ALGORITHMIC DESIGN AND PERFORMANCE ANALYSIS OF ADAPTIVE FAÇADES

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Abstract. Building performance simulation tools have the potential for aiding the decision-making process in early design stages of an architectural project. As traditional simulation tools are based on a static design and adaptive façades encompass an envisioned movement of construction elements, there is a lack of supporting tools and workflows that can correctly evaluate the performance of such building envelopes at an early stage. The presented ongoing research focuses on developing efficient parametric performance-based approaches for assessing the energy consumption in buildings with adaptive façades, combining generative architectural design and performance analysis in a seamless workflow. To this end, we combine a new algorithmic design research tool with the well-established whole-building simulation engine EnergyPlus. The purpose of linking both tools lies in the possibility of generating and simulating models with adaptive façade mechanisms through a single script, evaluating and using the simulation results to adjust the model's parameters and develop optimized control strategies.

Keywords. Building performance simulation; Adaptive façades; Algorithmic design; Energy analysis.

1. Introduction

Performance-driven design should follow a procedure that focuses not only on the aesthetics and functionality, but also on a wider understanding of the project's environmental context. Reducing the ecological impact of future buildings can be expedited by informed decision-making processes on the basis of performance predictions. Adaptive building envelopes allow for a space reconfiguration that follows environmental changes and user needs, focusing primarily on the increase

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of efficiency and reduction of energy consumption in constructions (Barozzi et al. 2016). As this concept rises into consideration, it is important to find an efficient way to predict the combined benefits and constraints of specific design propositions, which may vary in terms of materials, components, and systems. Ideally, such performance assessment should be executed at an early stage of the project, so that the architect continually develops design variations while comparing them to the original design intent. However, simulation tools are mostly used during the detailed design stage, when most of the decisions regarding building massing and system types are already made (Brahme et al. 2009).

Choosing an analysis tool implies considering the flexibility given to the various building performance simulation (BPS) tools available, regarding model resolution, solution algorithms and user-friendliness. Surveys led by Attia et al. (2011) reveal that architects prioritize the integration of an intelligent knowledge-base over the usability of the interface or the accuracy to simulate complex building components. In parallel, Shi and Yang (2013) explore the concept of performance-driven architectural design by integrating multiple performance simulation programs into a parametric CAD context, exposing a need for the addition of program development and code writing into the proposed workflow. Both Karssies (2017) and Strunge (2017) use inter-model comparison to assess the validity of basic functionalities in the interface of parametric analysis plugins for CAD tools - although showing a wide parameter flexibility for early-stage design, overall deviations are denoted between the produced output and the baseline results.

The adoption of responsive building elements is impeded by a lack of integrated design processes and intelligent controls (Heiselberg 2009). Moreover, geometric patterns in adaptive façades are constantly shifting in the design outcome (Moloney 2011). Modelling and simulation approaches for adaptive building envelope assessment are still at an early stage of development, with many aspects yet to be explored (Loonen et al. 2017). Current trends focus on combining energy simulation software with dedicated data post-processing (Goia and Cascone 2014) or optimization and control procedures (Favoino and Overend 2015), as well as on model-based parametric simulation (Sharaidin, Burry and Salim 2012; Kim, Asl and Yan 2015; Kormaníková, Kormaníková and Katunský 2017). The latter opens the possibility for architects to assess various design alternatives by integrating adaptive building components, both visually and quantitatively. However, the visual paradigm of plugins that interface BPS tools with CAD programs is limiting regarding the modelling of complex and large-scale designs, due to its shortcomings in abstraction and control mechanisms and, in other parts, to the time-consuming metaphor of program construction based on the manipulation of wires and boxes (Leitão, Santos and Lopes 2012). Developing generative and parametric design methods, advanced visualization techniques, and the integration of BIM can further help reducing the barrier for applying BPS in exploration-driven projects (De Klijn-Chevalerias et al. 2017).

1.1. OBJECTIVES AND AIMS

Although not being a fundamental requirement for architects, the use of computational design techniques allows for the exploration of design options that would otherwise not have been considered in the geometric and analytic study of complex projects. There is a growing potential in this field which remains largely unexplored, both regarding early stages of the architectural design and non-static building envelopes. The presented research aims to develop a unified algorithmic design (AD) and analysis workflow for the parametric assessment of buildings with adaptive façades. The goal is to further reduce the current gap between generative design and simulation and analysis tasks, bringing architecture closer to performance-based design.

Section 2 provides a description of the proposed workflow, including a validation test of the algorithmic modelling approach. The introduction of adaptive façade elements through AD is supported by a case study, the details of which are presented in section 3. Subsequently, section 4 reviews the outcomes of the proposed workflow. Final remarks are discussed in section 5, along with future work regarding this research.

2. Workflow

Focusing on the performance of the building from an early project phase emphasizes a comprehensive optimization of various quantifiable performance outcomes. Typically, such assessments are postponed to later stages of the design, serving as verification of compliance with standards. However, by combining design and simulation into an integrated approach, it becomes possible to change geometric and analytic models simultaneously, and also to automate the generation of these models. In the past, this methodology was applied to lighting and structural performance analysis (Castelo Branco and Leitão 2017; Caetano et al. 2018). Our research extends it to also include energy performance simulations. The AD approach we introduce in the following subsections is illustrated in Figure 1, integrating the generation of parametric models in CAD and the execution of energy analysis into a single script.

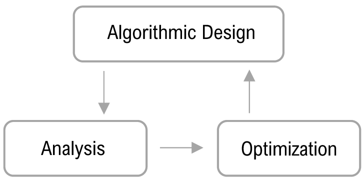

Figure 1. Proposed workflow.

Most building energy simulation tools demand considerable expertise on their use, given their requirements and data processing methods. Tools like EnergyPlus (EP) rely on manual data entry processes, which are time-consuming and error-prone. Consequently, despite acknowledging the significance of energy efficiency assessments, not every architectural design studio is prepared to make use of this tool's modelling capabilities. A workaround for this impediment is the use of modelling plugins, which support the set-up of basic EP system objects through visual programming languages. For this study, we are using Honeybee to construct an input data file (IDF) to be executed by EP, containing the building's geometry produced by the AD tool.

2.1. VALIDATION EXAMPLE

Different simulation tools have distinct initial settings and calculation methods that are difficult to control, causing small discrepancies in outputs for the same analytic model. Aside from the required domain knowledge, credibility assurance passes through the exclusion modelling, simulation, or reporting errors. Inter-model comparative testing allows the comparison of any cases that two or more tools can model. BESTEST (U.S. Department of Energy 2015) defines specific cases modelled with several whole building simulation tools, specifying acceptable performance ranges from the minimum and maximum values of the compared outputs. To ensure an efficient workflow, we assess the validity of basic functionalities required for early-stage design by comparing the output of BESTEST case 600, modelled in EP, with the output of an equivalent AD model.

2.1.1. Input

Both cases are defined by identical rectangular single zones, with a lightweight building construction defined as stated in BESTEST. The South façade has two windows, totalling 12 m^2 of glazing area. The building's geometry is modelled parametrically in the AD tool, where all the building elements are placed in the corresponding layers in Rhinoceros. The content of each layer is then imported to Grasshopper's plugin Honeybee, where construction materials, internal gains and simulation inputs are applied. Figure 2 presents the internal gains considered for this model.

(a)

Occupancy	-
Lighting Load	-
Equipment Load	200W
Heating Setpoint	20ºC
Cooling Setpoint	27ºC
Infiltration	0,5ACH

(b)

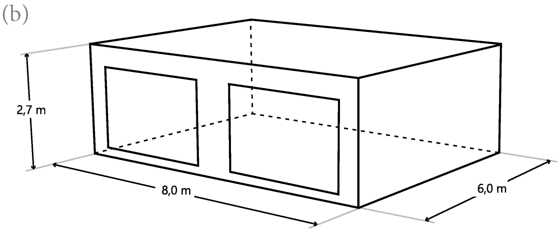

Figure 2. BESTEST internal gain description (a) and base geometry (b).

A weather file from Denver, U.S.A, characterized by cold clear winters and hot dry summers, is used to run both the EP and the AD simulation. The AD script executes EP with the IDF produced by Honeybee, consequently simulating and gathering the results in a designated file address. Requested outputs include zone mean air temperature, sensible heating and cooling energy, and incident solar radiation on the outside of the building surfaces.

2.1.2. Output

EnergyPlus' model for BESTEST case 600 is used as a baseline for comparing the outputs produced by the AD model. Figure 3 shows the predicted daily average air temperatures over the year, and Figure 4 summarizes the monthly heating and cooling demand for both simulations.

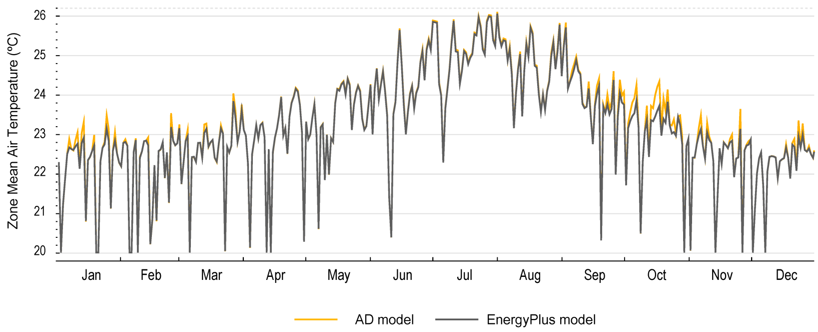

Figure 3. BESTEST case 600 daily average temperature plot.

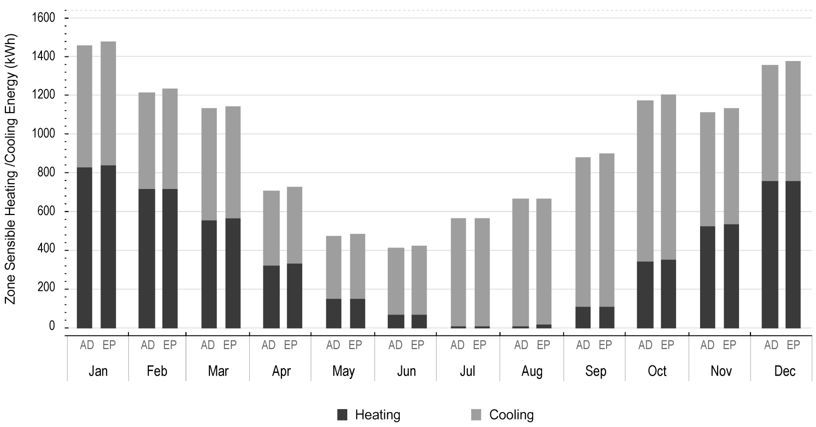

Figure 4. BESTEST case 600 heating and cooling demand per month.

It is important to consider that comparative testing is not a certainty over the actual performance of a building performance simulation, but merely an approximation. It exclusively proves that the presented AD tool is computing solutions that are reasonable when compared to the standalone use of EP for building modelling. With that in mind, we identify enough similarity between the simulation outputs to consider the AD modelling approach valid.

3. Introducing adaptability: a case study

The presented case study is based on the south façade of Jean Nouvel's Arab World Institute, built in Paris in 1987, which holds a kinectic system inspired by traditional patterns of the Arab geometry. Each module, called mashrabiya, has a set of 73 diaphragms divided into five distinct aperture mechanisms. We model a single-zone building of simplified geometry that incorporates these façade mechanisms.

3.1. GEOMETRY

The shoebox geometry of the validation study is maintained, replacing the glazing elements by a set of three mashrabiyas. In a building analysis context, simulation time increases along with the complexity of the model. Hence, we simplify the opening of each diaphragm by reshaping it as a circle with an equal area, as illustrated in Figure 5. The radius for each circle is calculated from the opening area of each diaphragm.

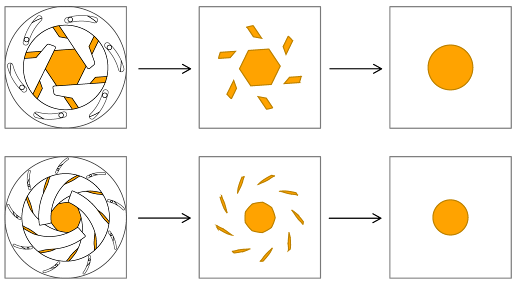

Figure 5. Simplification examples for the diaphragm's opening.

However, the geometry of a circle is not processed by EP and, therefore, produces no output in the analysis. To solve this issue, we replace the circular openings with regular polygonal openings with the same area. Ideally, to better approximate the circles, these polygons should have a large number of sides. However, this negatively affects the simulation time. Table 1 compares the overall simulation time, along with the annual heating and cooling demand, for year-long analyses using openings of sixteen, eight, and four sides. The latter case shows that the polygon rotation angle is also relevant for reducing simulation time. As the variation in the annual output variables between the four geometries is minor, we opt for the use of axis-aligned squares for the diaphragm openings, as these provide significant reductions in the simulation time.

Table 1. Simulation with different polygonal openings. Δ refers to the percentile variation between the simulation of the 16-side polygon model and the ensuing ones.

Polygon	○ (16-side)	octagon	Δ (%)	diamond	Δ (%)	square	Δ (%)
Simulation Time (s)	23953	2127	167.4	422	193.1	88	198.5
Sensible Air Heating [GJ]	15.162	15.134	0.2	15.114	0.3	15.096	0.4
Sensible Air Cooling [GJ]	5.896	5.901	0.1	5.903	0.1	5.905	0.2

As formerly stated, there are five types of diaphragms present in each façade module. For each diaphragm, we assume a minimum opening radius, $r_{\min}$, and an opening amplitude, a, based on measurements from the original geometry. The opening radius for each diaphragm, r, is calculated by $r_{\min} + a \cdot f$, where f is a factor between 0 and 1 that describes the level of aperture opening for the façade panels.

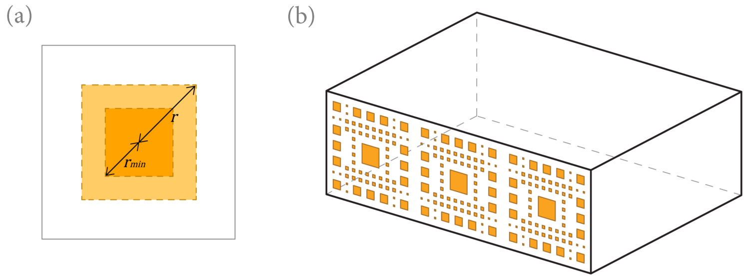

Figure 6. Illustration of the aperture opening variation of the façade diaphragms (a) and case study geometry (b).

3.2. ANALYSIS

We consider the modelled zone to have the building program of an exhibition room, attributing a lighting density of 11 W/m^2 and an occupation of five people. The remaining internal gain description matches the one of BESTEST case 600. A daylight control system is added to the model, with an illuminance setpoint of 500 lux. The control type is set to 'ContinuousOff', meaning that lights switch off completely when the minimum dimming point is reached.

Through the AD tool, we request the simulation of a series of models with static properties that represent different aperture levels for the façade openings. Outputs of heating, cooling and lighting energy use are compiled in a post-processing stage to optimize the adaptive façade.

3.3. OPTIMIZATION

Responsive systems in building envelopes must be linked to their surrounding environmental space, so that motion inputs can be applied and, consequently, allow the fulfilment of performance requirements. EP allows the implementation of energy management systems (EMS), linking sensors, actuators and control logic to the building model. However, when it comes to window shading control, devices are limited to exterior, interior or between-glass shades or blinds, which are either fully on or fully off. Thus, there is a need to find a more flexible method to model the façade diaphragms with different levels of opening.

The control system of the Arab World Institute was originally designed to activate motion in the diaphragms based on the amount of daylight. However, in order to optimize not only the luminous conditions but also the thermal comfort conditions, two sensors are used in the case study's adaptive façade, namely the incident solar radiation and the outdoor temperature. The purpose is to find the optimal value of f, i.e., the aperture level that produces the lowest energy use, for the correspondent matrix of values formed by the two sensors. The total energy use for each simulation timestep is calculated as the sum of the heating, cooling and lighting energy use. The heating and cooling energy use was determined from the heating and cooling energy needs divided, respectively, by a coefficient of performance (COP) and an energy efficiency ratio (EER). In the present study, COP and EER assume the standard values of 3 and 3.4, respectively.

4. Results and discussion

Optimization results are illustrated as a scatter plot, shown in Figure 7. The optimal opening factors are displayed as a collection of points, each determining its position according to the outside temperature and incident solar radiation on the adaptive façade.

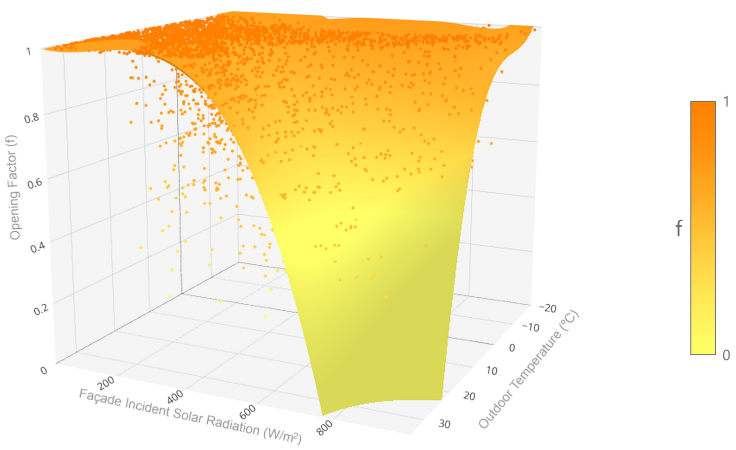

Figure 7. Optimal opening factor (f) for the adaptive façade diaphragms, in function of the façade incident solar radiation and outdoor temperature levels.

The analysis scatter plot contains a significant amount of outlier values. Such means that multiple values of f in the same timestep may result in equally low building energy needs. It can also mean that for different moments with the same environmental conditions, different optimal responses can occur. Other possible causes for the outliers are the chosen light dimming strategy, which largely affects the total energy sum, and the presence of infiltration in the building caused by the modelling approach. To remove noise from the collected data, we interpolate the timestep lines of the output table in which there are multiple optimal opening factors. Other pre-processing steps include the elimination of lines where (1) incident solar radiation is positive but no energy consumption is verified, or where (2) the difference of one timestep's f value and the one preceding it is superior to 0.5. As a final step, we apply a Bi-Variate SmoothSpline interpolation, which generates a series of normalized curved lines based on the scatter output.

The resultant surface from the connection of these splines creates a control strategy for the adaptive shading device formed by the façade diaphragms. As expected, the value of f decreases as the outdoor temperature and incident solar radiation increase. The site location of the case study translates into a saturation of higher opening factors, as temperatures in the region often fail to reach 0 °C during periods of cold weather. The final outcome of the presented AD workflow satisfies the initial aim, thus placing this research a step further into the development of an early-stage performance-based design approach for adaptive façade systems.

5. Conclusions and future work

The present research aims for the finding of a workflow that combines, in an early design stage, the parametric modelling and the energy performance analysis of buildings with adaptive façades. To this end, we develop a unified algorithmic approach that joins the two tasks in a single script, successfully validating it through the BESTEST comparative study. This workflow is applied to a case study of reduced geometric complexity, which is analysed and optimized to create a control strategy based on solar radiation incidence and outdoor temperature levels. The AD approach opens the possibility of quickly generating several design options from the same parametric model and, immediately after, executing energy performance analysis and optimization tasks for each individual geometry. In spite of the identified need to decrease the amount of noise in the simulation outputs, the workflow carries out the outlined objectives.

One limitation of the presented work is that it does not yet encompass iteration processes where analysis results are used to improve the original design. This could be used, for instance, to identify an optimized number of panels or the limits of the diaphragm opening ranges. We are currently working on incorporating this feature. Additionally, we plan to improve the scalability by removing Honeybee from the proposed workflow, so that we can expand the AD approach further from an early design stage, integrating a larger fraction of the process of an architectural project. Other future objectives are the exploration of different adaptive façade systems and new modelling approaches.

Acknowledgements

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