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EnergyFacade -
operational energy optimisation for conceptual facade design.

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Abstract

This paper presents the results of the investigation into the possibilities for the implementation of a Building Performance Simulation design toolbox during the early stages of façade design, based on the sustainability-open framework [2]. The background and development of the EnergyFacade toolbox will be discussed which has been built on the principles of parametric and associative design [3] as a strategy for operational energy assessment and optimisation.

Keywords: design and engineering computing, conceptual design, energy performance, façades, sustainability-open, BPS.

1. Introduction

Computational Building Performance Simulation (BPS) is a powerful strategy to tackle the complex task of assessing the operational energy demand of buildings. In current design practice it is often restricted to the final design stages, since the application of common simulation tools is limited to the analysis of a single design solution, given the difficulty and time intensity of producing the digital model. However, many decisions taken in the initial design stage, such as the building's orientation, massing, percentage of glazed area, choice of shading devices etc., strongly influence the operational energy expense. Therefore, the potential impact of building simulation would be greatly enhanced if its use was extended to multiple variant design optimisation and included much earlier in the design process [6].

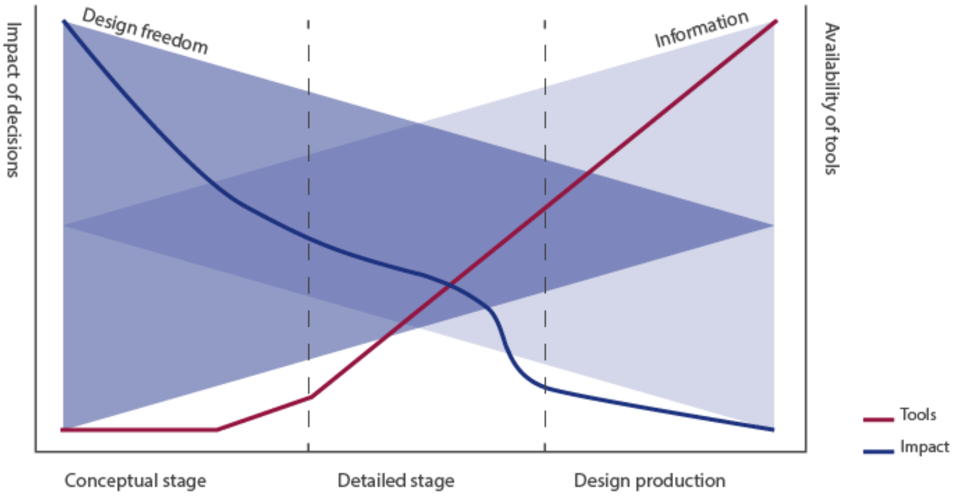

Figure 1: Discrepancy between availability of tools and impact of decisions
(based on: Wang et al [13] and and MacLeamy [9])

1.1. The conceptual design stage

The conceptual stage is commonly the first step in the design process of a building. It starts by defining the constraints and requirements on the system imposed by environmental and performance demands. Next, the conceptual outline of the design is decided upon, followed by an often iterative process, the generation and analysis of models and their evaluation. This phase is ideally characterised by a strong collaboration between the designer and consulting experts in different disciplines. The constant input of new information, resulting from this cooperation, demands a continuous adaption of the initial model, creating a dynamic and cyclic process of design and evaluation.

The initial design stage is also characterised by a discrepancy between amount of information available and the flexibility of the design (Figure 1). Whereas the designer is given large freedom in his decisions, there is only little data available to base these decisions on, as many key parameters of the design are yet uncertain or unknown. Nevertheless, as mentioned above, choices made in the initial design stage often have a substantial impact on the rest of the design process. It is therefore crucial to get an understanding of the magnitude of consequences on key parameters such as cost, energy consumption etc. as soon as possible. Throughout later stages of the design and construction process the adaption of the model becomes more burdensome and costly, making it sometimes even impossible to compensate for poor design decisions taken in the conceptual stage.

1.2. Parametric and associative design

In this context, the principles of parametric and associative design were found to provide a potential solution strategy. From the software point of view, parametric design is the setting up of computable models, in which the user is allowed to explicitly define parameters that can serve as (dependent) variables in a logic definition. These parameters can be linked together through a set of associations, which allow to replay the logic definitions upon change of the upstream parameters at any time in the design process [4]. In combination with a geometrical representation of these parameters, parametric systems (such as Grasshopper) offer therefore the ability to quickly compose, adjust and evaluate different design alternatives and give feedback in the impact of design choices.

Given these characteristics, parametric design systems show a growing popularity amongst architects and designers in the early design stage. Nevertheless, it is rarely used in the field of sustainability and BPS. Reasons for this shortcoming are, amongst others, the lack of proper tools, the many (sometimes even conflicting) parameters concerning the assessment of sustainability and the complexity of models used to describe building physics phenomena. These models depend on a wide range of variables, some of which are still undefined in the initial design stage. Therefore a simplification of the model is necessary, leading to results with questionable accuracy [5]. However, early tests can provide feedback in the influence of key parameters on the overall performance, allowing the designer to quickly compare design alternatives. Furthermore, since parametric design allows for real-time parameter update, the designer receives immediate feedback on the effect of his modifications, potentially allowing him to make informed choices between differing design solutions in terms of the buildings performance.

Another obstacle in the use of parametric and associative design strategies in the field of BPS is that current parametric and associative design system are mainly focused on geometrical objects, like points, lines, coordinate systems, surfaces, etc. [3]. These geometrical representations do not carry additional object related physical features, such as material information, which are needed for the assessment of building physics related topics, such as the operational energy

2. Scope

The research project has been subdivided into two phases with their respective objectives:

- Phase one has focused on the investigation and development of a design and analysis strategy, which would facilitate the application of BPS in the early stages of the design, engineering and construction process, by exploring the possibilities of parametric and associative design.
- Phase two has dealt with the design and implementation of the identified strategy in a software tool which assists designers in making informed choices regarding the design of the building envelop and which fits into the sustainability-open framework.

The restriction of the scope to facade design was based on preliminary background investigation, which found the building envelop to be both highly influential on a building’s overall energy performance and closely related to the parameters mentioned before, which are being defined in the initial design stage [7,10].

2.1. sustainability-open

sustainability-open (http://www.sustainability-open.com) is an open-source software initiative by the BEMNext Lab of Delft University of Technology to deploy design generation, quantitative analysis and assessment of sustainability performance [2]. The used version 0.0.2-alpha of sustainability-open was developed in the .NET framework using the C# language and consists in a framework, which lays out a computational infrastructure, and implemented base components. The present version of the framework consists of three types of components: Designers, Analysis and Assessment.

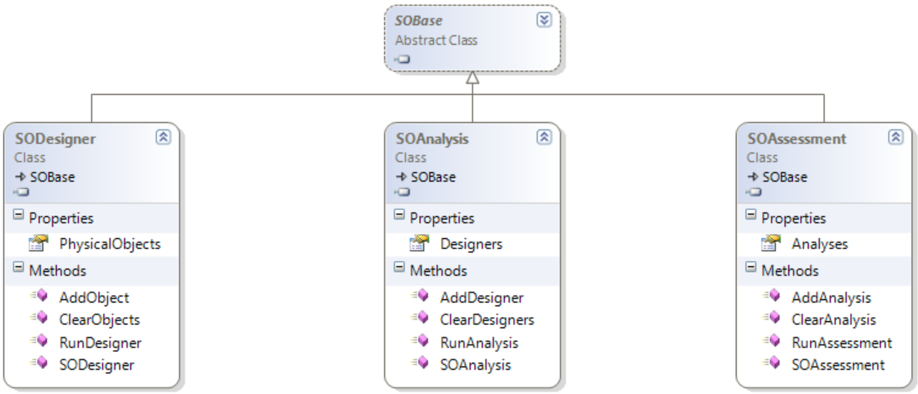

Figure 2 - UML diagram of the Sustainability Open framework

The ‘Designer’ components produce a ‘design’ on which the analysis and assessment will take place. The ‘Analysis’ components in turn take in a number of designers, which together form the design, and perform one or more analyses on it (e.g. all materials used in the design are added up to their total quantities). Furthermore they produce an output to be fed into the ‘Assessment’ components (e.g. known the total amount of material the embodied energy of the design can be calculated). Based on the outputs of the analysis components, the assessment components perform one or more assessments to produce an assessment result (e.g. calculate the total embodied energy in the design from the material quantities).

Next to the core framework a representation layer is provided, on which user-interfaces based on other software can be built. Currently, components which inherit their properties from classes contained in this layer can be loaded into Grasshopper, a graphical algorithm editor tightly integrated with Rhino’s 3D modeling tools (www.grasshopper3d.com).

3. Operational Energy Assessment in the early design stage

Since ideally buildings have long service lives, a significant portion of the energy demand will come from their operation, which can generally be summarised as the consumption of fuel/energy for space heating and cooling, ventilation, lighting, hot water, and electric power generation. [12] From these, the first three factors were found to be closely related to the design of the building envelope [11] and therefore within the scope of the research.

3.1. Calculation models

From the demands imposed by the characteristics of the early design stage and the principles of parametric and associative design, two main requirements for the definition of an appropriate calculation model could be established. Since the parametric nature of the EnergyFacade tool requires near-real-time interaction, the chosen model needed to assure the desired computational speed while maintaining acceptable accuracy. Furthermore, given the lack of information in the initial design stage, the model needed to be suitable to deal with a restriction to a minimum amount of input data.

Both these requirements could be met by defining a set of simplified dynamic equations based on hourly climate data over a year. For the assessment of the heating and cooling demand a one node thermal model as shown in Figure 3 was set up. In this type of thermal model, the heat storage in internal walls, ceilings and floors is represented by one mass node. The temperature of this node is assumed to be equal to the indoor air temperature.

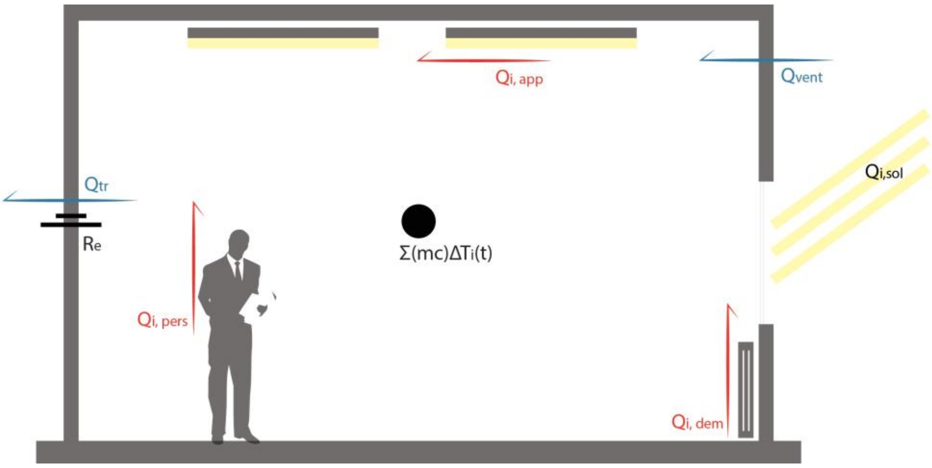

Figure 3- One node thermal model

The artificial lighting demand in turn is calculated as the difference between the illuminance levels reached by daylighting and the required lighting levels from the building regulations. The illuminance by diffuse light on a point in a room was in turn determined by integration of the solid angles subtended to the exposed window aperture and their luminance, with respect to the reference point [8].

Finally the overall operational energy demand (Equation 1) was calculated as the sum of the individual demands for heating/cooling (Equation 2) and lighting (Equation 3).

$$Q_{tot} = \sum_{m=1}^{12} N_t (Q_{dem,l} + \sum_{t=1}^{wh} Q_{dem,h}) * t \quad [Wh] \tag{1}$$

$$Q_{dem,h}(t+\Delta t) = \frac{[T_i(t+\Delta t) - T_i(t)] * H_{tot}}{1 - \exp(-\frac{H_{tot}}{C}\Delta t)} - Q_{int}(t+\Delta t) - Q_{sun}(t+\Delta t) + H_{tot}\big(T_i(t) - T_e(t)\big)\ [Wh] \tag{2}$$

$$Q_{dem,l} = \sum_{h=1}^{wh} \sum_{n=1}^{p} f * A_n \quad [Wh] \tag{3}$$

4. EnergyFacade

The implementation of the identified calculation models in a parametric and associative environment was achieved through the development of the EnergyFaçade toolbox. EnergyFaçade is meant to be used by designers in the early design stage to check the overall energy performance of their design and specifically the impact of the façade. Given the parametric nature of the tool, it is possible to easily adapt the building model and thus quickly test various design alternatives.

4.1. Scope

As mentioned before the EnergyFaçade tool is built in such a way to fit the sustainability-open framework and lends itself therefore to be part of a larger collection of components, which all together would finally stimulate the building industry that every building and structure will become more sustainable. The toolbox should be applicable to various buildings in terms of function and geometry. Furthermore it should allow to perform analyses for different climate zones around the globe. To this purpose climate data are provided through .epw files, that can currently be found for 2100 locations around the world.

The intended user of the tool is the designing architect. It provides him with basic building physics related information, which should allow him to make informed, energy aware choices regarding the design of the building envelop. Specifically, it offers the possibility to control the operational energy demand of the building by changing the façade typology, material and adding or re-sizing components. In this way, energy expenses become an extra selection criterion for one design solution over the other, adding another dimension to the decision making process. Especially in the initial, experimenting stage unfeasible solutions can so easily be sorted out, facilitating the architect in making proper design decisions.

4.2. System Architecture

Following the principles of sustainability-open, the tool has been implemented in the .NET framework, using the C# programming language. In its core the tool is structured as shown in Figure 4.

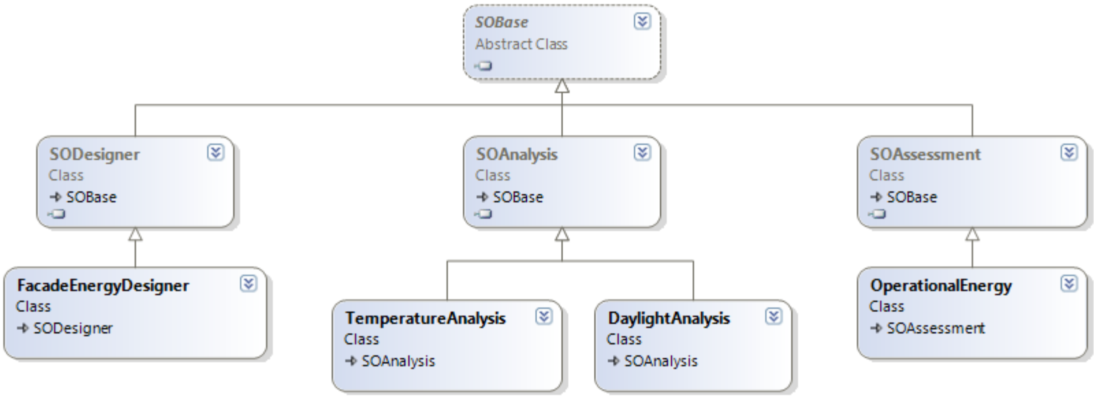

Figure 4 - Core layer of the EnergyFacade tool

The SOBase class serves as an abstract base class for the three main components, namely SODesign, SOAnalysis and SOAssessment. These contain abstract methods, which will be overwritten by the various components of the toolbox.

The SO Designer class retrieves data from the FacadeEnergyDesigner, which in turn is composed by adding a list of PhysicalObjects that together form the building model. The structure of these PhysicalObjects is shown in Figure 5 Their purpose is to translate plain geometry into custom parameters, defining and storing material related physical properties, necessary to perform energy analyses.

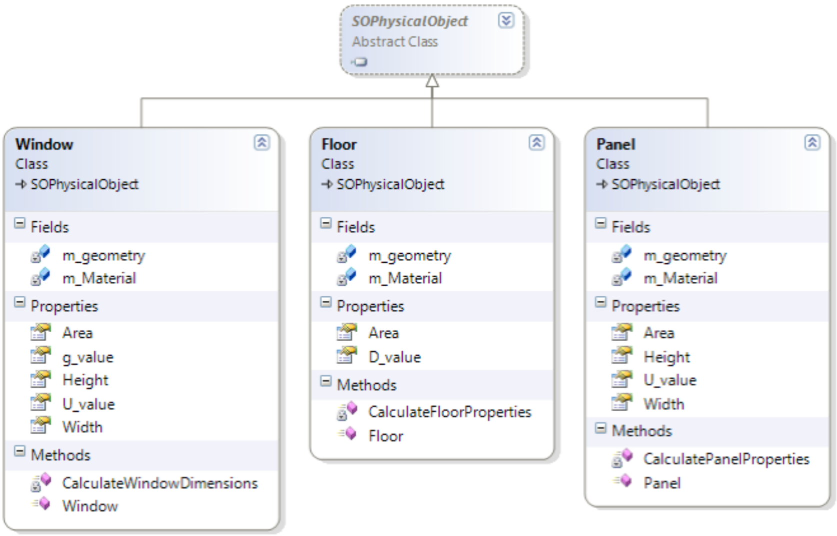

Figure 5 - Structure of PhysicalObjects

The selection of Physical Objects comprises Windows, Walls and Floors. Each of these parameters is defined by a BRep and a Material from the affiliated Material Selection List. The term BRep (boundary representation) is often used in solid modelling and computer-aided design, and stands for a method to represent shapes using their limits. The Material parameters in turn are derived from the SOMaterial class and have physical properties embedded. These data are transferred onto the specific geometry so that every geometrical object forming the design will contribute to the final outcome of the analysis.

The SOAnalysis class takes one Designer as input and runs specific analyses on the provided design. These analyses are sequential, meaning that it is not possible to perform two different analyses simultaneously. The current version of the EnergyFacade tool comprises two analyses – thermal and daylight. Based on the models presented in Paragraph 3.1 these analyses provide hourly data over a full year, once provided all required input data. Besides geometry and material data, information about the local climate and the functional purpose of the building has to be defined. These data will be extracted from .epw files that are read in trough the ClimateData component in the user interface, namely Grasshopper.

The SOAssessment class finally collects the results of an analysis in order to perform an assessment on the provided data and give a final evaluation of the design.

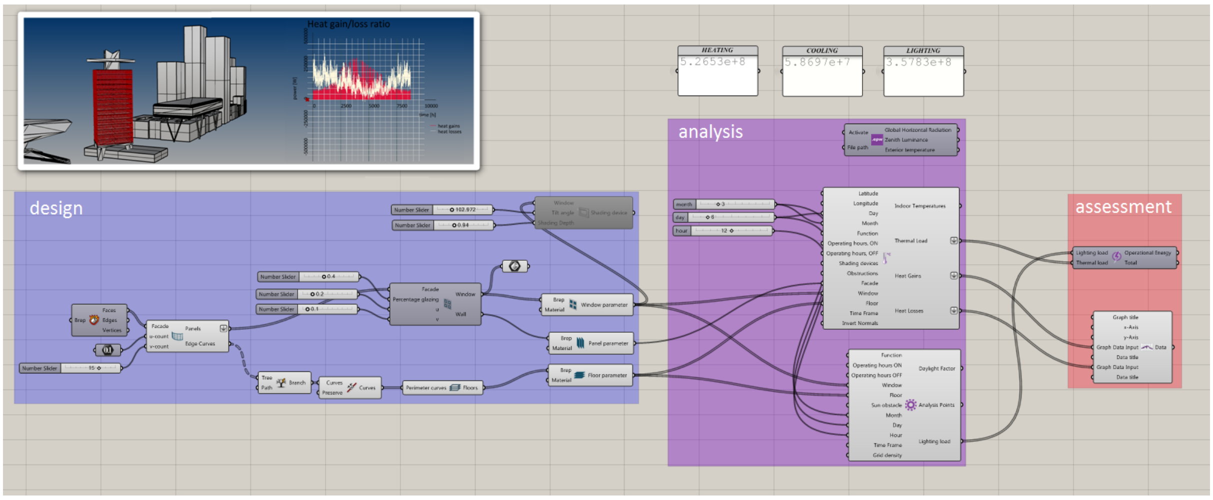

Figure 6 - Implementation of the EnergyFacade tool in the Grasshopper/Rhino interface

4.3. User Interface Design

From background research in the difference between engineers and architects as BPS tool users it could be concluded that the key parameters for a simulation tool developed for the early design stage are (1) an intuitive user friendly handling, (2) a quick feedback and (3) an easy to read output [1]. With these requirements in mind, the EnergyFacade tool was designed as a plug in for Grasshopper (see Section 2.1). Just like in the case other Grasshopper components, the custom components are displayed in the Menu bar under the name sustainability-open. This folder contains the three main categories of the framework, which in turn collect the associated EnergyFacade components. The manner of use of the EnergyFacade tool reflects the usual Grasshopper logic. The user of the toolbox can assemble a facade model by adding and combining custom developed components to the Grasshopper definition (Figure 6). All custom developed components are also cross-linkable with the standard Grasshopper components, allowing for a flexible adjustment of the program in the development of new projects. Outputs from the facade components can thus be used as inputs for regular Grasshopper components and vice versa (except for the custom output parameters, which can be used only as inputs for other custom components). All design related components include visualisation information, meaning that once dragged onto the canvas and given valid input parameters, their inherent geometry information will be displayed in Rhinoceros. Feedback from the energy analysis is displayed in a separate window in Rhinoceros, in order not to interfere with the modeling process.

5. Discussion

The current prototype of the EnergyFacade tool can be seen as proof-of-concept and starting point to explore ideas. In the course of development, the modular set up of the tool, following the structure of the sustainability-open framework, facilitated the implementation of additions and extensions. Given the ease of adding functionality or making adaptations to meet specific design requirements, the tool offers itself therefore for further developments.

Regarding the chosen analysis strategies, the implementation of simplified dynamic calculation models showed to be suitable for the initial design stage in terms of available data as well as in terms of calculation speed. However, further testing and verification will be needed in order to draw conclusions on the accuracy of the results.

Finally it needs, to be said that, although the EnergyFacade toolbox was developed following the structure of the sustainability-open framework, some adjustments still need to be made before fully implementing the tool in the newest version of the framework. These changes comprise the complete separation of the analysis components from the Rhino/Grasshopper layer to keep the tool usable cross platform.

6. Conclusions

Following the characteristics of the parametric and associative design strategy, the EnergyFacade tool offers the ability to quickly compose, adjust and assess different facade design alternatives and give insight in the impact of design choices on the operational energy performance. The assessment of the operational energy follows from a combination of thermal and daylight analyses based on hourly data over a full year for a specific location around the globe. To facilitate the evaluation of the problem on different scales, the tool provides the option to display daily, monthly or yearly results. Whereas daily calculations can be used to point out peak demands troughout a day, the monthly calculations give indications about seasonal fluctuations and indicate possibilities for seasonal systems (e.g. smart shading).

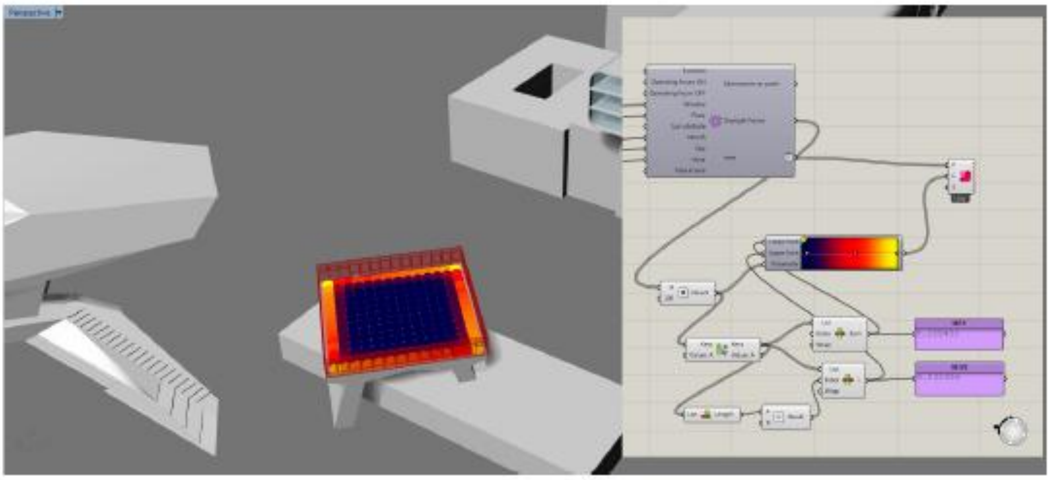

Figure 7 - Example of a daylight analysis using a combination of generic and custom Grasshopper components

The design knowledge implemented in the toolbox together with the results following from the assessment, provides the designing architect with feedback of the energy performance of the facade already during the conceptual design stages. In this way the tool enables the designer to more accurately see and understand the impact of changes on the key features of the design and potentially make more informed choices from the beginning of the design process. The parametric and associative nature of the tool furthermore stimulates the interaction between designers and engineers. By providing a design environment which offers the possibility to simultaneously model and get near-real-time feedback on the energy performance, the engineers are exempted from the task of performing repetitive initial calculations on various design option and assembling laborious models in a BPS software, gaining time for working out details in the later stage of the design. In this way, rather than the final design object itself, the design process can be highly enhanced.

7. Acknowledgements

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