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Integrated Building Energy Design of a Danish Office Building Based on Monte Carlo Simulation Method

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Abstract

The focus on reducing buildings energy consumption is gradually increasing, and the optimization of a building's performance and maximizing its potential leads to great challenges between architects and engineers. In this study, we collaborate with a group of architects on a design project of a new office building located in Aarhus, Denmark. Building geometry, floor plans and employee schedules were obtained from the architects which is the basis for this study. This study aims to simplify the iterative design process that is based on the traditional trial and error method in the late design phases and improve the collaboration efficiency.

Monte Carlo Simulation method is adopted to simulate both the energy performance and indoor climate of the building. Building physics parameters, including characteristics of facades, walls, windows, etc., are taken into consideration, and thousands of combinations of these parameters are screened to find those can achieve the design criteria. The software Be15 and BSim are used as two-step solvers to process the calculation of energy consumption and indoor environment.

A solution pool is then obtained for architects to choose from, see Fig. 2 and 3. All these solutions can fulfil the requirements and leaves additional design freedom for the architects. This study utilizes global design exploration with Monte Carlo Simulations, in order to form feasible solutions for architects and improves the collaboration efficiency between architects and engineers.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: Monte Carlo Simulations; building design; building performance; multi-collaborative design process.

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1. Introduction

In the latest years, the building design community has been challenged by the increasingly stringent regulations on building energy demands and indoor environment. The collaboration between architects and engineers becomes more and more demanding during the building design process. A close cooperation at an early stage will help ensuring a high quality outcome and reduce implementation costs of design solutions. However, there is sometimes a lack of awareness of early-stage cooperation in practice, due to e.g. prioritizing aesthetic or conceptual parameters. It is necessary to find an efficient and feasible method to optimize the building performance, without compromising those prior parameters. Kanters and Horvat [1] emphasize that parameters such as uncertainties, resolution of model and frequent design changes may be challenging, especially in the search for the most optimal design. Previous studies [2-5] proposed a simulation framework and emphasizes that such a framework may assist a design team by exploring a broad design space in the early design phases. Østergård et al. [6] states that their methodology gives more guidance regarding how to improve a building's design pro-actively when using building simulations compared to the evaluative use.

In this study, we collaborate with a group of architectural students on a design project of a new office building located in Aarhus, Denmark. The building has eight floors with five staggered stories from the 3rd floor and up. These staggered stories forms an atrium in the middle, which stretches through the entire length of the building. The building utilizes hybrid ventilation during the summer and mechanical ventilation in the winter. Through a building energy simulation it was documented that the design proposal from the architects did not meet the legal energy requirements. Therefore, adjustments and optimization become necessary in the late design phase. We aim to simplify the iterative design process and improve the collaboration efficiency by supplying various acceptable optimization solutions based on the design preferences of the architects. The design solution given prior to the optimization contains building geometry, floor plans, as shown in Fig. 1, and employee schedules and energy calculations.

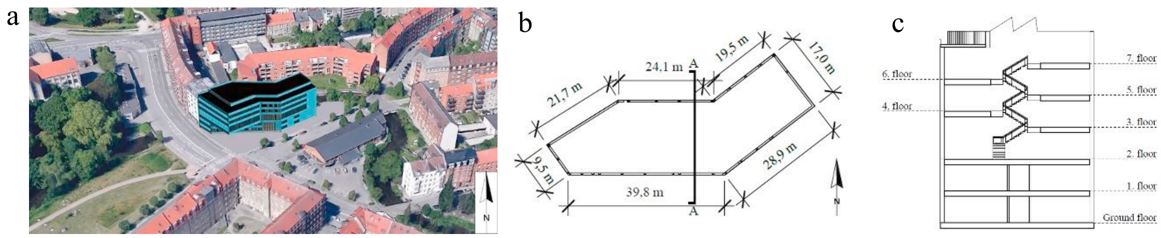

Fig. 1. (a) 3D model; (b) plan view of the outer geometry; (c) cross section view of the architects' design.

2. Methodology

The goal is to conduct a global exploration of the design space, and to obtain the spectrum of the building performances. It is expected that the thorough awareness about the consequences of various design choices would allow a high level of design freedom for the architects. The consequences will be presented by an illustrative method that links the energy efficiency and indoor environment performance to the combination of building physics parameters. Monte Carlo simulations based on a sophisticated building performance model can ensure the exploration of both the realizations of stochastic parameters and the choices of deterministic parameters. The latter are selected to fit the architects' design proposal to have minimum aesthetic impact. The latter are selected since they have minimal aesthetic impact on the architects' design proposal.

The input parameters are inserted into a deterministic model and related outputs can then be examined. Applying Monte Carlo filtering yields the input parameters that potentially have a high influence on the outputs based on the inputs' distributions. If the distribution of an input parameter is uniform after the Monte Carlo filtering, it is likely to have less influence on the output. The results of the Monte Carlo simulation are presented through a visualization technique called parallel coordinate plot, where each line represents a unique solution with its in- and outputs.

To explore the design space of the energy use, the simulation tool "Be15" [7] is used. This tool calculates the energy demand based on monthly-averaged values according to EN ISO 13790 [8], EN 15316 [9] and EN 15193-1

[10]. To get a building permit in Denmark, it is mandatory to use Be15 to document that a building meets the stated energy performance requirements from the building regulation.

To examine the indoor environment the simulation tool "BSim" [11] is used. This building simulation tool uses hourly dynamic calculations to evaluate the indoor environment and building energy performance. Both building simulation tools are developed by the Danish Building Research Institute. BSim is a commonly used building performance simulation tool in Denmark and its features can be compared with EnergyPlus.

The exploration of the energy consumption is based on the entire building, where the exploration of the indoor environment is based on a large open office landscape facing south, which is considered to have higher risks of overheating problems. The open office landscape is connected to the atrium where natural ventilation is utilized in the simulations.

2.1. Stochastic modelling with Be15

The generation of the samples requires boundaries for the parameters and distribution types. These are presented in table 1.

The sample which contains the parameters is created using the low-discrepancy method Latin hypercube. It takes the previous point into consideration when generating a new point for the parameters. Thus, the generated values are not highly represented in one end of the spectrum of a parameter compared to the other.

Table 1. Parameters, distributions and boundaries used in the Be15 simulations.

Parameter	Unit	Distribution	Boundary
Lighting	[W/m^2]	Uniform	4,0 - 12,0
U-value, external wall	[W/m^2K]	Uniform	0,085 - 0,300
U-value, windows	[W/m^2K]	Uniform	0,7 - 1,4
g-value, windows	[-]	Uniform	0,5 - 0,8
Mechanical ventilation	[$l/s\ m^2$]	Uniform	0,93 - 1,20
Night cooling, summer	[$l/s\ m^2$]	Uniform	0 - 4
Natural ventilation	[$l/s\ m^2$]	Uniform	0 - 1,2
Window-to-floor area	[%]	Uniform	10 - 35
Solar cells	[m^2]	Discrete	0; 50; 100; 150; 200

We evaluate the impact on the architects' design proposal during the input selection process. Though some parameters are very sensitive to the architects' design preferences, e.g. such as the window-to-floor area, they are still selected due to their importance on the building performance.

Solar cells are included in the simulations since they increase the design space with feasible solutions. Solutions with solar cells were approved by the architects and are therefore acceptable to implement on the roof.

The following four outputs are used to evaluate the pool of solutions.

- Required heating
- Excessive temperatures
- Electricity for building operations
- Total energy requirement for energy frame Danish Building Regulation 2015 [12]

Then 10.000 combinations of the inputs are calculated by the building performance model, and 10.000 sets of outputs are obtained.

2.2. Stochastic modelling with BSim

BSim is a more sophisticated and time-demanding tool than Be15. Factorial sampling is used to run multiple BSim simulations. Therefore fewer parameters are selected to calculate corresponding solutions. Based on the outputs of the simulated energy consumption by Be15, some parameters, e.g. U-value of walls and windows, are kept as constants for the indoor environment simulations. The parameters, their distributions and their boundaries used in the BSim model are shown in table 2.

Table 2. Parameters, distributions and boundaries used in the BSim simulations.

Parameter	Unit	Distribution	Boundary
Mechanical ventilation	[m^3/s]	Discrete	0,2; 0,3; 0,4; 0,5
Window opening fraction	[-]	Discrete	0,04; 0,08; 0,12; 0,16
Shading coefficient	[-]	Discrete	0,3; 0,4; 0,5; 0,6
Window recess	[m]	Discrete	0,3; 0,4; 0,5; 0,6
Window-to-floor area	[%]	Discrete	18,8; 23,6; 28,3; 33,0

The window recess is the windows placement within the external wall. A recess of 0 m means that the window is aligned with the inside of the external wall. The window-to-floor area is altered by changing the height from the bottom of the windows to the floor, while keeping the width and top height constant.

Every possible combination is simulated, yielding a total of 1.024 models. The simulations are evaluated using the following four outputs:

- Hours above 26 ºC
- Hours above 27 ºC
- Hours with CO_2-concentration above 850 ppm
- Required heating

The amount of hours above the requirement is only evaluated within the working hours (8 am to 4 pm during working days). From the two solution spaces created for energy consumption and indoor environment, the best solutions can be chosen.

3. Results and Discussions

A parallel coordinate plot (PCP) is used to illustrate the results from the simulations. The PCP is a tool for factor mapping. It can provide illustrative information to the decision makers when designing a building in the early design phase. In this paper the plot is used in the late design phase to allow the highest-possible efficiency in the collaboration between architects and engineers. No iteration process will be necessary since the design spaces have been thoroughly screened.

The inputs and the outputs from the Be15 and BSim simulations are compiled into PCPs, see Fig. 2 and 3, respectively. The solutions, which does not meet the requirements, are removed by filters. The grey histograms on the in- and outputs show the distribution of solutions for each parameter.

Fig. 2 reveals that most of the satisfying solutions are obtained when choosing efficient lighting equipment, high air flow for night cooling, low window-to-floor ratio and large area of solar cells. The window-to-floor ratio and solar cells are the most sensitive parameters for the architect's design preferences, and thus changes to these parameters has

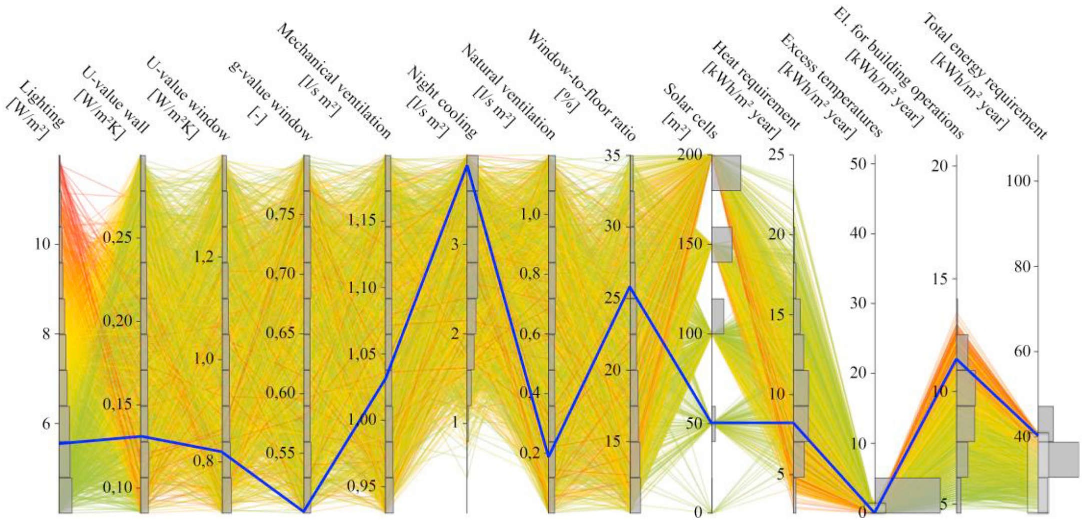

Fig. 2. PCP for 2.010 Be15 simulations with varying input parameters and total energy requirement. The color scale is determined by the total energy requirement. The blue line represents the preferred solution of the architects.

to be achieved based on a consensus with the architects. Regarding the other parameters, the pool of solutions that meet the requirements leaves a high degree of design freedom. A filter is added to the excess temperatures to obtain the best possible thermal climate based on the Be15 calculation.

Based on the solution preferred by the architects, the parameters and their values from the Be15 solution are implemented in the BSim simulations as deterministic parameters. An exception was made to the window-to-wall ratio as it have a significant impact on the indoor environment.

Fig. 3 presents solutions that meet the requirements for the indoor environment. Even though the collaboration started in the late design phase, it still grants the architects a wide design space to choose from. All these solutions are then reviewed by the architects and the optimal solution may be chosen based on the design criteria from both the architects and the engineers. The window-to-floor ratio was not varied to keep the current building concept, however optimization of other parameters were accepted by the architects. For example, improvements to the artificial lighting was accepted due to the fact that the light quality of energy saving LED systems have improved in the later years.

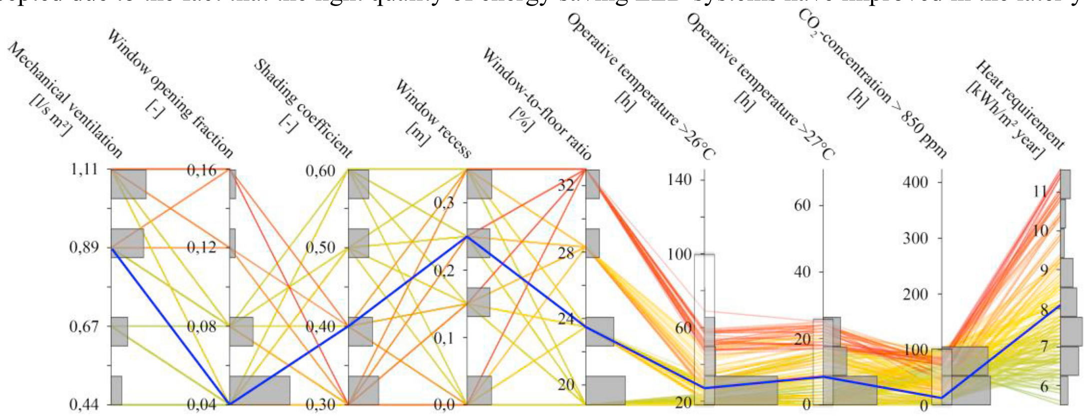

Fig. 3. PCP for 273 BSim simulations with varying input parameters and resulting indoor environment. The color scale is determined by the heating requirement. The blue line represents the preferred solution of the architects.

The reduction in energy consumption makes up for the higher window-to-floor ratio which improves the daylight. It can be observed that the collaboration efficiency was improved due to the enhanced communication by graphical presentation of the quantitative solutions.

4. Conclusions

In this study, we collaborated with a group of architectural students on a design project of a new office building. A solution pool that fulfills the requirements of the energy demand and indoor environment was obtained for the architects to choose from, based on further requirements. All these solutions can fulfil the requirements and leaves additional design freedom for the architects.

This study utilized a global design exploration in the late design phase with Monte Carlo Simulations, and it was accomplished to obtain feasible solutions for the architects and improve the collaboration efficiency between architects and engineers.

The main reasons that the requirements were met while not changing the design significantly was because of the natural ventilation from the atrium and the low energy use for artificial lighting. Though solutions, which meet the requirements were obtained, even better solutions would likely occur if the global design exploration was utilized before the design was finalized.

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