Design Decision Support – Real-time Energy Simulation in the Early Design Stages

F. Ritter[1], G. Schubert[2], P.Geyer[3], A. Borrmann[1] and F. Petzold[2]

[1]Chair of Computational Modeling and Simulation, Faculty of Civil, Geo and Environmental Engineering, Technische Universität München, P.O. Box 80333, Munich, Arcisstrasse 21; PH +49(0)89.289.23047; FAX +49(0)89.289.25051; email: fabian.ritter@tum.de
[2]Chair of Architectural Informatics, Department of Architecture, Technische Universität München, P.O. Box 80333, Munich, Arcisstrasse 21; PH +49(0)89.289.22171; FAX +49(0)89.289.22179; email: schubert@tum.de
[3]Centre for Energy Efficient and Sustainable Design and Building, Faculty of Civil, Geo and Environmental Engineering, Technische Universität München, P.O. Box 80333, Munich, Arcisstrasse 21; PH +49(0)89.289.23990; FAX +49(0)89.289.23991; email: philipp.geyer@tum.de

ABSTRACT

Today's design teams have to consider many different parameters and design options from an early stage which can ultimately have a significant impact on the final performance of the building. Simulations can be used to help design teams understand the consequences of the decisions they take and assess potential variants. In the early stages of the design process, however, the information needed to conduct accurate simulations is often lacking.

To address this issue we developed a new method for Design Decision Support (DDS) that makes it possible to run simulations based on vague and incomplete input data using a method called surrogate modelling which implements parametric simulation data as a quick response performance model for the early design phases. This method is based on parametric simulation models that contain the required information. Designers can use these models to obtain instant feedback on their design and suggestions for further improvements. In our implementation, we have linked this system to a multi-touch environment that links physical volumetric models with the surrogate models allowing designers to employ familiar approaches to design thinking.

This prototype provides designers with direct access to energy performance simulations in the early design stages. This will be expanded in future to provide further simulations.

INTRODUCTION

The implications and cost of making significant design changes increases dramatically the further a project progresses. For this reason it is useful to obtain feedback on the consequences of design decisions – for example through simulations and analyses – as early as possible in the design process. The problem, however, is that in the early design stages, the information needed to conduct simulations is either not yet known or vague, making it difficult to define simulation models and resulting in long computation times. In addition unintuitive user interfaces for conducting design-relevant calculations and analyses represent a hurdle to designing in the early design stages.

The laborious setup of simulation models and the computation time required hinders the current practice of using such technology in early design phases. However, in certain fields, such as energy efficiency performance, simulation is the only way to capture the many dynamic effects, for example the thermal storage capacity of the building construction or local decentralised energy generation methods using solar power. The approach we present here applies surrogate modelling to provide a quick indication of the energy performance of design variants based on typical parameters that are available in the early design stages. These are applied to a universal parametric model of a building to obtain quick and accurate performance feedback during design sessions without having to interrupt the design process to prepare and run simulation models.

Using the approximate information available in a real physical model at a scale of 1:500 as its starting point, the goal is to obtain feedback on the potential energy consumption of the design in real time without having to input the parameters manually. To this end we developed parametric models for evaluating energy performance that contain predefined systems to handle the lack of information in this early design stage. This "surrogate information" makes it possible for the system to provide fast Design Decision Support (DDS) despite the little amount of information available at this stage. It also offers the design team insight into how the design could be improved further.

THE DESIGN PROCESS

The development of a design tool begins with a consideration of the design process. Since the middle ages, the preparation of plans – as an anticipation of the final building – have been a fundamental part of the architectural design process. Over time, this act of envisioning a future condition developed into a process in its own right. Since then, countless attempts have been made to describe and operationalize the sub-processes into a generally applicable approach. But because design tasks usually involve finding solutions to ill-defined problems, no single theoretical approach is applicable in every situation, as evidenced by the more than 100 design theories collated by Dubberly (2008). Despite the lack of a universally applicable approach, recurring methods and patterns can still be identified. The tools that we employ as designers play a key role in the creative thinking process, providing us with a way of iterating towards an as yet unclear solution. An examination of the design tools used in the architectural context reveals a series of common characteristics: tools must be simple of use, flexible in their application, provide some form of direct cognitive feedback from gesture to brain, be able to accommodate vague input, and facilitate a step-by-step approach to problem solving.

The search for a solution is therefore commonly a process of generating variants and evaluating their relative merits (Rittel and Reuter, 1992). Described as visual thinking (Arnheim, 1971) or reflection in action (Schön, 1983), the tools facilitate a creative feedback loop between ourselves and the visual representations of our ideas. By externalising our thoughts in the form of sketches, i.e. by formulating them in a manifest form, we can then respond to them and evaluate them. These manifestations express different variants and considerations and are assessed and compared. We evaluate these according to both subjective and objective criteria. Because these criteria are often interdependent, there is no automatic way of conducting this process of evaluation.

DDS – DESIGN DECISION SUPPORT

While digital tools may not be able to operationalize the design process, they can assist designers by providing information that is helpful for evaluating variants, making decisions and steering the direction of the design process. Simulations and analyses in particular offer a means of assessing design variants according to objective criteria. The integration of energy analysis and simulation in the design process is a very common topic in the building industry (Hopfe, 2005). Nevertheless, many of these methods are of limited use in providing design decision support.

Current tools focus mostly on analysing a defined design option and do not provide any suggestions for possible changes that could further improve the design. Examples are the Design Performance Viewer by Schlueter (2009) and Green Building Studio (2013). While the first example uses a simplified quasi-static energy analysis, the second example runs simulations on a cloud-based cluster with a short but noticeable feedback time. The response surface method (RSM), as one popular method of surrogate modelling, is able to overcome this drawback. Tests have been undertaken with RSM on buildings (Chlela et al., 2009). Furthermore, an adaptation of RSM makes it possible to generate surrogate models automatically without interfering with their mathematical structure (Geyer and Schlueter, 2014). This makes it much easier for designers to make use of energy calculation during early design phases.

Many of these tools provide support for a single designer, for example the H.D.S. Beagle by (Lin und Gerber 2014) which integrates optimizations for reducing costs and energy consumption in the design process. Most of the available collaborative and interdisciplinary design platforms connect different single workspaces, and only where possible. To be properly effective, design tools need to facilitate collaboration between all stakeholders (Soubra, 2009). Current tools do not assist designers in making selections. They do not record the rationale behind the best variants or assist in understanding the larger impact and values of design alternatives (Gane 2012). Moreover, many simulation approaches are highly complex and have a correspondingly steep learning curve, with the result that they are only used by experts.

To summarise, we can identify three key failings in currently available approaches: (1) they do not provide Design Decision Support (DDS) from the outset;

(2) they do not support collaborative and interdisciplinary teamwork; and, (3) they can only be operated by experts.

COLLABORATIVE DESIGN PLATFORM

Taking the above as its starting point, a concept for a digital design platform was developed as a prototype as part of an interdisciplinary research project. The underlying idea is to develop digital tools that strengthen rather than hinder the design process. Rather than replacing established design tools (i.e., physical models) with corresponding digital methods, the approach combines real models and digital simulations to make the most of both worlds. By combining the advantages of each realm, we expand the possibilities of designing in real and virtual environments; the process of simulation and evaluation is directly integrated into the creative workflow of the designer and the information content of the real model is augmented by additional layers of digital information.

The resulting “CDP | Collaborative Design Platform” is a hardware and software prototype. The technical basis of the project is a large-format multi-touch table with integrated 3D-object scanner that facilitates a seamless connection between a real haptic working model [scale 1:500] and interactive content in real time. To respond to the individual needs of design and construction tasks, we developed a software framework with plug-in architecture making it possible to easily connect plugins written in C# code for effecting a direct connection between physical models, GIS data and digital design-supporting tools such as simulations, analyses and calculations.

ENABLING PERFORMANCE FEEDBACK

With the help of these simple digital tools, simulations that are normally undertaken at the end of the design phase can be applied in order to analyse and assess the implications of design decisions at a much earlier stage in the design process. For example, statutory planning constraints such as building regulations can be incorporated into the design process at an early stage. As a means of optimising the design, they save time and provide objective assistance that can have a direct effect on the quality of the design. The aim is to simulate tendencies during the early design phases, where the data available is often vague and incomplete, and to display design-relevant parameters with a view to making the spatial quality and functional aspects of a design more legible and the decision-making process more transparent, effective and clear. Such simulation tools provide the designer with additional information that can inform the design but the subjective process of assessment, evaluation and exploration remains in the hands of the architect. One can imagine this as a creative cycle in which the computer provides real-time objective feedback on a variety of relevant issues, which can in turn inform the direction of the architect’s design decisions. The boundary between sketch, simulation and analysis blur into a continuous, creative design process.

While simulations that rely on the shape of the building, such as analysing solar gain, shading and visibility studies, can be performed on the basis of the physical models, more complex calculations, like energy analysis, need additional information. These are typically entered by specialist consultants using their own software, but this means that this information is not immediately available during the design process. To make this information available to the design process in the form of real-time feedback on the effect of design decisions, we employ the principle of surrogate modelling.

Surrogate Modelling. By surrogate models we mean parametric non-physical performance models with an interface providing the same information as simulation. They already contain simulation results for different parameter combinations and as a consequence of their mathematical approach allow the completion of simulations in combination with given parameters with error assessment. This structure makes it possible to provide rapid feedback on initial designs within a very short calculation time (i.e., 50 to 500 µs on a usual desktop PC).

The surrogate modelling approach we use is based on the RSM mentioned above. The basis is a polynomial term structure. However, in contrast to traditional RSM, we use a method with a flexible mathematical structure. The following equation expresses this novel general RSM model formulation:

$$\mathbf{y}_{M,k} = \sum_{j=1}^{n_e} ß_j \prod_{i=1}^{n_f} \mathbf{x}_{k,i}{}^{\mathbf{E}_{j,i}} \text{ with k=}\left\{1..\text{n}_\text{p}\right\} \text{ and } \mathbf{x} \in \left[\frac{1}{n_l}, 1\right].$$

The design matrix $\mathbf{x}$ includes all normalised design configurations with n_l levels. The matrix $\boldsymbol{\beta}$ contains the coefficients to fit the surrogate model response $\mathbf{y}_{M,k}$ for the kth experiment of the n_p experiments. The exponent matrix $\mathbf{E}$ serves to adapt the mathematical structure of the model to data.

The simulation results, which derive from a subset of parametric combinations selected by design of experiments (DoE), are fitted by composing the exponent matrix step-by-step, doing regression as standard in RSM and observing the improvement. This method is described in detail by Geyer and Schlueter (2014). The advantage of the method is that a very good fit is achieved without the user having to interact with the mathematical structure of the model as is normally required for RSM.

Aside from the speed of response of the model, the interpretation of the exponent matrix makes it possible to draw conclusions about the effect of the parameters and their interaction. This information helps designers to select parameters for specific investigation.

Parameterization. In our approach, we limited the parametric simulation and the surrogate models to office and administrative buildings because of their repetitive structure. Furthermore we focused on rectangular shapes, which is a very common design for these kinds of buildings.

The parameters implemented in the current approach are: length (1), width (2), height (3), orientation (4), class of outer skin (including u-values and g-values from transparent and opaque façade elements) (5), and the glazing factor (6). While parameters (1) to (4) and (6) are very easy to understand, parameter (5) needs a little more explanation. We defined three different combinations of exterior walls, windows and the roof. This allows us to support the early design process, in which the quality of the façade is defined by the client but no materials are selected. The materials are selected to enable sustainable design according to Ritter et al. (2013).

The surrogate model also possesses further depending parameters that are not defined explicitly by the designer. Instead, these are automatically derived from other input parameters. This helps to ensure that the design task as kept as simple as possible to avoid hindering the designer's train of thought. The depending parameters are: internal masses representing the inner walls (7), the HVAC system (8), and the railing height (9).

The depending parameters are determined by following rules; (7) is defined by the length (1) of the building. It divides the length sequentially in equal parts by a minimum width of 5 metres. (8) corresponds to the selected class of the outer skin (5). It is selected by its efficiency. The better the class of the outer skin, the less the efficiency of the HVAC system. This reflects the implications of design choices, e.g. highly-insulated façades offset the need for efficient systems. In addition, a high class of outer skin and very efficient HVAC systems are both very expensive and most building owners decide for one or other of these two options. (9) depends on the glazing factor (6) and is selected in a way that maximizes the daylighting factor inside the offices.

Simulation. The whole building is modelled as one building block resulting in a single zone for energy analysis. This results in a fast and general model that delivers accurate results as long as all internal masses are also modelled (Struck, 2011). The boundary conditions are obtained from METEONORM weather data sets that include hourly values for air and ground. For the simulation engine, we use the EnergyPlus (2013).

USE CASE

The functionality of the CDP is best explained using a typical case study. Our fictional design task is for an office building that is to be built on site in an urban context. The architect begins his or her conceptual design by creating physical blocks cut out of styrofoam or similar that represent the building volume. The architect sets up the multi-touch table to show the current urban plan of the location. The architect can then proceed to examine not only the configuration and massing of the building design but also the corresponding energy performance if the building.

Output. With the help of the surrogate model, the parameter values for the recent design are displayed along with the current performance, i.e. the heating and cooling demand (see Figure 1). The geometrical parameter inputs, (1) to (4), are taken directly from the physical model, while parameters (5) and (6) need to be additionally input via the touch interface of the CDP. Furthermore, we are able to plot a specific performance graph per parameter describing the design space, which also assists the architect in exploring the design space and making decisions.

After the designer has found a solution that works both from an aesthetic viewpoint and also fulfils performance requirements, he or she can involve other stakeholders. Together with the client, for example, the architect can examine the current design and discuss the implications of possible changes. Other specialist consultants and planners can also be involved from an early stage of the design. The feedback provided by the CDP can serve as a basis for these discussions.

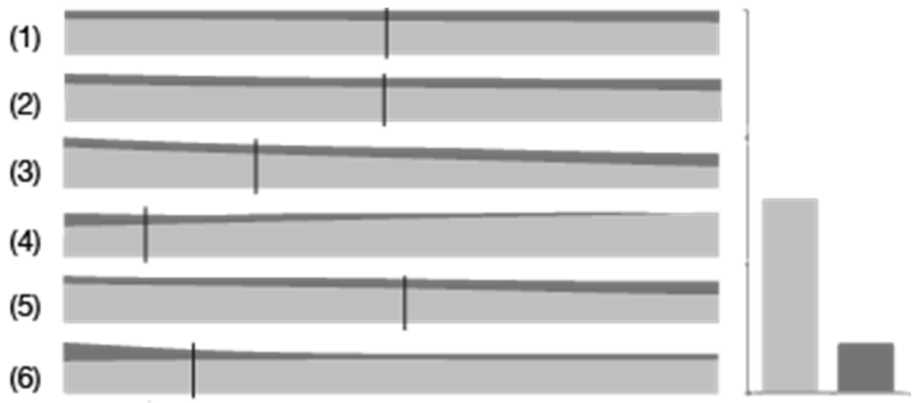

Figure 1. The output of the model shows the current selected parameters with their specific performance graph and the calculated heating (light grey) and cooling (dark grey) demands. It also displays how the parameters have to be changed to obtain a more effective solution.

CONCLUSIONS

Using this approach we facilitate Design Space Exploration (DSE) and Design Decision Support (DDS) by implementing energy simulation at the very beginning of the design process. For this purpose, we use an approach called surrogate modelling. It enables the design team to evaluate their current design variants with the help of a mathematical substitute model based on parametric simulation. The system is also able to indicate how the current design could be improved.

This surrogate model is connected to the Collaborative Design Platform (CDP) to incorporate the approach within the design process using physical volumetric models so that energy performance can be assessed in real time at this early stage of the design process. The design team can therefore explore the option space of energy modelling in a familiar design environment without the need to learn new software tools. It also provides a common basis for all stakeholders to discuss the different alternative solutions and informs the decision making process by making simulations available to the early design stages.

Further improvement. In future steps, we want to provide automatic generation of surrogate models depending on the position of surrounding shading elements. This would need the provision of some extra parameters at the beginning and may result in additional computation time, but it would also contribute to improving the quality of the surrogate model and making it more related to the current design task.

Additionally, the approach needs to be adapted to more complex building shapes, firstly to combinations of rectangular shapes, e.g. L-shaped or T-shaped buildings, and then to freeform shapes.

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