Integrating Indoor Climate, Daylight and Energy Simulations in Parametric Models and Performance-Based Design

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Abstract: This paper presents a method for using parametric models to generate design support for the performance-based design process regarding indoor climate, daylight and energy performance. The method is operationalised in the Grasshopper programming environment. In the method, the designer suggests a room design and decides a certain degree of parametric freedom of parameters defining the room e.g. based on an overall architectural idea, a conceptual thought or something third. The method then employs a system of simulation tools and an optimization algorithm to generate a range of design proposals fulfilling user-defined indoor climate, daylight and energy performance criteria. The geometries of these solutions are presented to the designer together with performance data for decision making. The system of simulation tools includes the thermal simulation tool called ICEbear which is a newly developed plug-in to Grasshopper. It is ICEbear that enables the integrated indoor climate, daylight and energy performance simulations of complex geometries.

Keywords: Parametric Design, Building Simulation, Complex Geometry, Indoor Climate, Low-Energy Buildings.

Introduction

The European Performance Building Directive states that all new buildings constructed after 2020 should consume "near zero energy" (EPBD 2010). This demand requires that design decisions in the early design phase are based on careful considerations about their potential impact on energy efficiency. Design decisions also have to respect other design issues such as thermal comfort, cost, aesthetics and other design issues. Choosing the appropriate combination of design options is therefore a complex task which requires the management of a large amount of information on the properties of design options and the simulation of their performance. Computer-based building simulation tools are ideal for facilitating these tasks.

There is a well-established research movement that seeks to enhance the use of building simulation tools in the early design stage and, consequently, there are many suggestions, experiments and examples on how to do this, e.g. Morbitzer (2003), de Wilde (2004) and Petersen (2011) to cite but a few. However, there seems to be a low uptake of these research efforts in professional design practice. Researchers are investigating the potential reasons for this, e.g. Attia (2011), Holst and Kirkegaard (2010) and de Souza (2011). Reasons can be divided into issues related to the capabilities of tools (interface, input/output, etc.) and issues related to the integration of tools in design practice (work flow, culture, eye of the beholder, etc.). The lack of integration in design practice is the major motivation for proposing the method described in this paper. Building simulation is mainly used for an evaluative purpose. The aim of this paper is to contribute to a development where building simulation is used for a generative purpose.

Parametric Design and Simulation Tools

The proposed method is based on the principle of parametric design. The basic principle of parametric design is to iteratively modify different parameters of the design while continuously evaluating its performance. The principle has been applied for design before the age of computers. It was for instance used by the architect Antonio Gaudi when he designed the Cathedral Sagrada Familia in Barcelona in 1910. Gaudi used physical parametric models to optimize the shape of the cathedral according to aesthetical or structural criteria. One of the more simple parametric models of Gaudi was the cylinder shaped by two circles connected with strings (figure 1). While rotating one of the circles the overall shape of the cylinder changed. In this case the rotation degree of the circle was the varying parameter in the parametric model.

Figure 1. Parametric Model of a Cylinder Made by Gaudi, 1910 (http://ilaba.wordpress.com/2009/06/14)

Today, parametric models with high complexity can be established relatively fast and easily in computer programs like Grasshopper (2014). According to Nembrini *et al* (2014), computational parametric models are furthermore an effective way to intertwine architecture with indoor climate and energy performance. Programs for handling computational parametric models are therefore a suitable platform for a new generation of generative building simulation tools embedded in geometrical model platforms which are already familiar to architects. There are already several tools available for these programs. In the Grasshopper environment, there are simple tools like Ladybug (2014) which provides climate visualizations, and more sophisticated ones like the daylight simulation tool DIVA-for-Rhino (2014). These evaluative plugins can be linked to optimization algorithms like Galapagos (2014) to become more generative. There are, however, still barriers for full integration of indoor climate, daylight and energy considerations in the generative design process. These barriers can often be linked to the limitation in the available simulation tools, such as a limited capability of indoor climate evaluation, lack of integrated daylight and thermal simulations, lack of the capability to evaluate natural ventilation concepts, and limited possibilities for adjusting operation schedules and HVAC systems. This paper therefore also presents a new plug-in tool for Grasshopper that accommodates these barriers.

Method

The proposed method is inspired by the paradigm of performance-based design as described by Kalay (1999), see figure 2a. Here, the first step is to define performance requirements, which for instance could be a maximum use of energy, desired amount of daylight, range of acceptable indoor temperatures, conceptual thoughts on architectural expression, structures etc. The next step is to make a design proposal. The performance of the proposal is then predicted and the designer determines whether the performance is desirable or not. If the design proposal is desirable, the design is completed. If not, the designer enters an iterative process where new designs are proposed, performance predicted and evaluated until a desirable solution emerges. In this rather traditional workflow, the designer uses intuition and pre-experienced knowledge to come up with design proposals. Consequently, an unexperienced designer has a distinct risk of making inexpedient design decisions resulting in an inefficient design process where iterations is running in (too) many loops.

To minimize the number of iterative loops, Petersen and Svendsen (2011) suggest using simulation-based performance predictions and parametric analysis to inform decisions made in this part of the process (figure 2b). This has an educational effect on the designers and will (hopefully) save some loops and thereby time. However, just as in figure 2a the workflow of figure 2b still heavily relies on the judgment of the designer who in each loop needs to consider which parameters to analyse and make decisions upon.

The method proposed in this paper is depicted in figure 2c. The method starts by setting performance requirements just as in figure 2a and 2b. The designer then proposes a design formulated as a parametric model with a number of parametric variables. The proposal could be based on an overall architectural idea, a conceptual thought or something third – a practice similar to the parametric works by Gaudi in early 20th century. The model is then linked to a system of simulation tools including the newly developed thermal plugin (see the section "Operationalization of the method"). These tools are linked to an optimization algorithm that automatically generates the optimal and a range of near-optimal geometrical solutions. These solutions are presented to the designer together with performance data for decision making. The parametric model can be adjusted accordingly if none of the geometries are desirable, and the performance of the new model can be predicted or a new range of design proposals can be generated.

The fundamental difference in this proposal compared to the methods in figure 2a and 2b is that the generation of design proposals fulfilling performance requirements has been automated. This means that designers no longer have to consider how to remedy any misfit to the performance requirements. Instead designers can concentrate on assessing the architectural quality of the automatically generated designs. The trade-off of this functionality is that the automation deprives the designer from the iterative learning process on indoor climate, daylight and energy as in case of figure 2a and 2b.

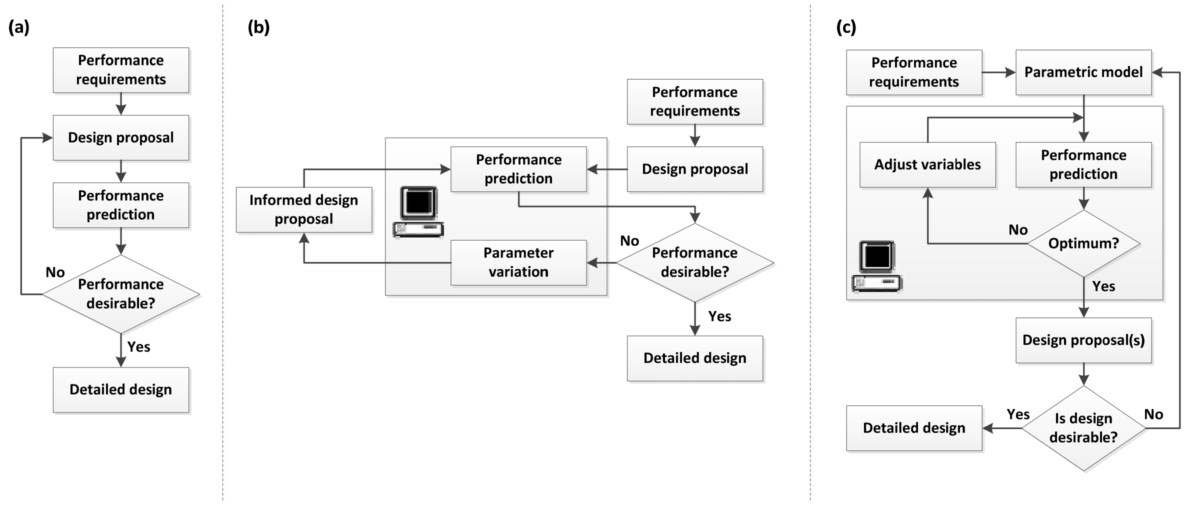


Figure 2. Development of the Performance-Based Design Paradigm, (a) Performance-Based Design (Kalay, 1999), (b) Implementation of Parameter Variation to Inform Design Decisions in Performance-Based Design (Petersen, 2010), (c) The Proposed Method that Automates the Generation of Design Proposals.

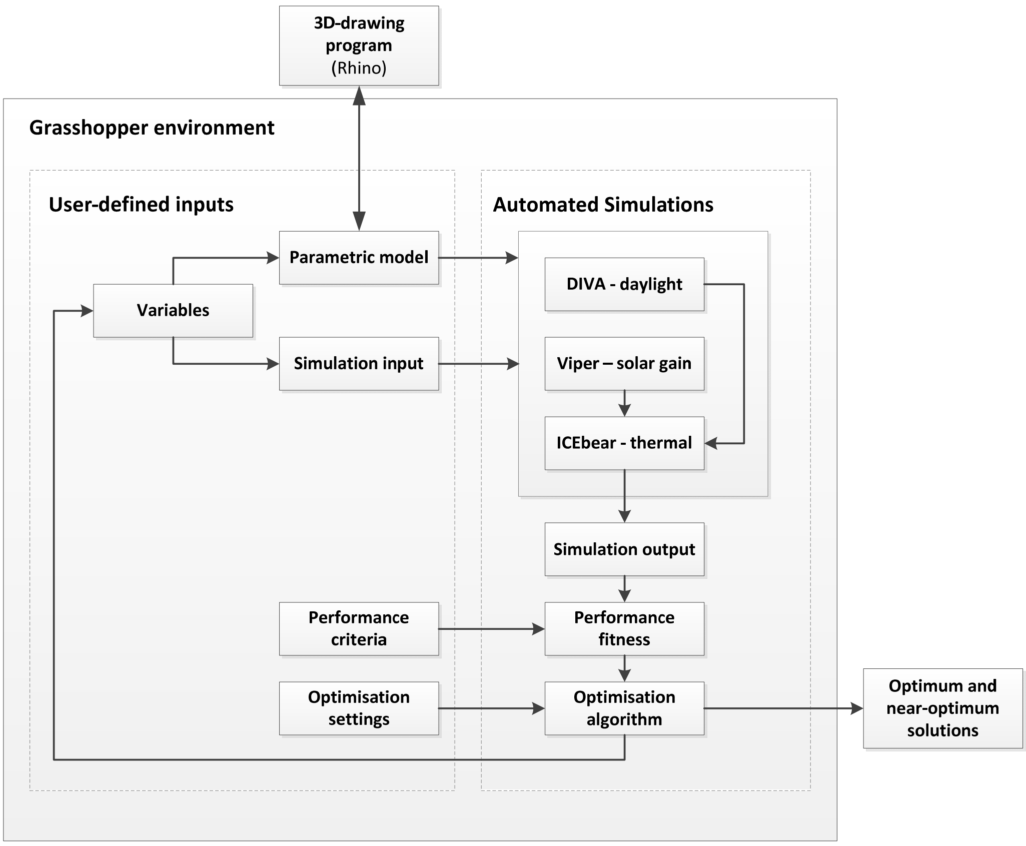


Figure 3. Flow Diagram of the Operationalized Method

Operationalization of the Method

The method is operationalized to automate the generation of room design proposals which fulfils user-defined performance criteria for energy efficiency, thermal comfort, air quality, and daylight levels. The operationalization is implemented in the parametric programming platform Grasshopper (2014) which is a plug-in to the 3D-drawing program Rhinoceros (2014). The flow chart in figure 3 illustrates the data flow of the implementation. The user first defines a basic geometry of the room. The user can choose to make the geometry of the design directly in the Grasshopper environment or as a parameterization of a Rhino model. The user also has to specify a range of simulation inputs used by the DIVA-for-Rhino plug-in (2014) and the newly developed thermal calculation plug-in. The new plug-in is based on the algorithms of the hourly-based thermal simulation tool BuildingCalc (Nielsen 2005) and a network model for natural ventilation combining stack and wind ventilation (SBi 2002). The plug-in is thus capable of predicting indoor climate and energy performance of design proposals.

The plug-in is called ICEbear: ICE is an abbreviation for "Indoor Climate and Energy" and the "bear" is added because the Grasshopper plug-ins often uses animal names. Furthermore an "ice bear" is close to a polar bear which has anatomic mechanism to keep the body in right temperature and is often associated with sustainability and climate change. The aim of the ICEbear plug-in is to generate more sustainable building designs and by that the name is found suitable.

The next user task is to decide which of the geometrical parameters and simulation input that are variables and to define their limitations e.g. as a possible ranges or movement patterns. Finally, the user has to specify performance criteria and optimization settings.

The geometric model and simulation inputs are sent to the automated simulation environment where the DIVA-for-Rhino component DIVA is used to calculate hourly illuminance levels in a reference point, and the component Viper is used to calculate hourly solar heat gain. The output from DIVA and Viper is then sent to ICEbear. Here, the DIVA output is used to determine the need for lighting in user-defined schedules which consequently leads to a heat load in the model, and the output from Viper constitutes the solar heat gain to the model. Other inputs to the thermal calculations such as schedules defining additional heat loads due to people and equipment, HVAC systems operation, weather data, and pressure drop characteristics for any natural ventilation are defined by the user in the simulation inputs. The DIVA/Viper/ICEbear complex then executes an hourly-based integrated daylight and thermal simulation with a simulation time of approx. 30 seconds. The simulation output (indoor climate, daylight and energy performance) is evaluated according to the performance criteria set by the user. This information is sent to the optimization plug-in Galapagos (2014) which is adjusting the user-defined variables and running simulations until an optimal solution is found. This solution is displayed together with range of near-optimal solutions. This way it is in fact the use of the Galapagos optimization algorithm that automates the generation of design proposals.

Practical Application of the Method

In the proposed method, the generation of design proposals that fulfil predefined performance criteria is automated. But the design freedom is still in the hand of the human designer who defines the solution space, i.e. the boundary conditions for the generation of design proposals. In other words, it is the human designer that freely defines the initial geometrical model, the geometrical and technical variables and their degree of freedom.

Figures 4, 5, and 6 show examples of user-defined parametric models ready for the automated generation of design proposals. The examples are divided into three geometrical design tasks: The façade, the room or the overall building. The rooms shown in figure 4 have the same room geometry but different conceptual ideas for the façade geometry, and figure 5 are examples of different geometrical issues on room level. The proposed method could in principle also be applied for generation of overall building shapes. As an example, the variable could be the rotation degree of the building torso similar to the idea of the high-rise "Turning Torso" in Malmö designed by Calatrava (figure 6). The degree of rotation could be optimized according to indoor climate, daylight and energy using the proposed method and its tools.

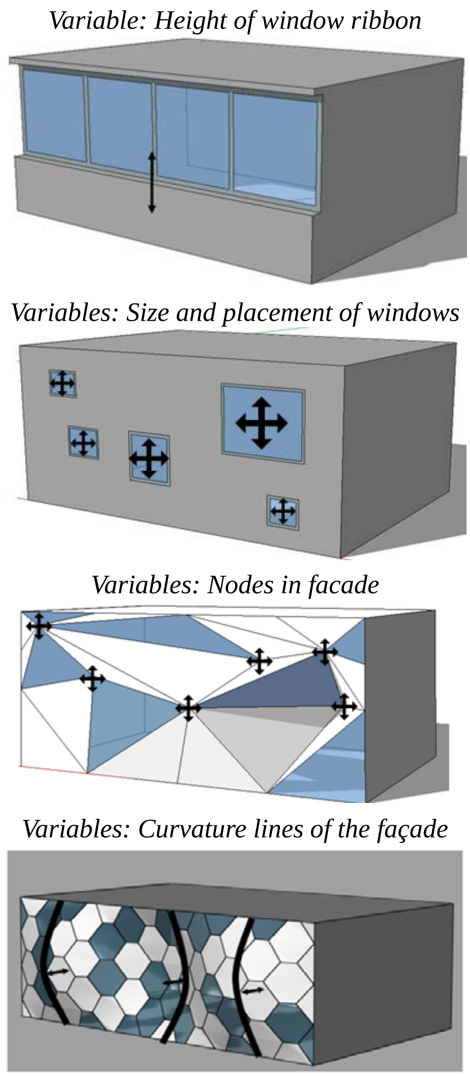


Figure 4. Examples of Parametric Models of Façade Concepts and Variable(s)

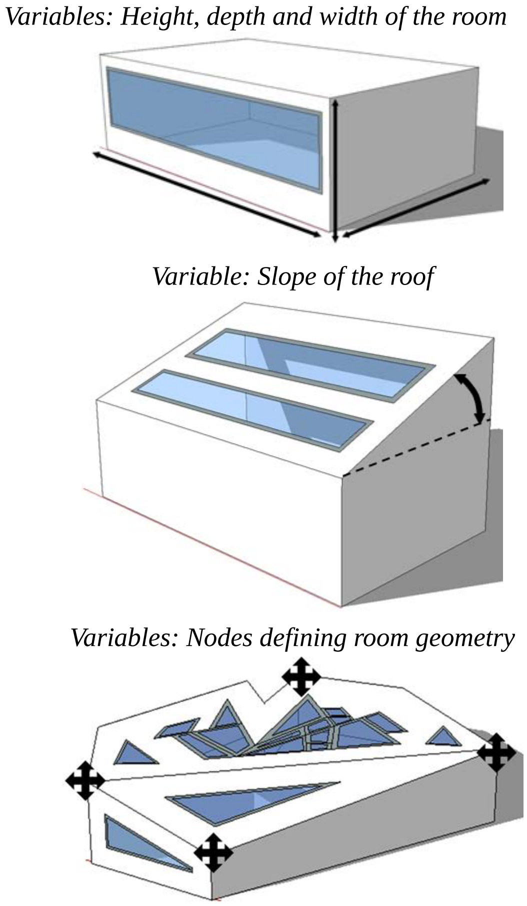


Figure 5. Examples of Parametric Models of Room Geometry and Variable(s)

Figure 6. Turning Torso by Calatrava, Malmö, Sweden. In the proposed method, the variable could have been the rotation of the building torso. (www.bizzbook.com/map/turningtorso2004.html)

Case

A case featuring the geometry of a façade was executed to illustrate how the operationalized method works in practice. It was decided that the aesthetical expression of the façade design should create a feeling of diamonds. Therefore the façade elements were made of triangles connected in six points, see figure 7. These six points could move in three directions (x, y and z) with boundary conditions of ±1m in y-direction and inside each $^1/_6$-part of the façade for the x and z directions (the dashed boxes in figure 7). The room was naturally ventilated through two bottom hung window near the ceiling. The placement of the two additional windows was to secure a view out. The room was in connection with an atrium where the ventilation exhaust was located at the roof. The performance criteria was to reach a maximum energy use for building operation 25 kWh/m2/year while fulfilling thermal class II according to DS/EN 15251 without having more than 100 hours above 26 °C, air quality class II (ibid.) and a minimum daylight autonomy of 60 % in a point in the middle of the room.

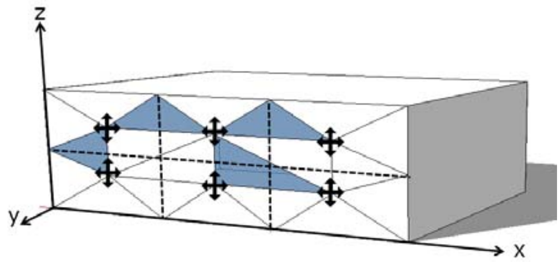


Figure 7. Case Example Featuring a Façade Design with Six Variable Nodes in the Façade.

Results

Optimization of the case was made for a north-oriented room and a south-oriented room. Figure 8 shows that the solution for the north-oriented room started to converge after approx. 160 iterations. The performance criteria regarding indoor climate were fulfilled but the energy criterion was never fulfilled. The minimum energy use of 34.8kWh/m^2/year was found after 254 iterations. This solution is visualised in figure 9.

No converged solution was found for the south-oriented room after 234 optimization iterations, see figure 10. Instead the optimization seems to oscillate between a few different shapes. The optimization algorithm has a hard time finding an optimum because the heat gain from direct sun is fluctuating a lot as it is very sensitive to the area and tilt angle of the windows. However, after 234 iterations there are a number of solutions that fulfil or almost fulfil the performance requirements. Some of these are pointed out in figure 10 (top) and illustrated in table 1 together with their performance data. An interesting aspect from an architectural point of view is that the solutions have different appearance even though the indoor climate and energy performance are quite similar.

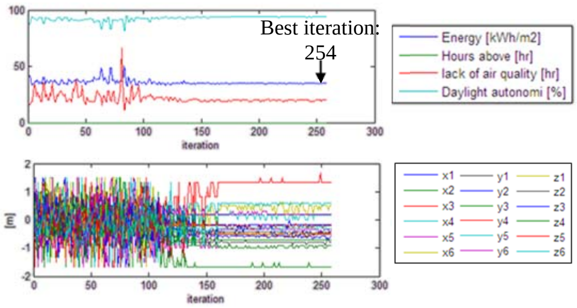


Figure 8. Optimisation of North-Oriented Room. Top: Performance. Bottom: The Relative Location of the Variables

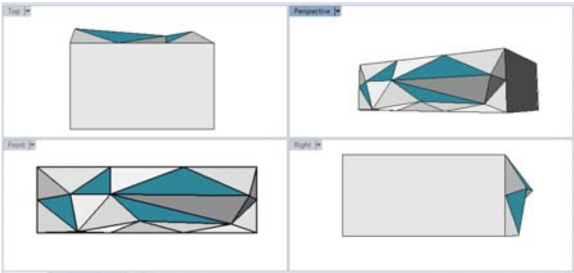


Figure 9. The Façade Geometry of Iteration No. 254 for the North-Oriented Room

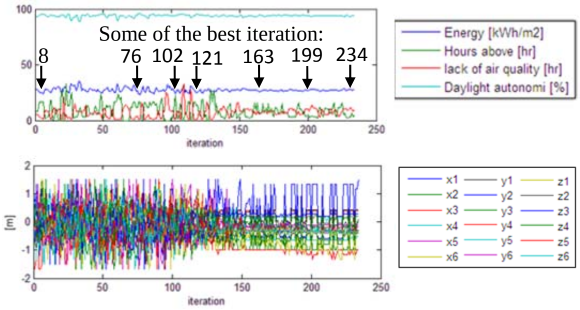
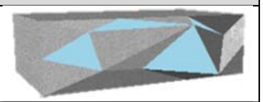
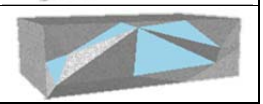
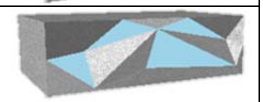
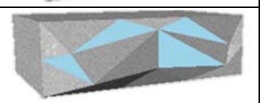
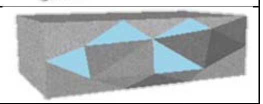
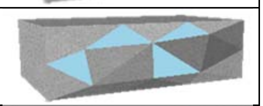
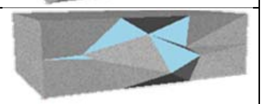


Figure 10. Optimisation of South-Oriented Room. Top: Performance. Bottom: The Relative Location of the Variables

Table 1. A Selection of Façade Design Proposal for the South-Oriented Room which Fulfils or Almost Fulfils the Performance Requirements

Iteration number	Energy Consumption [kWh/m2/year]	Above 26 ^{o}C [hours]	Poor air quality [hours]	Daylight Autonomy [-]	Visual appearance of the façade
8	25.3	20	1	0.95	
76	24.0	17	1	0.96	
102	24.8	17	1	0.95	
121	24.8	17	1	0.95	
163	26.8	7	6	0.94	
199	26.6	12	5	0.94	
234	26.1	3	8	0.95	

Discussion

In the proposed method, design proposals fulfilling certain performance criteria are generated automatically by a computer instead of a human designer. This might raise the question: Can computers replace the human designer? This method could be perceived as a small step in that direction. However, this is not the case as the method does not work without having a human designer stating the architectural idea and its boundary conditions. The few examples in section "Practical application of the method" illustrates that design freedom is practically unlimited. The only limitation is the imagination of the designer and how well the geometry can be described in Grasshopper. In the case of this method, computers are therefore merely a powerful tool for the human designer: $1.3 \cdot 10^{24}$ simulations were needed if all solutions in the example (section "Case") were to be simulated. This would take the same amount of time as ½ billion times the age of the earth. The computer found possible solutions after only 200 iterations (approx. 7 hours). Furthermore, the human designer always has the right to dismiss geometries generated by a computer for whatever reason. The ultimate power of design is thereby still in the hands of the human designer.

Conclusion

This paper presents a method for using parametric models to automatically generate design proposals that fulfils predefined performance criteria regarding indoor climate, daylight and energy performance. These proposals should be perceived as an input to a performance-based design process. The operationalization of the method includes a newly developed thermal calculation tool called ICEbear which is a plug-in to Grasshopper. ICEbear is able to simulate the annual indoor climate, daylight and energy performance of complex geometries based on hourly weather data. This tool is used together with an optimization algorithm for automatically generation of design proposals based on input from the human building designer regarding the conceptual idea. A case example illustrates that the method can generate a range of near-optimal solutions regarding criteria for indoor climate, daylight and energy performance. It is then up to the human designer to make the actual design decision on which solution to refine further.

Future work on this method includes investigations on whether the proposed method is useful to practicing designers working on real life building projects. Another task is to ensure that the information used for the simulations can be exported from the current sketching platform to any BIM model platform more suitable for the detailed design phase.

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