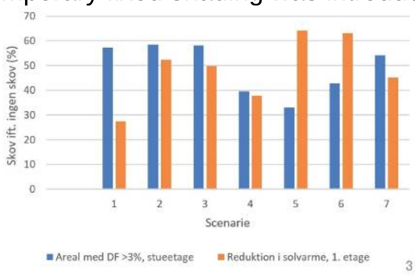
2. Cases

Three cases of conceptual integrated design projects have been developed with the aid of HB for climate-based daylight and hourly thermal simulation using state of the art performance metrics [9,10]. As most clients apply the platform of Rhino, only minor adjustsments is made to translate the sketched geometry into energy models. As eloborated in the following sections generally cases are progressed through the theoretical model described in Section 1, demonstrating how a tool can be used in such a mindset.

2.1 Integrating design of context with façade and hvac

In a design competition of a school with a brief on sustainable design that supported nudging of sustainability a design question was whether mechanical cooling in classrooms could be avoided considering lightweights wall and an open cleared site. Through analysis in HB it was learned that this was not possible. Without building automation and due to the fact that fixed shadings would decrease daylight levels from diffuse skylight, the team came up with the idea of planting the new forest surrounding the school. Using volumetric deciduous trees such as beech or elm, close to the façade, they would function as passive shading with a natural regulation of increased daylight outside the cooling season, integrated in the design of the façade and the ventilation system. HB was used to simulate the daylight factor and hourly simulation of thermal adaptive comfort in a classroom and a transmittance using a schedule to simulate the estimated yearly variation of diffuse and direct transmittance of the trees. Variations of heights, distances and number of rows geometrically simplified as seen in *Figure 1*, was investigated in balancing diffuse daylight and solar heat gain. The best combination was simulated for indoor comfort. As the needed height was larger than the height of new trees from supply, a temporary fixed shading was introduced during the short growing period.





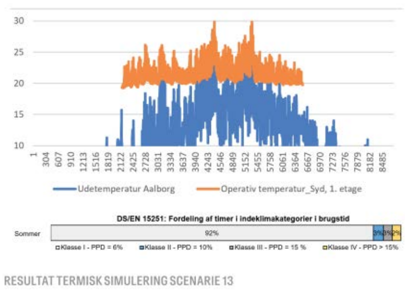


Figure 1. Analysis of context. Energy model (left), reduction of daylight factor and solar gain in percentage respectively (middle), operative and outdoor temperature (right)

2.2 Envelope design for contradicting view and daylight

In the design of the daylight openings and structural system for a new church and cultural center with complex geometry called a multidisciplinary design approach was undertaken. One goal was to elevate daylight levels without allowing for a direct view in from an exterior surrounding spiraling ramp and maintaining structural integrity. Through collective conceptualization one idea was to introduce an integrated wall reflector below the overhanging ramp. A daylight factor, Useful Daylight Index and spatial luminance was simulated in HB. This improved daylight factor slightly from 0-0,25% to only 0,5-1%. The solution was adjusted by elevating the wall diffusor above the ramp which elevated the daylight factor to 2-4%. In a following series of design investigations of other candidates was selected, deselected and combined.

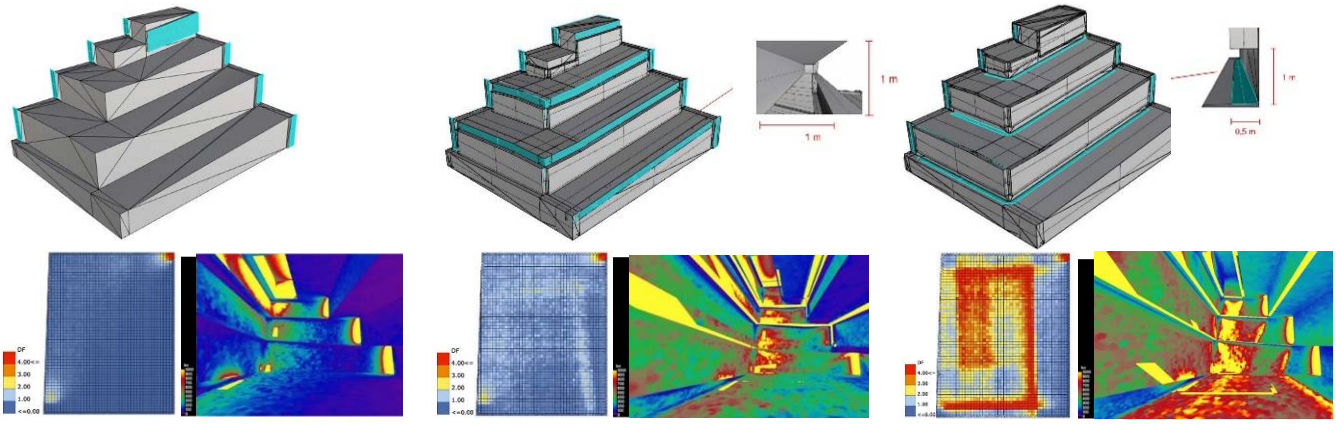


Figure 2. Daylight analysis of variations in envelope openings. Upper: variations in geometry, Lower: Daylight factor in plan and spatial illuminance. Exterior walking ramp is not shown.

2.3 Flexibility to balance high performing façade with plan

In the conceptual planning of functions and façade design of a hospital, the goal was to realize high openness towards the exterior while keeping a high level of thermal and visual comfort. The concept was variations of window area with varying depth and distance of exterior fins. Through massing studies of incident radiation using Ladybug (LB) [2] an understanding of placement of zones of different typologies could be applied per orientation and function. Since then a simulation of operative temperature and Useful Daylight Illuminance was found valuable in selecting between solutions.

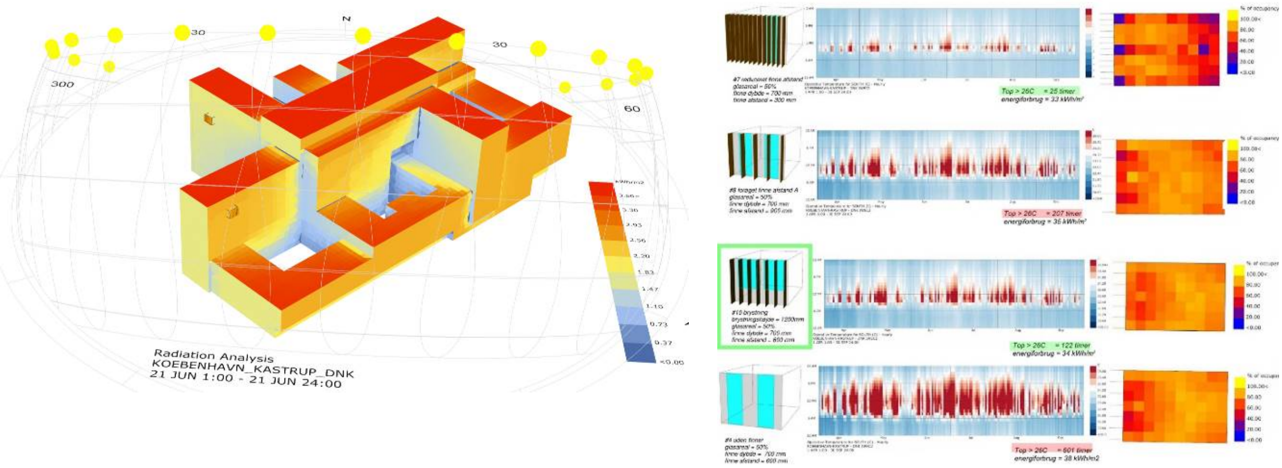


Figure 3. Comfort analysis of hospital. Left: incident radiation for planning of functions and façade typologies using LB. Right: holistic facade study of operative temperature heatmap and UDI using HB

3. Validation

3.1 Scope

HB is developed by a group of contributing programmers and tested by large community. The need for new functionalities is identified and fixed, and so are errors in the interface. The present validation will test the validity of basic functionalities needed for early stage design with emphasis on massing and envelope. The tested version of HB is 0.0.61 coupled to OpenStudio 1.12.0, a validated BPS [16] fully integrated into Grasshopper3D. The scope therefore concerns the interface and the dataflow of HB, including parsing Rhino geometry to zones, writing a full EnergyPlus input-file (IDF/OSM), running the simulation, and reading the simulated result file (CSV) into Grasshopper3D for post-processing and visualization as illustrated in *Figure 4*.

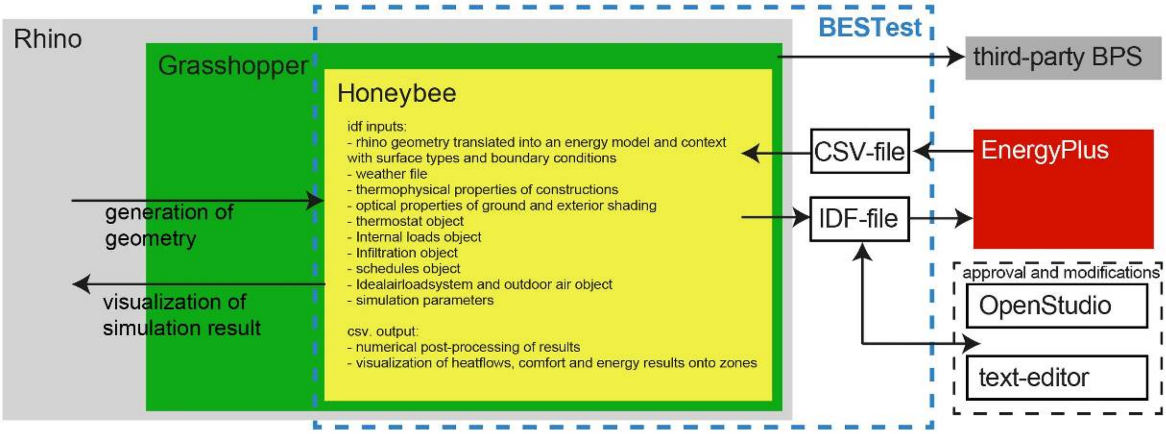


Figure 4: Dataflows occurring from and to HB and scope of BESTest in blue dotted line

3.2 Method

The BESTest validation is a procedure developed for testing, diagnosing and validating the capacities of BPS tools [13, 14]) assumed as the official standard procedure for new BPS validation by IEA. CEN has adopted the procedure as the test for checking the reference cooling load and energy calculation methods based on the requirements of several standards addressing various aspects of the EPBD [15]. The procedure consists of a series of analytical tests in which the results from new tools is to be compared with results obtained by 7 current state of the art tools. Cases that concerns the building thermal envelope and fabric tests are documented. Geometrical and energy modelling inputs are scripted in Grasshopper3D following the procedures described in the ANSI/ASHRAE Standard 140-2014 [13], *Figure 5* and *Figure 6*.

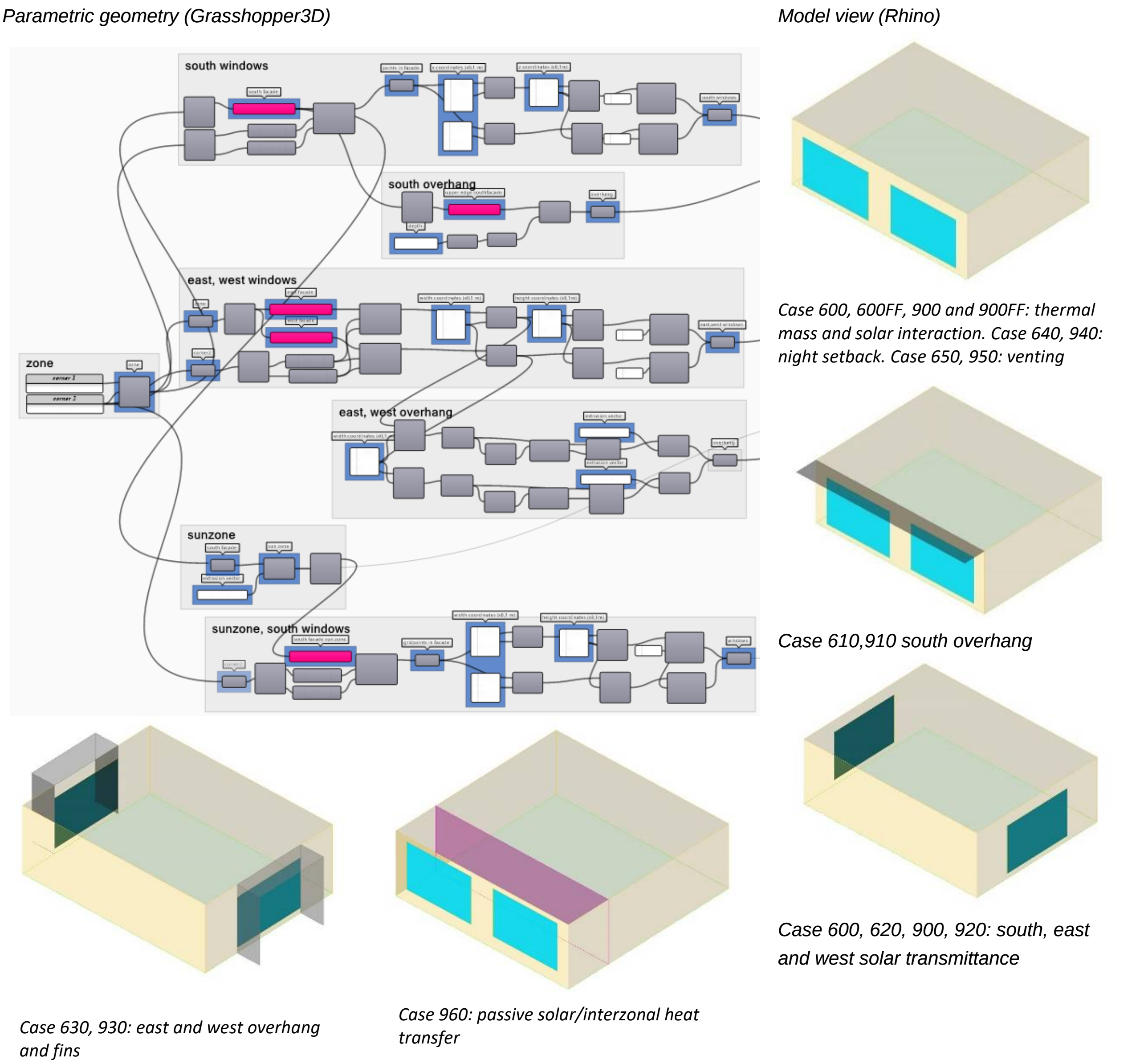


Figure 5. Parametric model and characteristics of BESTest Cases 600 to 960. The following modelling settings are used: Inside/outside convection algorithm = TARP/DOE-2. Solar distribution effect for shade surfaces = FullInteriorAndExterior. Shadow calculation = average over days in frequency of 1 day. Fixed ground temperature = 10C. Timestepsperhour = 4. Min. warmup days = 7.

3.2.1 Energy modelling procedures in HB

Honeybee supports the set-up of basic EnergyPlus system objects as illustrated in *Figure 4*. In addition. The workflow is such that a full input file with standardized values for selected EnergyPlus objects is created when Rhino geometry initially are converted to HB zones "MassingToZones", as mentioned in [2].
In the downstream dataflow, as HB modules such as constructions, schedules, thermostat setpoints, and systems, the upstream data is overwritten. The complete energy model needed for setting up the properties of the validation cases is illustrated in *Figure 6*. To determine boundary conditions, the zones is to be processed in "SolveAdjacencies". Constructions is defined for the low and high mass case respectively using the modules "EPConstruction" and "EPMaterial". The default HVAC system is an idealairloadsystem, including an air economizer. In the validation cases the system should supply cooling or heating air to the zones to meet the zone loads specified by the thermostat. The air economizer therefore is deactivated downstream in "HVAC systems". The output variable for annual incident solar radiation on exterior surfaces

cannot be requested by default. By parsing this in the module “Read Result Dictionary” a corresponding EnergyPlus output variable is identified and inputted for simulation.

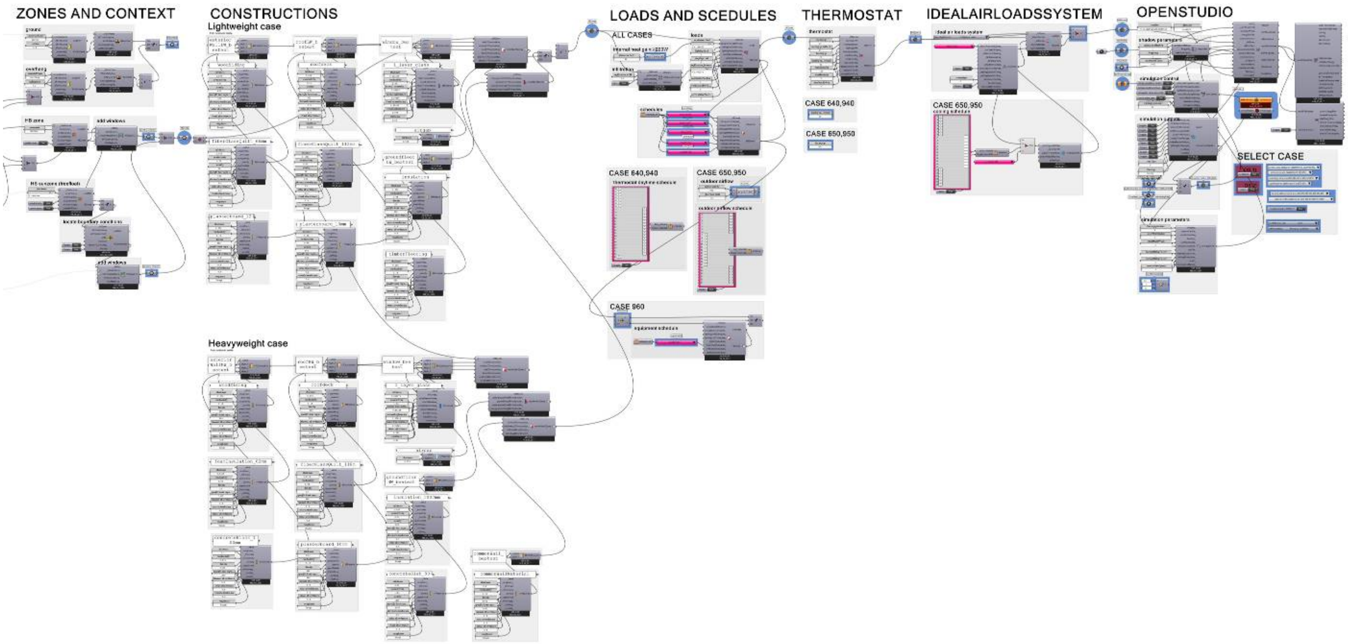


Figure 6. HB input modules CASE600-960, BESTest in Grasshopper3D. From left to right: creating of condition zones, and downstream specifying inputs and finally coupling to OpenStudio.

Inputs can be applied for the zones collectively or separating zones to create individual and inputs to account for differentiated properties of different zone characteristics, as exemplified in *Figure 7*.

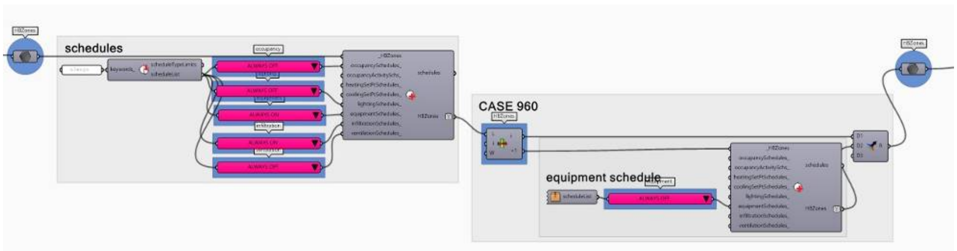


Figure 7. Specification of global schedules (left), specification of schedule for internal loads separate for the sunzone (right)

3.3 Results

HB surpasses the BESTest for Case600 through 960. Overall low deviations are obtained in the results from all the simulated cases against those provided in the validation procedure. One deviation is the annual heating that are too low, otherwise no errors were found in the tested native HB modules using the exemplified in workflow in section 3.2.

3.3.1 Transmitted and incident solar radiation

All cases show results that are within the lower and upper limits of the results for comparison, except for the annual indicent solar radiation on the horisontal surface that exceed the upper limit by 2%, see *Figure 8.*

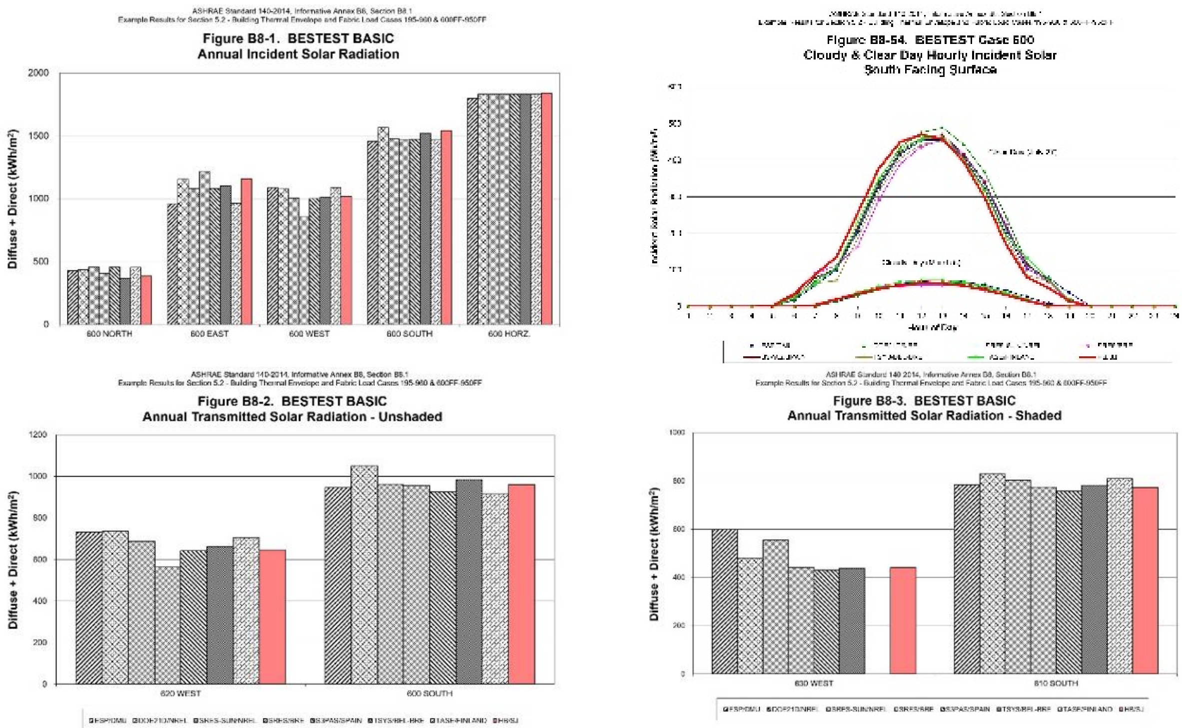
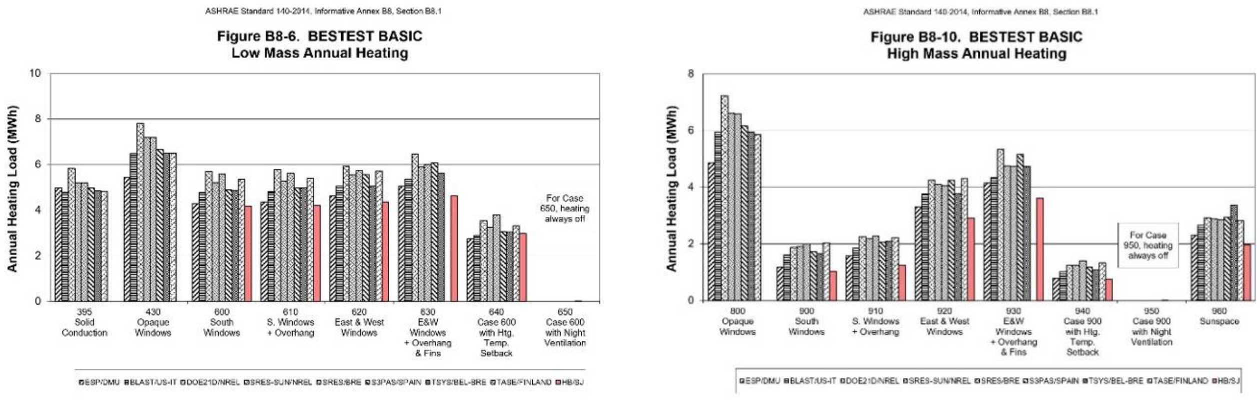


Figure 8.Results from HB BESTest on transmitted and incident solar radiation

3.3.2 Heating and cooling loads

The annual loads results in *Figure 9*, show heating demands with a general lower values among the tools. The low mass cases are 3-8% lower than the second lowest, and the high mass are about 6-20% lower. The official EnergyPlus BESTest [20], show similarly some of the lowest values implying that the code itself provides calculate low heating values. However with this large exceedence, this must be ascribed to some lesser input error and will be reported. For both low and high mass cases all annual cooling loads are within the limits, as are all peak heating and cooling loads as shown *Figure 10*.



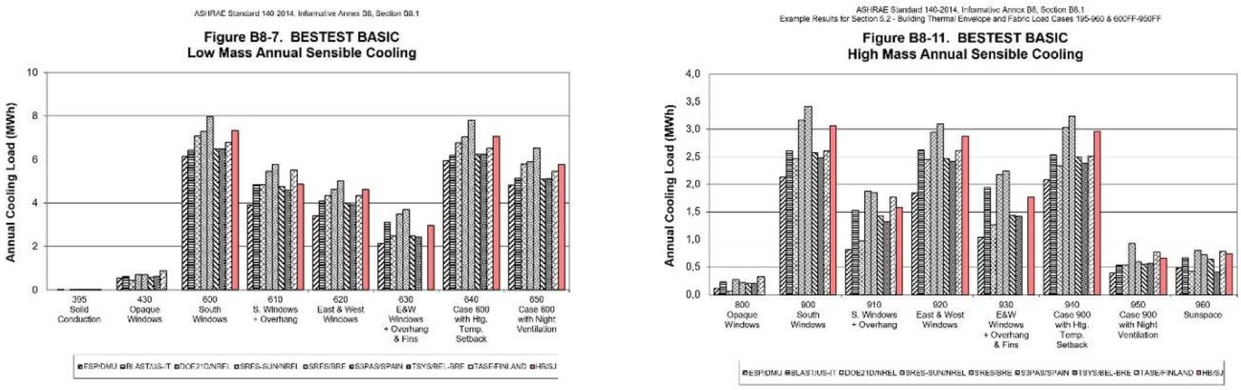


Figure 9. Results from HB BESTest on heating and cooling loads

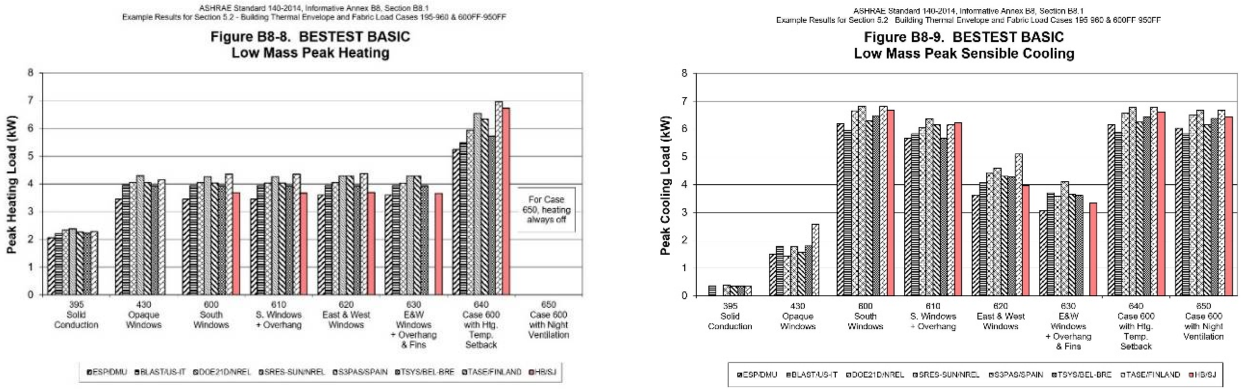


Figure 10. Results from HB BESTest on peak heating and cooling loads

3.3.3 Free-float temperatures

The results in *Figure 11* show hourly and extreme temperature from the simulated series of free-floating cases. Most results, including hourly cold and hot days and yearly min. and max. temperaures are within the limits, except for Case600FF and 900FF that exceeds the limit of the yearly average temperature by 4-5% These results indicate the the found delta annual heating load might originate from user- or module input erros concerning the heating system.

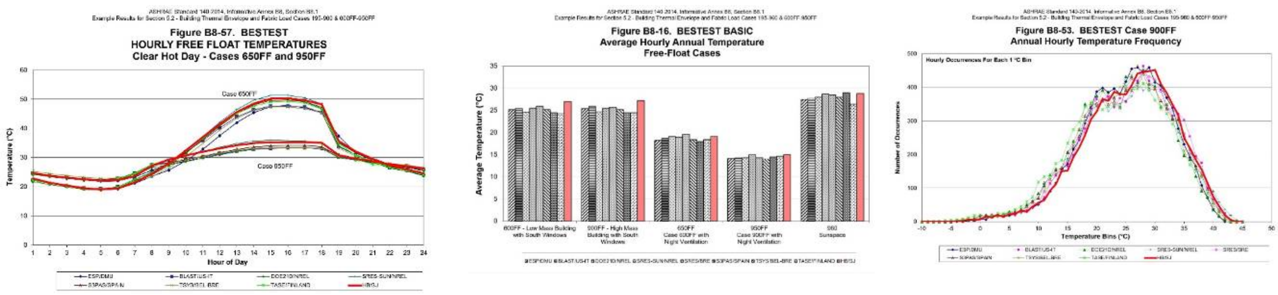


Figure 11. Results from HB BESTest on free-floating temperatures

3.4 Speed

Simulation speeds was measured during the validation with aim of identifying appropriate HB simulation parameters with potential settings to improve speed without compromising validity, see *Table 1*. The findings show potential time savings of 280% of changing inputs in selected three input parameters as shown below with insignificant changes in results. The time spent on reading results in all cases, doubling the total computation time for one analysis. By combining 1) and 2) the total computational runtime for single zone can be reduced to 12,2 seconds for a single zone model and 14,2 for a two-zoned model, respectively.

As complex geometry and multiple zones are not considered, more extensive study however is advisable. The duo-zone to single-zone model has about 20% slower simulation speed.

	idealairloadsystem						**hvac system[2)]**	
	max shadow calc.				**red. shad. calc[1)]**		**max shadow calc.**	
	51 output var.		**4 output var.[3)]**		**51 output var.**		**51 output var.**	
Case	Run [sec]	Read [sec]	Run [sec]	Read [sec]	Run [sec]	f. loads** [%]	Run [sec]	Read [sec]
600	18,2	16,1	18,4	2,5	9,7	1,5 / 4	34,0	22,4
630 (shading)	17,5	18	17,5	2,5	10	0,2 / 1,5	31,9	22,3
960 (multizone)	21,6	19,7	19,9	2,2	12	0,5 / 4	31,6	27,9

Table 1. Time durations on simulation and result read for variations of three HB BESTest cases using a Surface 4 (8 GB ram, i5-6300U 2,5 GHz). For 1)-3) see description above table,

1) Recued shadow calculation by changing averaging of calculation from daily to monthly. The difference in the total heating and cooling load is in the range of 0,5-4%. The simulation time is reduced by approximately 80%. Changes in parameter maximum figure have no real influence.
2) Simulation of a full HVAC template system (OpenStudio System 5: Packaged VAV w. Reheat, selected inputs: 1 outdoor air change and no economizer). Compared to the idealairloadsystem the simulation run speed is 80% more time consuming for the single zones, and 45% for the multizone.
3) Reducing the number of requested output variables from maximum HB setting, to only the ones necessary to post-process the BESTest results the load duration is reduced 5-600%.

4. Reflection

4.1 Framing vs. optimization

The use of an innovation model including an iterative process of finding problems and solutions holds challenges in a seemingly common view of high performing design as being optimization. As optimizing one problem does not necessarily the most value, if it is not the right problem, the cyclic solution findings of the seggregated disiplines have to be integrated ongoingly, because this will create experiences that inspires new questions regarding the design development. The finding from the cases is that designers can benefit from being mindful of design thinking and parametric design and the process is very mush depended of a willingness from all parts.

4.2 User skills and the balance with inputs and outputs

Being analogue or digital each professional each seek distinctive characteristics of their tools. For BPS engineers seek validity, control and transparency whereas architects seek speed, flexibility and visualization [12]. Seen in the context of the innovation model all tool characteristics needs to be present, as validity is needed for learning on problem and solution, flexibility for broad and advanced investigation, visualization for collective reflection and speed to allow for rapid changes. Through the 3 cases these traits are considered as handled by HB making it an all-encompassing tool. As the characteristics vary the building professional in between, it remains unclear how users of different backgrounds should apply it. Considering early stage analysis as the ability compare which solution are better in comparison, this includes simplifying problems of high input uncertainty to match sensitivity of the output related to the design problem. For massing analysis, window ratios and SHGC is less influential on the relevant output metric, while façade analysis will have other parameters that are sensitive in relevant analysis. This includes making a series of assumptions on parameters as these are unsettled at the time of analysis [7]. The process therefore benefits from knowledge that enables transformation of abstract concepts into appropriate meaningful building physical analysis including understanding design goals and which to outputs to request. The process is therefore, besides the flexibility of the tool, limited to the skills of the user. The process of conceptualizing and analyzing strategies that creative innovative solutions fundamentally requires expert knowledge in each respective professional field.

LB/HB enables segregated levels of details in inputs and output levels and thus multiple entrée in users. When using hourly energy simulation two parent methodologies for is found. A simplified method concerns analyzing fabric loads from a system of unlimited capacities to meet the setpoints. A similar analysis can be made using LB [2] using incident radiation on the building envelope emitted from the sky patches is calculated through geometrical relationships. Pursuing a design strategy, such as reducing a cooling need, designs can be compared. This approach limits experimentation to rough massing strategies as it disregards consideration of risk of draft and cooling capacity regarding how much excess heat can be removed, without exceeding the comfortable correlation between airspeed and inlet temperature.
Understanding project specific challenges on thermal and visual comfort involves considering project specific inputs related to analyze the operative temperature. This enables balancing solar heat gains to limit excess seasonal comfort temperatures with appropriate daylight availability to add more comfort value when evaluating alternatives. This is crucial when investigating e.g. feasibility of strategies for reducing energy consumption and system sizing through substitutional strategies such as passive cooling systems.

4.3 Suggestions for improvement of HB

The basic workflow for the building envelope and a simple load system have been tested according to the procedures BESTest. Meanwhile the current intention on delivering a modular complex interface that requires expert knowledge concerning each module, has a downside even to the expert user. In the following, suggestions for improvement as considered in the context of supporting early stage interdisciplinary prototyping, according to findings in section 1.

- idealairloadsystem is found to be provide advantages in terms of simulation run speed. The HB module does currently not support hard sizing the maximum air rate, a crucial parameter to evaluate thermal comfort as described in section 4.1. This in turn should be combined with a baseboard heater object enabling a simplified but true representation of a common energy efficient mechanical ventilation system using district heating and the ability to separate and identify the actual energy consumptions for fans.
- Simplify model set-up. The Grasshopper3D BESTest script is large as described in section 4.2.1. Predefined standard inputs such as typical light, medium and heavyweight constructions and U-value will ease the need for rapid changing assumptions.
- Implementation of advanced HVAC control to broaden hollistical investigations. HB supports the direct text input of advanced EnergyPlus objects for non-native HB functionality. Furthermore, as mentioned in section , workflow to request and simulate among hundreds of output variables that EnergyPlus is capable of, enables a more advanced simulation possibility. It is however found inapplicable to assign objects in multizone models.
- Automation of output side. The number of output variables increases the computational time significantly. Optimizing this step, e.g. by accessing the result file through a cloud service could help overcome insights on larger number of result files in larger parameter studies.

5. Conclusion

In the aim to contribute to the understanding of emerging parametric BPS tools in the design of building of high sustainable quality it is found that HB successfully supports analysing and reflecting on the aspects of physics of an idea in prototyping. This is achieved through the coupling of NURBs geometry (Rhino) and BPS (HB) as indicated by a BESTest. Through three cases the functionality has been found to increase the value of the projects. This is achieved through flexible analysis with the ability to vary speed and level of detail of inputs and output metrics including with a runtime speed of 12,5 seconds and intuitive visualization needed for interdisciplinary solution selection. Meanwhile a high learning curve with limited HVAC input controls of HB are considered remaining potential barriers for a more widespread adoption in the AEC industry.

The site conditions, goals, and building application that characterizes the specific design problem is parameter dependent as much in building physics with expected comfort and energy consumption as it is in form and function. The problem cannot sufficiently be solved through heuristics and optimization. In the process of understanding of the design problem and solution building physics are often overlooked. It is found that that emerging parametric BPS tools enables an influential role of the specialist when entering in such a process. For this he or she should be mindful of design thinking and less oriented towards optimization, by engaging in iterative problem and solution finding with reflections on user centered value and conceptualization of ideas implement in new knowledge and technology.

A tool itself does not ensure valuable design, it is rather the implementation of the skills and knowledge of user. Considering the functionalities of HB in relation to design thinking, a user with no background in building physics could benefit by including a specialist at the steps of problem finding and solution selection. If the analysis is simplified innovation will be low. A user with a background in building physics on the other hand is more likely to perform more advanced experimentation to develop and identify the right solution to the right problem.

6. Acknowledgement

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