OPTIMIZATION-BASED DESIGN EXPLORATION OF THE MUTUAL INFLUENCE BETWEEN BUILDING MASSING AND FAÇADE DESIGN

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ABSTRACT

In architectural design, the design processes of building massings and facades are typically separated, which hinders the synergy of the two elements in sustainable building design. In response, this paper proposes an integrated design optimization workflow that can evolve design incorporating building massings with different formal characteristics and various façade schemes. With the proposed workflow, a case study is presented to demonstrate how the two design elements mutually influence one another and how the two-element can complement one another to maximize their potential for performance enhancement. The result indicates that different combinations of building massings and façade schemes can effectively drive the optimization toward different design directions, which significantly impacts the optimization result and the revealed architectural design implications related to performance improvement. As a result, the proposed design workflow can help architects better understand the performance implications of building massing and façade design and make more informed design decisions.

Keywords: Building Massing, Façade, Optimization-based Design Exploration, Daylighting, Solar Radiation.

1 INTRODUCTION

Building massings and facades are not only essential to architectural design when it comes to functionality and aesthetics but also play a critical role in building performance related to ventilation, daylighting, and energy efficiency in view of the demands for low-carbon building design and sustainable city development. Hence, the design of building massings and facades are often included in performance-based design optimization (Karagkouni et al. 2014; Negendahl and Nielsen 2015; Yi et al. 2019). By integrating parametric modeling, evolutionary optimization, and building performance simulation, performance-based design optimization can automatically generate a large number of design variants and identify the high-performing ones. However, in most performance-based design optimization studies, it is common for researchers or designers to handle the building massing and facade independently and optimize each element separately, which jeopardizes the effectiveness of the optimization and undermines the collective effect of the two elements for performance-based design. Apart from the established design norm, there is a technical challenge that the conventional parametric modeling approach requires too many parameters to one-to-one define all the windows/openings on the building façade surface, which can lead to an overwhelming problem complexity for optimization algorithms (Wang, Janssen, and Ji 2018).

1.1 Research Background

To address the above-mentioned issue, a few studies adopt a hybrid generative approach that combines a parametric building massing model with a self-adaptive facade generation algorithm to incorporate the two elements for the optimization of building performance (Janssen and Kaushik 2013; Zhang, Wang, and Ji 2021; Wang et al. 2022). By encoding a facade scheme into a self-adaptive generative algorithm and including it in an optimization process, design solutions can be found that incorporate the potential in both elements for performance improvement under the given design condition. In addition, the hybrid approach also facilitates keeping the number of parameters at a reasonable level and makes the optimization computationally resolvable. The previous applications of this hybrid generative approach demonstrate that the integration of building massings and facades can achieve a more progressive performance improvement than the conventional non-integrated design approach.

When it comes to its utility in design exploration, the hybrid approach also allows to investigate and examine multiple façade schemes for building design optimization. As highlighted in one of the previous studies, different facade schemes can strongly influence the shape of the building massing in the optimization result (Wang et al. 2022). For instance, when using a façade scheme with a weak shading effect, the building massing typically exhibits the self-shading feature to compensate for the need to reduce excessive solar heat gain. In contrast, with a strong shading effect, the building massing features fragmented forms and narrow floor plans to enhance the natural daylight accessibility as most solar heat can be filtered out by the facade. For architectural design, such design optimization can enable designers to systematically explore the relationship between building massings and facades at the outset of the design process.

As the previous study indicates that different façade schemes can greatly impact the building massing, it raises the question of how building massings can reversely affect the feasibility and adaptability of different façade schemes. This question underscores a limitation in the previous study, where the overall formal characteristic of the building massing was set invariable in the design generation process. In other words, the design (solution) space denoting the building massing design remained constant, which, thereby, limits the scope for the optimization process to explore.

In this regard, a recent study indicates that the overall formal characteristic of the building massing can affect the performance-based design optimization in terms of wind flows and sunlight accessibility (Shen et al. 2021). The study shows that different formal characteristics (solid/dense, fragmented/porous, and balanced) can drive the optimization search toward different directions and result in markedly different performance implications related to building massing design. This underscores the role of formal characteristics in performance-based building design optimization, which can significantly affect post-optimization design exploration and information extraction.

In summary, the two above-mentioned studies have respectively investigated the impact of different façade schemes (Zhang, Wang, and Ji 2021) and different formal characteristics of building massings (Shen et al. 2021) on performance-based design optimization. In this regard, the two studies shed light on a previously unvisited topic of how the two design elements can be integrated into one design process and how these two elements will interact with one another through the optimization process.

1.2 Paper Overview

For further investigating how the building facade and building massing mutually influence one another in performance-based design optimization, this study focuses on the building formal characteristic and its impact on the performance feasibility of different building facades. The study includes both the change in the formal parameter of the building massing design generation and the change in façade schemes in performance-based design optimization, thereby allowing the variation of both design elements to affect one another. The variation of the formal characteristics of the building massing also differentiates this study from the previous study mentioned above, in which the impact of formal characteristics was overlooked.

The paper first presents the optimization workflow used to conduct the performance-based design optimization. Following this, a case study design optimization and its result are presented to demonstrate the mutual influence of the two design elements. Finally, the paper concludes by discussing its relevance to performance-based design optimization and identifying future research directions.

2 METHOD

2.1 Design Optimization Workflow

The optimization of the study is conducted using a hybrid design generative approach that combines EvoMass for building massing design (Wang et al. 2020b) and a self-adaptive façade generative algorithm library that encodes multiple façade schemes. EvoMass is an integrated building massing design generation and optimization tool in Rhino-Grasshopper. With the use of EvoMass, different design spaces containing building massing designs with distinct formal characteristics can be obtained by varying the user-defined parameters. In addition, the self-adaptive façade generative algorithm library allows the optimization algorithm to select and generate different façade patterns on the surface of the building massing generated by EvoMass. Figure 1 illustrates the overall design generation and optimization workflow implemented by this study, which consists of six steps:

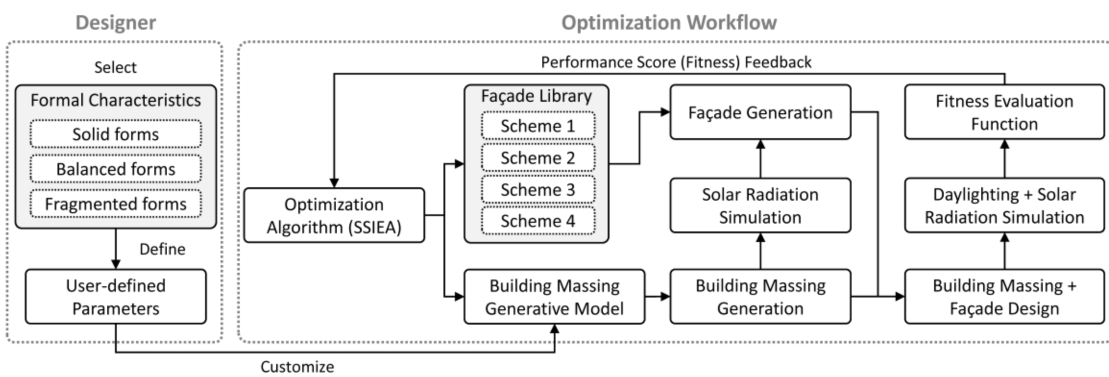

Figure 1: Building massing and façade integrated design generation and optimization workflow

- The workflow begins with the generation of building massing design, which is controlled by a set of parameters sent out from the optimization algorithm.
- After the building massing design is generated, a solar radiation (SR) simulation is conducted to calculate the solar heat intensity on the surface of the building massing.
- Next, a façade scheme is selected from the generative algorithm library according to another independent parameter sent out from the optimization algorithm.
- Based on the generated building massing, the pattern of the selected façade scheme is generated according to the solar heat intensity on the surface of the building massing.
- Following the generation of the façade pattern, another round of performance simulation is conducted to evaluate the façade-massing integrated design. The performance score (fitness) is fed back to the optimization algorithm.

- Once the optimization algorithm receives the performance score (fitness), the design population is updated, and a new set of parameters is sent out for the next iteration of building massing design generation and the façade scheme selection.

2.2 Building Massing Design Generation

EvoMass is used for building massing design generation, which provides two generative models, each abstracting and encoding the subtractive or additive form generation principle. For this study, the additive form generative model is used, which generates the building massing by aggregating several mass elements. With the parameter sent from the optimization algorithm that defines the spatial position and the dimension of each mass element, the additive form generative model can generate building massing designs with great topological variability. The topological variability is essential for the optimization to broadly explore a wide variety of designs and identify the high-performing one for the design problem (Wang et al. 2020a). Previous studies have demonstrated that the additive generative model can produce site- and task-specific designs reflecting rich architectural implications associated with passive building design.

The high topological variability in the additive form generation principle also allows it to serve as a "meta-model" that derives various families of building massings displaying distinct formal characteristics through the specification of form-related parameters, such as the number of mass elements and the size range of the mass elements. With different parameter setups, the additive generative model can produce building massings with fragmented, balanced, and solid forms (Shen et al. 2021). By changing these parameters, designers can specify the desired formal characteristic of the generated building massing. From the design space perspective, the change of the formal parameters makes the additive model delineate various design spaces containing a subset of building massing designs according to different input user-defined parameters that all comply with the additive form generative principle.

2.3 Façade Design Generation

To generate the façade of the building massing, a library of self-adaptive façade generative algorithms is created for this study. In this library, each façade generative algorithm implicitly generates a façade pattern according to the solar heat intensity on the surface of the building massing. For instance, in the surface region with a higher solar heat intensity, the density or the size of the shading device is increased to reduce the heat gain of the interior space. During the optimization process, a parameter sent out from the optimization algorithm selects one of the façade generative algorithms from the library. Based on the solar heat intensity, the selected generative algorithm first transforms the solar heat intensity into an indicative value that determines the adaptive component of the façade scheme, such as the number of shading devices and the Window-to-Wall ratio. Following that, the corresponding façade pattern is generated and attached to the building massing generated in the previous step.

Figure 2 exemplifies the generative procedure of a façade pattern adopted in this study. When generating the specific façade pattern for each generated building design, the façade surface is first divided into smaller sub-surfaces. For the algorithms implemented in this study, the division creates three sub-surfaces between every two columns. Afterward, the simulated solar radiation value of the sensor point that is closest to each sub-surface’s center point will be attached to the corresponding sub-surface. The solar radiation value is then transformed into the indicative value that controls the adaptive components in each façade scheme.

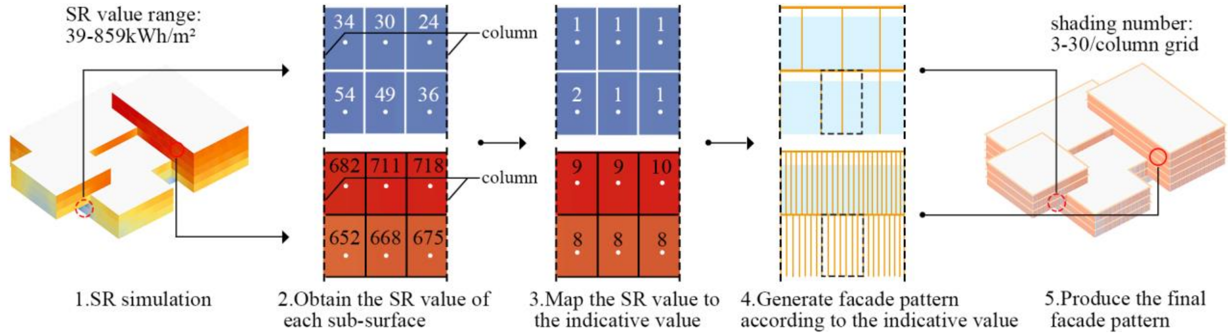

Figure 2: Facade generation steps

2.4 Performance Evaluation

To evaluate the generated design, this study primarily considers the performance metric related to daylighting and solar heat, because solar heat intensity is set as the driving factor in the façade pattern generation. At the same time, the performance metric is chosen according to geographic location and climate. For instance, the case-study design we selected in this paper is located in a region with hot summers. Thus, the optimization objective can be set as minimizing the solar heat gain while maximizing the natural daylighting, since reducing the solar heat gain often undermines daylight accessibility.

As part of the proposed design optimization workflow, Ladybug and ClimateStudio are used to simulate the solar heat gain and daylight autonomy or discomfort glare. For the solar heat gain, the amount of solar radiation (SR) reaching the indoor floor surface is used to measure the solar heat gain. For daylight autonomy or discomfort glare, the surface on the workable height (0.75m) is used to measure the spatial daylight autonomy (sDA) or spatial discomfort glare (sDG). This study is primarily focused on daylighting and solar heat gain, while the workflow can be used for other performance factors. Therefore, to include different performance factors in the design optimization processes, such as natural ventilation and views, the workflow can be extended and customized by connecting other simulation tools.

2.5 Design Optimization

For the design optimization, the embedded optimization algorithm in EvoMass, called Steady-State Island Evolutionary Algorithm (SSIEA), is used as the optimization solver (Wang, Janssen, and Ji 2020). SSIEA is also able to produce optimization results with higher design diversity and differentiation by using the island-based model. In addition, with the use of a steady-state replacement strategy, SSIEA has competitive search efficiency compared with other optimization solvers implemented in Rhino-Grasshopper.

Pareto (multi-objective) optimization is used in this study because there are two conflicting objectives defined in the design fitness evaluation step. By using Pareto optimization, not only can we find the best trade-off solutions for the optimization problem, but we can also compare and investigate the performance behavior in a two-dimensional objective space defined by the two selected performance metrics.

3 CASE STUDY

This section demonstrates how the proposed design optimization workflow can be applied to an optimization-based design exploration scenario for building massing design and façade design. The case study describes a middle-rise multi-functional building in Nanjing, China (Figure 3). Nanjing has hot summers, resulting in heavy cooling loads. Hence, avoiding over-heating in summer is a critical issue in the building design in Nanjing. According to Section 2.4, we define the optimization objective as minimizing the solar heat gain during summers while maximizing indoor daylight availability.

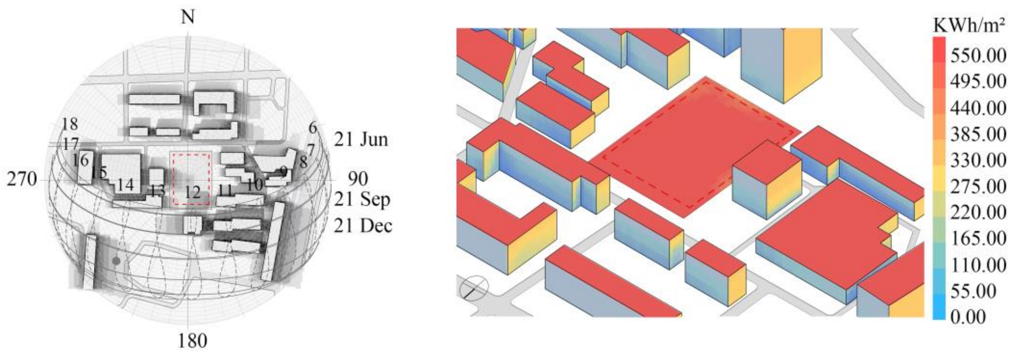

Figure 3: Sun path analysis of building site (left) and solar radiation of building site (right)

3.1 Building Form

In this case study, three different user-defined parameter setups are specified in EvoMass to define the formal characteristics of the generated building massing and, thereby, create three corresponding design spaces containing building massings with distinct formal features. Each of the design spaces is intended to denote building massing designs with a distinct formal characteristic. Thus, to differentiate the overall formal characteristic, the three setups are defined to generate building massing designs featuring solid forms, balanced forms, and fragmented forms, as shown in Figure 4.

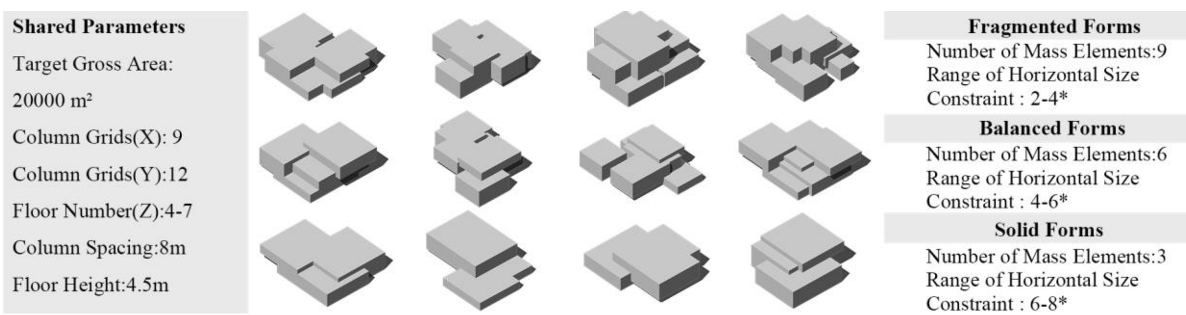

Figure 4: The parameter setups and the corresponding random sampling design variants (* the value indicates the number of column grids)

As shown in Figure 4, the three setups differentiate the formal characteristic using two parameters: the number of mass elements and the size range of each mass element. For solid building massings, it is composed of three large mass elements; for balanced building massings, it is composed of six medium mass elements; and for fragmented building massings, it is composed of nine small mass elements. Apart from the parameters affecting the formal feature, other user-defined parameters are set to be the same for all the building massing design generations to ensure the generated design can satisfy the functional requirement, such as the column grid system, floor height, and the target gross floor area.

In this case study, the formal characteristics not only contribute to the visual appearance of the building but can also play a significant role in the performance characteristics. For instance, solid building forms tend to create buildings with deeper floor plans and lesser external façade areas, which can lower the heat exchange between the building and the outer environment. In contrast, fragmented building forms tend to create buildings with shallow floor plans and more façade areas, which can be conducive to daylighting.

3.2 Façade Scheme

In this case study, four different façade schemes are encoded and included in the façade generative algorithm library (Figure 5). Each of the four schemes combines a commonly-used external shading strategy and a type of façade opening in Nanjing and is expected to play a unique role in affecting the building's performance. In general, the adaptive element is adjusted to reduce the solar heat entering the indoor space. Therefore, for the façade region with intense solar radiation, more shading devices or a smaller opening area will be applied to this region to prevent excessive sunlight from entering the building. In contrast, for the façade region with a smaller amount of solar radiation, fewer shading devices or a larger opening area will be applied to facilitate more daylight to reach the indoor space.

- Scheme 1 applies window walls with vertical shading panels. The solar radiation values are mapped to an integral value from 0 to 10 that determines the number of vertical shading panels in each façade sub-surface.
- Scheme 2 applies vertical strip openings. The solar radiation values are mapped to a float value between 0.3 and 2.3 that controls the width (meter) of the opening in each façade sub-surface.
- Scheme3 applies window walls with horizontal shading panels. The solar radiation value is re-mapped to a float value between 0.3 and 1.5 which determines the spacing (meter) of the shading panels in each façade sub-surface.
- Scheme 4 uses the same horizontal shading panel and control parameter as Scheme3, while it combines the shading panels with horizontal long windows, which reduces the size of the opening.

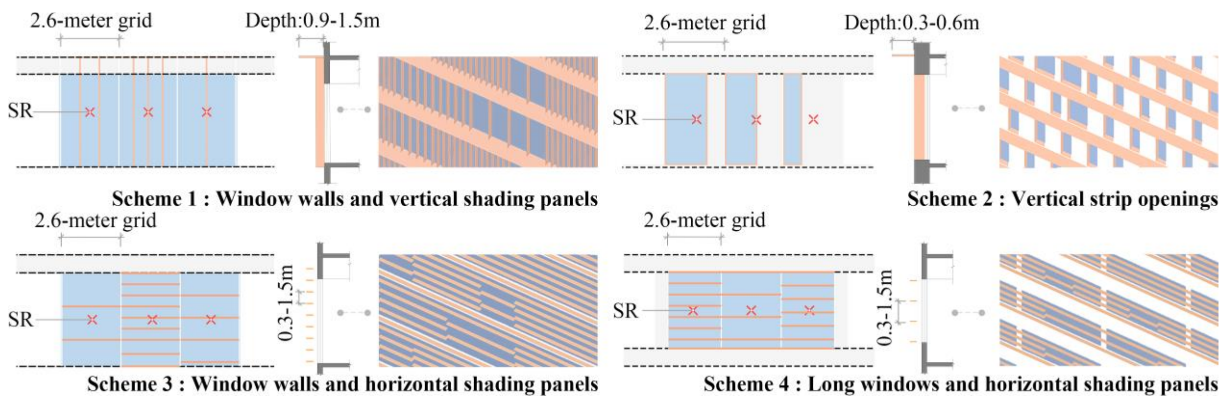

Figure 5: The four façade schemes in the self-adaptive façade generative algorithm library

Note that according to each particular design task, the selection of the façade schemes in the library is not invariable. In the presented case study, we select four different façade schemes combining commonly-used shading strategies and façade openings according to the climatic condition of the design task. Nevertheless, these façade schemes can be removed from the library with others included when the workflow is applied to a different design task.

3.3 Optimization Setup

As mentioned above, the optimization objective is to minimize SR to reduce solar heat gain while maximizing sDA to enhance daylighting accessibility, both of which have been widely used in previous studies. As the decrease of the solar heat gain can partially decrease daylight accessibility, these two objectives conflict with one another. Therefore, the two factors are defined as independent objectives for the Pareto (multi-objective) optimization. In addition, the gross floor area (GFA) of the building is set as a soft constraint for optimization. Hence, a penalty function is applied to both performance evaluations to punish designs that fail to meet the functional requirement regarding the target GFA. The punishment will proportionally scale down the value of sDA and scale up the value of solar heat gain according to the difference between the actual GFA of the generated design and the target GFA (20,000 m^2).

In the case study, the embedded optimization algorithm in EvoMass is used, and three optimization processes are conducted, each using one of the three user-defined parameter setups for building massing design generation. In each optimization process, all the façade schemes are included in the optimization with the use of the façade generative algorithm library. To ensure that the design space can be sufficiently explored, 3150 iterations of design generation and evaluation are applied, and each optimization process lasts around 28 to 30 hours.

4 RESULT

4.1 Objective Space Analysis

Figure 6 demonstrates the Pareto front that results from the three optimization runs. It can be found that the three Pareto fronts intertwine with one another, which implies that there is no one formal characteristic that can completely outperform the other two. However, it is noticeable that the Pareto front associated with solid forms is mostly dominated by the other two Pareto fronts. In contrast, the Pareto front of fragmented forms surpasses the other two in the bottom-left of the objective space, while it is surpassed by the Pareto front of balanced forms in the upper-right of the objective space. By comparing these Pareto fronts, major tendencies related to each of the formal characteristics can be identified.

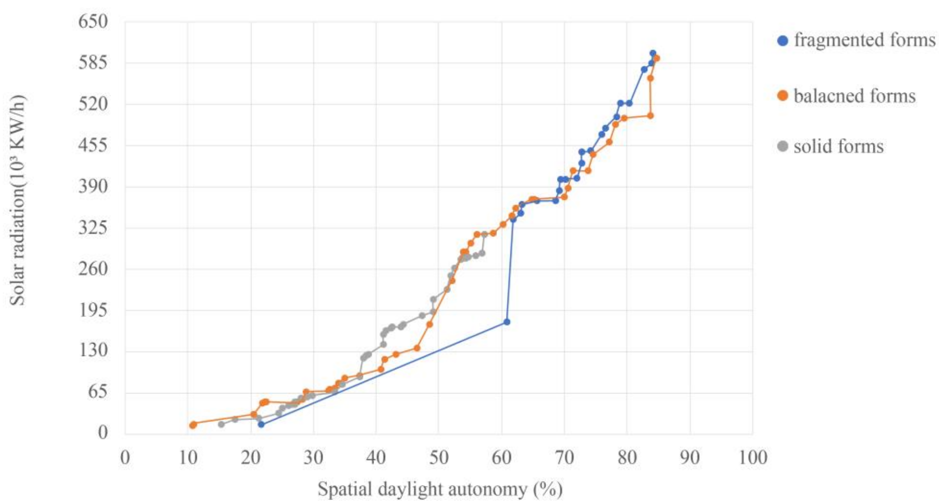

Figure 6: Objective space and the Pareto fronts based on the three optimizations

First, for the fragmented-form building massing, most of the designs on the Pareto front are distributed in the upper-right region of the objective space (the space defined by the two selected performance metrics). This implies that the fragmented-form building massing is more conducive to better daylighting but at the expense of higher solar heat gain. Second, for the solid-form building massing, the feature is the opposite of the fragmented-form one. Its Pareto front lies in the bottom-left of the objective space, indicating that these designs can reduce solar heat gain but cannot achieve good daylighting quality. Last but not least, the balanced-form massings have the longest Pareto front, which indicates that it is more flexible to incorporate different façade schemes to achieve different trade-off solutions than the other two.

Figure 7 presents all the designs on each of the Pareto fronts, where the design is also labeled with its associated façade scheme in different colors. First, with regard to the building massing featuring fragmented forms, most designs are integrated with façade scheme 4 featuring horizontal façade panels with strip openings, and only two designs are combined with façade scheme 2 featuring vertical strip openings. These two designs are markedly separated from the rest of the designs, which suggests that façade scheme 2 navigates the optimization search in another direction. Nevertheless, according to the quantity of the designs with the two façade schemes, the fragmented-form building is more conducive to achieving better daylighting incorporated with scheme 4.

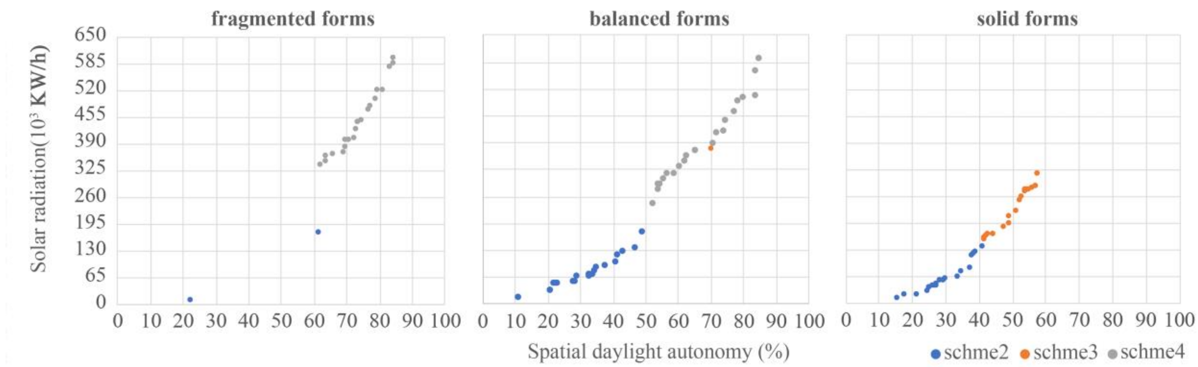

Figure 7: Design variants with their façade scheme in the three optimizations

Second, when it comes to the building massing featuring balanced forms, most of the designs incorporate façade schemes 2 and 4, with one exception combined with the façade scheme 3 incorporating window walls and horizontal shading. The designs with façade schemes 2 and 4 are separated in the objective space as two clusters, and there is also a noticeable gap between the two clusters. The separation of the two clusters implies the difference in the performance behavior of the two façade schemes, which also drives the search for compatible building massings in two distinct directions.

Third, for the building massing featuring solid forms, the designs can be also divided into two clusters in the objective space, each incorporating façade schemes 2 or 3. However, unlike the case in the balanced form, the two clusters site closer to one another, while there is still no overlapping between the two clusters. Lastly, the façade scheme 1 with vertical shading is infeasible to be applied in this case study, as none of the designs in the optimization result is integrated with it.

Moreover, the overlapping part of the Pareto fronts of the building massing with balanced and solid forms as shown in Figure 6 and Figure 7 highlights that building designs with different formal characteristics need to be integrated with different façade schemes to achieve similar performance regarding the two objectives. This reveals that the performance behavior of the façade scheme is closely connected to the formal characteristics of the building massing, further emphasizing the mutual impact between these two design elements. In other words, even for the same project, there is not a façade scheme that can suit every building massing form. The uncertainty further implies that simply following design guidelines or designing facades based on previous design references could not guarantee the desired performance will be achieved.

4.2 Formal Feature Analysis

Figure 8 illustrates a set of selected designs from each of the Pareto fronts. These designs are chosen evenly along the Pareto fronts to demonstrate the formal trade-off. The formal feature of these designs helps explain the distribution of the designs in the objective space and reveals the corresponding design implications related to the building performance.

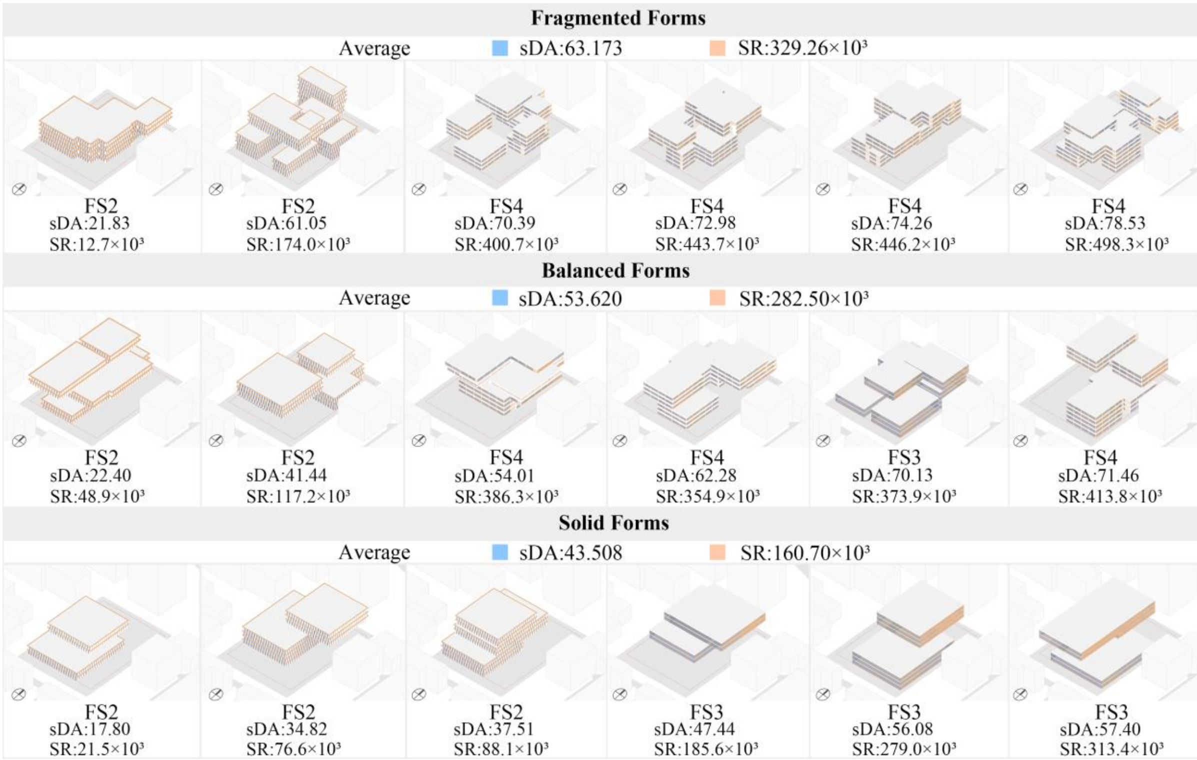

Figure 8: Part of the representative design in the three optimizations (FS: façade scheme)

For the building massing with fragmented forms, the design tends to maximize the daylight accessibility with narrow floor plans and scattered forms to reduce mutual obstruction. However, it also makes a huge compromise on excessive solar exposure. For the building massing with solid forms, the design shows an explicit feature of self-shading, which lowers solar heat gain but negatively affects daylight accessibility. For the building massing with balanced forms, the design is more flexible and demonstrates the feature both appearing in the other two sets of building massing designs. On the left-hand side, the building massing is characterized by a self-shading feature, which, incorporated with façade scheme 2, significantly lowers the solar heat gain. On the right-hand side, the building massing is fragmented and shows narrow floor plans, which, incorporated with façade scheme 3 or 4, markedly enhances the daylight accessibility.

With regard to the implications to design decision-making, even though the balanced-form massing shows greater flexibility, it does not mean that the balanced form is more advantageous in this design task. Instead, the conducted design optimization and exploration lead to a better understanding of the strengths and weaknesses of each alternative building massing design. As such, the designer can select the façade scheme that is compatible with the building massing forms and vice versa. This information also enables the designer to focus on how to further maximize performance potential, such as incorporating curved building forms, vertical greenery, and integrating PV panels.

5 DISCUSSION

The result of the case study demonstrates the interrelation between the building massing and façade in the performance-based design optimization and optimization-based design exploration. The result highlights that different building massing formal characteristics can affect the viability and efficacy of different façade schemes in terms of performance improvement. At the same time, different façade schemes can also reversely affect the formal features of the building massing. Thus, the result of the case study also underlines the insufficiency of only considering one formal feature for building massing generation or one façade scheme in the early design stage for architectural design exploration.

In terms of the relevant implication for architectural design, the study proposes a design workflow for early-stage architectural design exploration. The application of the workflow enables architects to conduct a systematic design space exploration in regards to building massing forms and façade patterns and allows them to gain insight into the interrelationship between the two elements. Moreover, the high adaptability and customizability of EvoMass for building massing design also render the workflow with greater re-usability, which supports the workflow and the design exploration approach to be applied to a variety of design tasks beyond the presented case-study design. Nevertheless, it is also possible to combine it with other bespoke parametric models to conduct the optimization-based design exploration for specific tasks.

The study also highlights the deficiency in the majority of existing studies focusing on performance-based design optimization for early-stage architectural design, in which the design of the building massings and facades is disconnected and independent. Thus, compared with the proposed design approach, the approach used in the relevant studies is unable to identify flaws that occur as a result of poorly-chosen combinations of the building massing form and façade pattern. However, for early-stage design, it is more critical to assist designers in detecting flaws in the designs than simply to help designers polish and refine their designs.

In comparison, the proposed design approach is able to compare alternative building massing designs and façade schemes using optimization rather than simply improving the performance. In this regard, the purpose of conducting optimization is to eliminate redundant information related to poorly-performed designs in each design space, thereby, filtering out the most relevant design information. In addition, in the case of a design with a different building type than the case study, the result of this study also implies the importance for designers to broaden their search scope at the beginning of the design process and include different alternative massings and façade schemes to prevent the exploration from being constrained by a limited design space and resulting in biased information.

5.1 Future Research

The study also sheds light on a broader scope for building design exploration. While the variation in formal characteristics already differentiated the design implications from the optimization result in this study, the application of EvoMass only allows the orthogonal building geometry to be explored. In light of this, more dramatic differentiation of the building massing forms could be included and further explored, such as free-form and curved geometries, which allow the workflow to provide the designer with more architecturally interesting results.

Apart from the inclusion of the more diverse building massing forms, future research considers additional performance-related factors in the optimization objectives related to health, well-being, and sustainable city development, such as uncomfortable glare, energy consumption, and carbon emissions. Furthermore, to obtain a more detailed design for building façades, we plan to develop more flexible façade design generative models that can attach different schemes and patterns to the façade in different orientations.

Regarding building simulation, using different performance metrics can significantly affect the design implications revealed by optimized designs. Therefore, it is important to choose the most relevant performance metrics for the optimization. Thus, future studies will also compare different performance metrics, such as sDA, DF (Daylight Factor), and UDI (Useful Daylight Illuminance), in terms of their impact on the features in optimized designs.

6 CONCLUSION

To conclude, this paper presents a study that integrates EvoMass and a self-adaptive façade generative approach to establish an integrated façade-massing design optimization workflow. Through the inclusion of variations in building formal characteristics and façade schemes, the workflow enables a more systematic design exploration of building massing and façade design compared with previous studies. The presented case-study design exploration not only produces various designs that the two design elements can incorporate one another for performance improvement. It also offers more comprehensive information about the performance implications of different combinations of building massings and façade schemes. As such, the application of the proposed design workflow is expected to assist architects in overcoming the data-poor situation at the early design stage and enabling them to achieve a performance-driven and -informed design for sustainable building design.

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