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Linking BIM and Design of Experiments to balance architectural and technical design factors for energy performance

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ABSTRACT

To transform the existing energy systems towards renewable energy sources, buildings need to use less energy, use energy more efficiently and harness local renewable energy sources. For the design of energy-efficient buildings, building energy simulation of varying sophistication is commonly employed. Types of simulations range from simple, static calculations to sophisticated dynamic simulation. Especially for building retrofit many assumptions on construction, material etc. have to be taken, which increases the uncertainty of simulation results. In conjunction with simulation, methods of Building Performance Optimization are increasingly employed. They are able to identify best performing designs however do not provide insights on the mechanisms and interdependencies of the different design factors, which are most valuable to make informed design decisions. We present a methodology that aims to provide a better understanding and create knowledge about the influence and interactions of different architectural and technical design factors on building energy performance of a specific design task. For this purpose, we introduce Design of Experiments (DoE) in an integrated design workflow using the Design Performance Viewer (DPV) toolset, combining Building Information Modeling (BIM), distributed dynamic simulation and statistical analysis of the extensive simulation results. The experiments created using the methodology allow to identify the strength of effects and interactions of different design factors on selected performance indicators. We apply the methodology on an office retrofit case, introducing a factor scatterplot for result visualization, development and comparison of retrofit strategies. We further evaluate its potential to identify high performing strategies while balancing architectural and technical factors and their impact on energy performance.

1. Introduction

Worldwide, buildings consume 32% of the global final energy and 25% greenhouse gas emissions (GHG) [1]. To transform the existing energy systems towards renewable energy sources and thus to meet the ambitious emission goals set by many countries and organizations such as the European Union [2], future buildings will need to use less energy, use energy more efficiently and harness local renewable energy sources. Compared to the existing building stock, the annual rate of new and retrofitted buildings in Europe, however, is low. In Germany and Switzerland, for example, retrofit rates stagnate at a low level of around 1–2% [3]. Studies claim that this is due to insufficient information, low cost-effectiveness of measures and regulatory constraints that make it challenging to find the appropriate solution [4].

To identify effective retrofit measures, building energy simulation is employed, sometimes during design, most often however afterwards in order to comply to energy codes. Such simulations range from norm-based steady-state calculations to sophisticated dynamic building energy simulations. Due to missing information about the building itself, they are often based on a variety of assumptions, simplifications and educated guesses. Whereas simulation data can easily be produced, knowledge and understanding about the effects and interactions of different parameters is often lacking. The objective of this work is therefore to develop a methodology and computational toolset to identify the influence and interactions of architectural and technical design factors on building energy performance and thus to derive strategic knowledge for the designer rather than just numerical results.

For this purpose, we link Building Information Modeling (BIM), which is used to create and store the necessary data and information, and Design of Experiments (DoE), an established and successful methodology used in engineering disciplines and industry. DoE is a method that uses simulation experiments and applies statistical analysis to obtain information on effects and interactions between different factors, aiming at the least number of experiments necessary. To embed DoE

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into the design process, we employ the Design Performance Viewer (DPV), a toolset that allows establishing a workflow from a Building Information Model (BIM) to parametric simulation, results collection and statistical analysis.

The paper is structured as follows: First, we provide an overview on existing approaches of parametric design and environmental simulation for sustainable building design. Next, we introduce DoE as a method and its previous application for building performance. In Section 3 we outline the integration of DoE into the Design Performance Viewer toolset to establish a DoE workflow based on a BIM. This workflow is exemplified in Section 4 using an office retrofit case study, identifying a range high-performing yet unique retrofit strategies. Section 5 summarizes and discusses the methodology whereas Section 6 concludes and provides an outlook on future developments.

2. Background

The field of parametric building modeling and simulation and related methods of data analysis and optimization constitutes the relevant background of this paper. Additionally, we briefly review the method of Design of Experiments and its application to buildings.

2.1. Building energy performance optimization

A large body of research exists that couples parametric building modeling, environmental simulation and optimization. The study of Gero et al. [5] and the Building Design Advisor [6] represent early, integrated design approaches combining multiple analysis and visualization tools. Caldas and Norford [7] utilize genetic algorithms to search for optimized environmental design solutions, focusing on façade configurations. Janssen [8] explores balancing heat losses of the envelope and potential heat gains through openings using evolutionary approaches. Turrin et al. [9] use genetic algorithms for the design of passive solar roofs. Heiselberg et al. [10] apply sensitivity analysis to identify the most important design parameters of a sustainable building design. Related to cooling in office buildings, Breesch and Janssens [11] utilize uncertainty and sensitivity analysis to predict the performance of free cooling using building energy simulation. More recently, multi-objective optimization techniques increasingly assist in performance-driven building design already at the conceptual stage [12,13], addressing energy, exergy, lifecycle cost and other domains. A study by Attia et al., which also provides an extensive review on building performance optimization, highlights a consensus on the general usefulness of building performance optimization tools to achieve energy efficient buildings [14]. The study also mentions shortcomings as perceived by experts in the field such as uncertainty of simulation model input, low trust in results and low interoperability for exchange between different applications.

In practical application, a range of available tools link parametric building modeling to environmental analysis, such as Autodesk Vasari or Design Builder, which uses EnergyPlus as simulation engine. Additionally, a range of plugins for similar purposes exist, such as DIVA, Honeybee or Ladybug for Rhinoceros. Both tools and plugins mainly focus on building geometry, materials and resulting heating/cooling load calculations, which are delivered as numerical results.

Rather than to base design decisions on numerical simulation and optimization results only, we advocate to use a performance-driven design workflow including DoE as a method to obtain an *understanding* of the nature and impact of design parameters, their interdependencies and trends, and thus to be able to build *knowledge* within a specific design context. Such a workflow can be automated; the interpretation however requires the judgement of the expert. The focus on knowledge rather than data constitutes the main difference to the aforementioned optimization approaches which provide results optimized for certain criteria, however little insight or understanding about the mechanisms behind.

2.2. Design of Experiments

Design of Experiments (DoE) has been established and successfully applied in various fields and industries, such as product design and development [15], chemical [16] and software engineering [17]. A number of comprehensive textbooks exist [18–20]; therefore the general methodology is outlined here only in brief. As part of the application, we exemplify each methodological step for the case study.

The general concept of DoE is to create a series of real or simulated experiments on a system or system model under observation. In each experiment, one or multiple of its design parameters are changed and the impact on the system or model behavior is evaluated. Which parameters are changed and how they are changed is defined using an experiment plan. The aim is to obtain as much information as possible using the least amount of experiment runs, as experiments are costly in terms of physical setups or computational effort. The behavior of the system based on the parameter changes is observed using a set of outputs. In the context of DoE, the outputs can be referred to as the 'performance indicators', the design parameters as the 'factors' and their value settings as factor 'levels'.

To analyze the impact of each factor on the system and its interactions with other factors, every factor combination would need to be tested and therefore would require an experiment. Due to the large amount of possible combinations this is an effort often infeasible in terms of time and costs. DoE offers a range of methods - referred to as experiment plans or design tables - to reduce the amount of necessary experiment runs to achieve as precise information as possible with the smallest number of experiments. The type of plan used depends on the experiment's objective. Finding the optimal design table, i.e. the least amount of experiments that is necessary to depict the systems behavior correctly has been subject to intense research. Using a set of statistical evaluation methods on the resulting experiment data, the impact, effect and interactions of the factors in relation to a chosen performance indicator is evaluated. The results of the experiments can be used to formulate a mathematical surrogate model, also called a metamodel in engineering disciplines [26,27].

2.2.1. Application for building energy performance

DoE has only rarely been applied in a building context. Chlela et al. [21] and Jaffal et al. [22] present the application of the DoE methodology for selected design parameters of new low energy buildings, targeting thermal performance. The focus of their work is on the exploration of various existing design tables that reduce the amount of simulation runs to derive a polynomial metamodel. Describing the mean and maximum error of the resulting metamodels as the main outcome and key evaluation criterion, the work focuses rather on the technical aspects of applying a DoE methodology for a new building design in general than on its qualitative outcome and applicability for retrofit designs.

More recently, DoE in combination with dynamic energy simulation has been applied to identify factors for cooling loads on a residential building [23], and similarly, for deriving a metamodel for heating and cooling of low energy housing in Morocco [24]. For the simulation of new buildings, the selection of factors for the experiments is only restricted by the simulation capabilities whereas for building retrofit, the choice of factors and factor levels is constrained by the condition of the existing building and the available design options. As it is not possible to alter factors such as location, orientation or basic construction, the balancing of the remaining factors is even more important.