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Building energy optimization in the early design stages: A simplified method

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ABSTRACT

This paper presents the application of multi-objective genetic algorithms for holistic building design that considers multiple criteria; building energy use, capital cost, daylight distribution and thermal indoor environment. The optimization focus is related to building envelope parameters. To obtain relevant feedback from multi-objective optimizations in early design stages, evaluation speed is a key concern. The paper presents a fast evaluation method fit for the early design stages. It uses a combination of two different quasi-steady-state methods for energy and indoor environment evaluations, a Radiance implementation for daylight simulations and a scripted algorithm for capital cost evaluations. The application of the method is developed around an integrated dynamic model which allows visual design feedback from all evaluations to be an integrated part of the design tool experience. It is concluded, that quasi-steady-state methods implemented as part of integrated dynamic models are fast and flexible enough to support building energy-, indoor environment- and cost-optimization the early design stages.

1. Introduction

Building energy optimizations during the early design stages, where information levels are low and design changes are frequent, induce risks of high uncertainty and excessive amount of calculations. Many researchers reason that building performance simulation (BPS) tools in the early design stages is beneficial for building performance such as energy, daylight and thermal indoor environment. However, BPS tools are rarely used in the early design process, consequently optimization with such tools are far from integrated in the early design stage in practice.

Augenbroe [1] argues to better inform the early design BPS tools need to support: (1) A rapid evaluation of designs alternatives, (2) different types of decision making processes and (3) designers' ability to solve nonlinear and multi-criteria problems. Struck [2] supplements that BPS tools must be flexible and fast enough to facilitate changing representations of innovative design concepts thus being able to dynamically scale the model resolution to fit the different information levels. Few tools live up to any such expectations. Simplified BPS tools are fast but only provide simplified feedback while more advanced BPS tools are difficult to use and are often slow in comparison to the simpler tools. Furthermore, only a fraction of these BPS tools can be used in automated processes required to perform building energy optimization. The choice of simplified BPS tools in the early design stages seems to be favored by most practitioners [3]. However, with the purpose of designing with optimization, simplified BPS tools may evidently increase risks of returning inaccurate results, which defies the purpose of using optimization processes in the early design stage. Even though techniques of BPS are undergoing rapid change and dramatic improvements in computing power, algorithms, not feasible only a few years ago [4], the balance between achieving sufficient accuracy and the ability to provide highly flexible and fast feedback to the designer, is still today base for discussion.

In general most methods which apply optimization in early design stages focus on non-geometrical variables such as changing *U*-values, or system requirements and rarely put the analyses in context of project specific architectural solutions. Obviously compulsory and ambitious use of optimization algorithms in the early design stage is of architectural concern. Hermund [5] reacts toward optimization in the design processes:

> Linear working methods that promote the reduction of the creative loops in favor of systemic optimization is one topic that must be addressed by architects . . . Relying on one integrated

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model (referring to IFC- and gbXML-models) could mean an eventual loss of control with real value of the architectural quality: to create meaningful and beautiful spaces for real people. Hermund [5]

The concern of using optimization processes in early design is very real, regardless of how the model is constructed. However, the benefit of optimization may in many cases exceed the downsides of artistic control if the optimization processes is controlled and supervised by the designers themselves. And to counter this problem, geometrical design concepts representing architectural ideas in variations must be easy to integrate with the optimization process. Based on Mora et al. [6] Struck et al. [7] point out such process is supported when the method is able to:

- Assisting rather than automating design.
- Facilitate the quick generation of integrated solutions.
- Shorten synthesis analysis evaluation cycles.
- Support an interaction and selection of most suitable design alternatives.

With the ambition to advance combined qualitative assessments and quantitative optimization in the early design stage, a simplified method to whole building energy optimization is proposed. Based on a real life design problem the article first explains the need for a very fast whole building simulation that could (to an acceptable level of precision) present the whole building energy consumption, the price of the façade, the amount of daylight in every zone and estimate the risk of thermal overheating problems inside the building. All this must be done in a way to make informed feedbacks to the designer on limited amount of information. As a response to these needs this paper shows a new method that allows multi objective optimization with the inclusion of project specific qualitative constraints.

Our approach chooses various simple BPS tools coupled together with a visual scripting tool and results are visualized in the architects design tool. The reasoning to use simple BPS tools over the more complicated and precise simulation tools, are compressed into three requests: (1) to overcome the limited time available in the early design stage, optimization must be as fast as possible. (2) The coupled BPS tools have to fit the early design stage, hence they must be able to make use of the limited amount of information available. And (3) the tools have to fit into an integrated environment that can take the entire design team's expertise into account.

The main focus is on the building envelope optimized for whole building energy consumption, daylight distribution, thermal environment and cost. The method relies on an integrated dynamic model [8] that incorporates a design (CAD) tool Rhinoceros [9] a visual programming language (VPL) Grasshopper [10], the existing BPS tools Radiance [11], Be10 [12] and a new hourly based quasi-steady-state tool (HQSS) to estimate hourly heat gains with the purpose to prevent overheating problems at zone level.

2. Background and related research

Optimization as a process favors limited aspects of a system, which need to be *differentiable in the design parameters* [13] while constraints and objectives need to be clearly defined. Therefore, optimization as a process will often discount those aspects, which has not been included in the cost function. This is arguably the main reason why research in optimization focuses on quantitative performance objectives over qualitative evaluations. Nonetheless many researchers have sought to reconcile the level of artistic control to optimize on predefined criteria with predefined constraints. One example is Petersen [14] who focuses on a list of very specific elements of the particular design instead of aiming for a complete evaluation of every parameter in the early design stage. By limiting the search space the design team saves time in the early design process and optimization may be handled by human thinking alone. However, when design problems grow with design variables and objectives, algorithmic optimization becomes ever more attractive.

To make the design exploration computational feasible to Hopfe and Hensen [15] argued the analysis of sensitive variables is a good starting point for a more integrated design analysis. This of course can be applied to project specific cases that employ stochastic analyses of building models to provide the designer faster indications on which variables are more sensitive or robust. To further speed up this process Hopfe et al. [16] used surrogate modeling techniques to approximate the objective functions on energy consumption and over/under-heating hours. The method used Gaussian processes (Kriging) which correlate quite strongly with the introduced noise on the design parameters, basically to model real-life uncertainties. The idea to use increasingly adaptive surrogate models have also shown promise to include more qualitative assessments (that often means many more design variables) by *listening to design variables and predicting user requests* as suggested by Negendahl et al. [17]. However, this concept has not yet been coupled with optimization algorithms and need further developments in predicting user requests are needed.

Another approach to decrease computationally expensive calculations is to implement adaptive precision control in the BPS tool and approximate cost functions for example Wetter and Polak [18]. This, however require deep access to the solvers precision parameters. In many BPS tools these are fixed at compile time and are hard to access. Nonetheless, Wetter & Polak showed promising results by applying a Hooke-Jeeves optimization algorithm with precision control on a static SPARK model.

Wright et al. [19] showed one of the more recent attempts in applying multi-objective optimization with quality defined constraints into the early design. The design in this context was considered by constraining the geometric proportions of the façade by the golden ratio and visualizing optimal solutions lying on the trade-off between energy use and capital cost. Other efforts to improve the integration of the design process and the energy performance domain include: Caldas [20] and Wang et al. [21] who attempts to involve the more subjective and qualitative objectives into optimization processes. Kim et al. [22] use an agent point strategy to control overall building geometry, this is coupled to a CFD tool and genetic algorithm to optimize wind flow around the building. They considered one building typology and argued that the method would provide design options and *educated intuition for architects to incorporate in design practices*. Gerber and Lin [23,24] showed a prototype tool (*H.D.S Beagle*) to integrate parametric geometry, energy simulation with Green Building Studio and optimization into the early design stage. And finally the ParaGen project [25] by Turrin et al. explored a performance based design process by combining parametric modelling and genetic algorithms correlating structural performance and solar energy. All these methods heavily depend on high computational power and are therefore difficult to use within the limited timeframe of the early design stage.

Ideally faster or even *real-time evaluation speed* like found in the approach of Sanguinetti et al. [26] combined with better quality assurances and implementation of robust optimization methods is to be preferred. Sanguinetti et al. argued for the fast performance feedback as one of the main drivers for designers to explore design alternatives. Their solution was an integration of design synthesis and analysis is implemented through coupling simple parametrically controlled geometric representations generated in a design tool with normative calculations in spreadsheets. The method proved to be highly flexible and could serve project specific