THE SYNERGY OF BUILDING MASSING AND FACADE

An Evo-Devo approach for performance-based design optimization combining facade design with building massing

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Abstract. One of the problems lies in performance-based architectural design optimization is the separation of building massing design and facade design. The separation of design processes significantly weakens the synergizing of building massing and facades for more progressive performance improvement. In order to overcome this weakness, this paper presents a performance-based design optimization workflow combining facade with building massing design using an Evo-Devo approach. This workflow enables architects to make a rapid design exploration of different façade design schemes incorporating building massing design optimization. For demonstration, a case study is presented to show how this approach can facilitate early-stage architectural design exploration, and how the combination of the two factors can outperform the results produced by separated design processes.

Keywords. Evolutionary development; building massing; performance-based design optimization; adaptive facade design.

1. Introduction

In performance-based architectural design, building massing and facades are the two critical elements that have great impacts on various building performance related to energy efficiency, daylighting, passive cooling/heating, and ventilation. Over the last decade, a growing amount of research and designs have started applying computational optimization to exploit the potential in building massing or facades for more desirable performance. However, no matter in conventional architectural design or the design with computational optimization, the design processes of building massing and facades are typically separated, where façade design is being scheduled after the building massing being finally determined (either by computers or architects). The separation of design processes significantly weakens the synergizing of building massing and facades for more progressive performance improvement.

In order to overcome the drawbacks mentioned above, this study applies an Evo-Devo approach to integrate the facade design into a building massing design

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generation procedure. This approach consists of a parametric model that generates building massing design and a bespoke algorithm for façade development. While the building massing design is controlled by external parameters, the facade development is defined by a performance-related property associated with the generated building massing. This approach can be included in an optimization process that allows the optimization to search for solutions that can maximize the building performance by synergizing the building massing and façade design at the same time. Furthermore, architects can use this approach to explore the interdependent relationship between different façade design schemes and building massing design and become more performance-aware and informed in the design process.

To place this research into context, we first discuss the progress that has been made related to the evolutionary development approach. In section 2, we propose the workflow based on the Evo-Devo approach, which integrates façade and building massing design into optimization processes, followed by a case study and a comparison study to demonstrate its efficacy. We conclude the study by discussing the advantages of the facade-integrated processes over the separated design processes and how this approach can help in architects' early-stage design exploration and promote the incorporation of building massing and facade for performance-based architectural design.

1.1. APPLICATION OF EVO-DEVO IN ARCHITECTURAL DESIGN

Getting inspiration from nature in architecture has a long-standing tradition in history. It began with mimicking nature form in the 19th century. Later on, inspired by natural processes and systems, research on biomimicry-based adaptive design rise gradually. According to John Frazer (1995), architects should evolve rules (relations) for generating form, rather than the forms themselves, which explained the adaptive design (in his words, responsive architecture) well. Soon after that, evolutionary developmental biology science (Evo-Devo) was on the horizon, bringing new insight into the design field. Michael Weinstock (2013), who recognized and adopt Evo-Devo strategies in the architectural field, was considered the initiator of the related works by Navarro and Cocho (2020).

Evolutionary developmental design (Evo-Devo-Design) is a design method that combines complex developmental techniques with an evolutionary optimization technique (Janssen et al. 2011). In the architectural field, Evo-Devo approach is often used in design generation. Navarro has explored the generative capacity to integrate patterns and flows analogous to Evo-Devo strategies to develop emergent proto-architecture with great diversity in forms (Navarro and Cocho 2020). Such diversity was valuable but from the perspective of architectural design practice, hardly can this be useful for real-world design tasks.

In contrast, Evo-Devo approach also has been applied to performance-based building design optimization, where façade design is treated as a developmental change to create design variants with high diversity and environmental responsiveness. Janssen has presented design approaches using Evo-Devo approach involving façade development with a simple shading and fenestration pattern (Janssen et al. 2011). Although this can be of greater relevance to practice, the approach simply integrates façade design into a linear workflow but without additional design consideration such as comparing different façade schemes. In real-world design scenarios, building facade is rarely determined at the outset of design, so that iterative design exploration of different façade schemes is often undergone to achieve an acceptable compromise among aesthetics, performance, budget, etc. Thus, this paper takes a step further through leveraging Evo-Devo approach for early-stage design exploration by including and synergizing building massing and different façade design schemes at the same time.

2. Method

As stated in section 1, this study applies an Evo-Devo approach for building design generation which can simultaneously combine the building massing and façade design in performance-based design optimization. Rather than merely searching for optimal solutions, this study is also aimed to facilitate architects' early-stage design exploration in regards to building massing and façade schemes, thereby, promoting a systematic investigation of the interactive relationship between them. This approach includes three steps, massing generation, simulation, and façade development.

First, the building massing generation procedure is based on an additive form generative algorithm, which is provided by EvoMass (Wang et al 2020a), a Rhino-Grasshopper plug-in. This algorithm creates the building massing by accumulating several mass elements, allowing the generated design to have high variability. The generated building massing design variants can be controlled by altering initial parameter settings, such as plane size, orientation, target area, etc. The strength of this algorithm is that it can be used for different types of building massing design, which, as a result, renders the proposed generation workflow high versatility beyond the presented building design task. Once the settings are defined, the generated design will be used as the basis for the following facade development.

Next, a simulation is conducted to calculate a performance-related attribute of the generated building massing. The attribute is affected by the building massing itself and the surrounding urban environment, which results in a large differentiation for the attribute of each façade surface. In this study, the simulation is executed by DIVA (Jakubiec and Reinhart 2011) relating to the solar irradiation. After the simulation, the generated building massing and the performance-related attribute will be sent to the next step.

The final step is facade development. With a predetermined facade design scheme, specific façade patterns are generated based on the corresponding building massing's surface and controlled by the performance-related attribute adherent to the surface. From the perspective of Evo-Devo, this step can be viewed as the building massing grows itself an adaptive skin in response to its surrounding environment.

The above design generation procedure can be included in an optimization process and evolved for high-performing design variants (Figure 1). Architects can not only use these optimal design variants for further design development but also extract useful information and performance implication from the result (the elites' building massing, façade, and the performance indicator), which can be helpful for decision-making and design ideation.

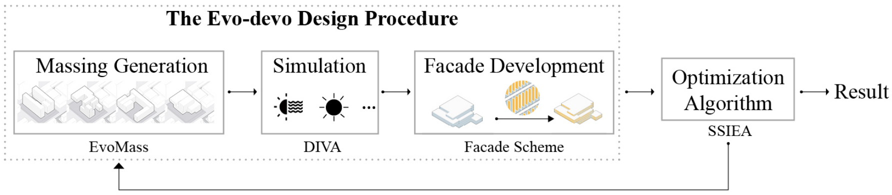


Figure 1. The proposed Evo-Devo design generation workflow.

3. Case study

3.1. DESIGN SETTING

For demonstrating the efficacy of the proposed workflow based on the Evo-Devo approach, a case study of performance-based building design optimization is presented. The target building of the case study is a 7-story building located in Wuhan, China (Figure 2). This region is characterized as a typical subtropical climate, which results in heavy cooling loads in summer due to excessive solar irradiation (SI) received.

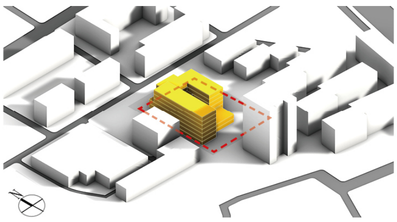


Figure 2. Case study design settings.

As shown in Figure 2, the selected site is situated in a complex urban environment with several high/middle-rise buildings, which leads to a complex micro-climatic condition. On the one hand, the surrounding buildings can cast shadows on the building plot, preventing certain parts of the building from being over-heated. But on the other hand, they also jeopardize daylight harvesting. Such a complex micro-climatic environment makes environmental factors (irradiation and daylighting) to be of great importance and can produce differences in the SI received on the façade surfaces. In this case, the façade's responses to the environment can be a significant factor in building performance.

3.2. BUILDING MASSING GENERATION AND FACADE DEVELOPMENT

First, building massing design is created by the generative algorithm. The main initial settings are 7 additive mass units, a 6-meter sized plan span(12×16), 7 floors with 4.5 meters in height each, and a target area of 15000 square meters. Second, due to the specific climatic conditions in Wuhan, solar heat gain is a more dominant factor affecting building performance than daylighting. Thus we conduct a simulation to calculate the solar irradiation (SI) received on the surface of the building massing, and use this to differentiate the feature of each facade surface.

Next, we define and encode three self-adjusted façade generative algorithms based on commonly-seen façade design schemes with distinguishing characteristics (Figure 3). These include a grille pattern (vertical shading), a sunshade pattern (vertical-horizontal mixed shading), and a fenestration pattern. Each pattern's generative algorithm remaps the SI intensity to a corresponding facade's attribute (density, depth, and numeric variation). With this attribute, an adaptive skin is grown from the generated building massing in response to the façade's thermal condition.

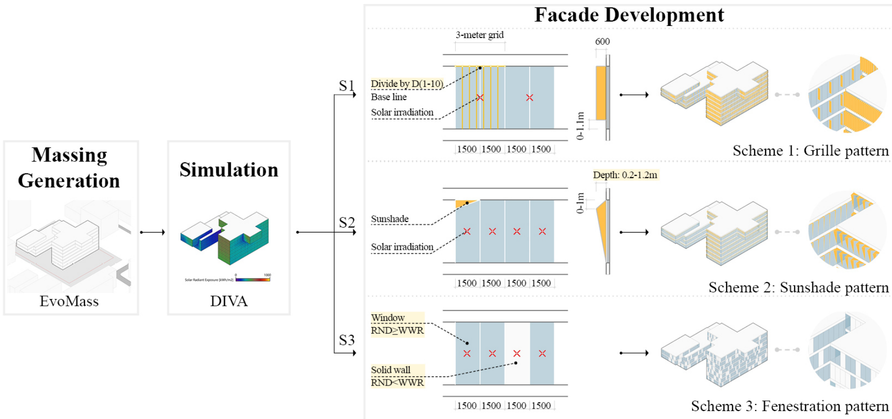


Figure 3. Three façade development schemes based on solar irradiation intensity received on the surface of the building massing.

Scheme 1 is a grille pattern with a density variation. First, the façade is divided into a 3-meter-width surface unit, and the SI data closest to the unit's central point is extracted for calculating the density of the grills in this façade unit. Then, the algorithm remaps the data of SI to an integer (D) between 1 and 10, and D defines the number of grilles in the façade unit. Thus, the grilles are denser where SI is higher. To make this pattern more influential, the length of grilles in the vertical direction also changes with SI intensity.

Scheme 2 is an external sunshade device with a depth variation. First, the façade is divided into a 1.5-meter-width surface unit. Next, an extruded triangular shading device is generated, while using the SI data closest to the unit's center as the basis for the sunshade's depth. The sunshade device has a greater depth in places with higher SI. To enhance the sun-shading capability of the device, the height of the sunshade's extruded peak is also changing with SI intensity.

Scheme 3 is a fenestration pattern with a numeric and Boolean variation. Similar to Scheme 2, the façade is first divided into a 1.5-meter-width surface unit. Next, the SI data closest to the unit's center is used to convert to the wall-to-windows ratio (WWR), and each unit is assigned a unique random value (RND). If RND is smaller than WWR, then the unit will be defined as solid walls between windows, otherwise, glazing curtain walls. Consequently, the window opening ratio is lower where the SI intensity is higher.

3.3. OPTIMIZATION PROCESS

The proposed generation workflow with different façade patterns' developmental algorithm is included in an optimization process to explore the solution with maximized daylighting quality and the reduced SI to avoid over-heating. After the generation process, the final design variant is evaluated against the daylighting and SI performance. The performance indicator of daylighting (sDA) and irradiation (SI) is used to calculate the fitness for the optimization process. Regarding the optimization process, SSIEA (Wang 2020b) is used, which is a diversity-guided evolutionary algorithm provided by EvoMass. Three optimization processes (S1, S2, S3) are carried, based on the three façade patterns respectively.

For the optimization processes, the total number of iterations was 3,150, concluding 5 subpopulations. It means that there will be 5 elites winning after 3150 rounds of calculation. The optimization objective is to minimize SI and to maximize sDA, which are formulated into a single-objective fitness function as below:

$$\text{fitness} = \left(sDA - \frac{\text{SI}}{10000}\right) \times \left(1 - \left|\frac{S_A - S_T}{S_T}\right|\right) \tag{1}$$

The fitness is calculated by subtracting indoor solar heat gain through the façade (SI) from the daylighting indicator (sDA). Thus, high-performing design variants receive lower SI while gaining higher daylighting. In addition, a target gross area of the building (S_T=15000 m²) is set and served as a penalty function so that the design variants (with the actual gross area of S_A) failing to satisfy the gross area requirement is punished by reducing the fitness value.

4. Result

In this case study, the five highest-ranking design variants (elites) from three optimization processes (S1, S2, S3) with different façade schemes are retrieved. Each process took about 35 hours to calculate. Figure 4 summarizes the elites and their performance indicators. Table 1 provides the average of each indicator of the elites from S1, S2, S3.

For optimization S1, it achieves the best average fitness among these three optimization processes. From the architectural perspective, the elites show the east-west strip shape with a small depth in floor plans, which is favorable for daylighting quality. It is because that the grille pattern is more efficient in blocking sunlight; therefore, the compromise on daylighting is trivial.

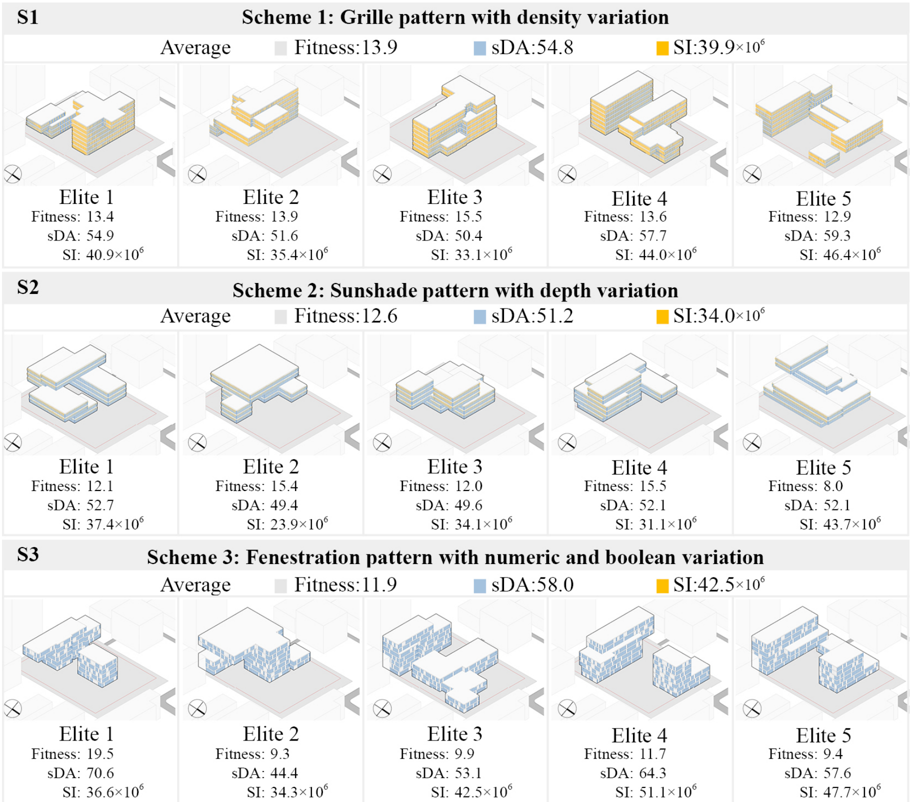
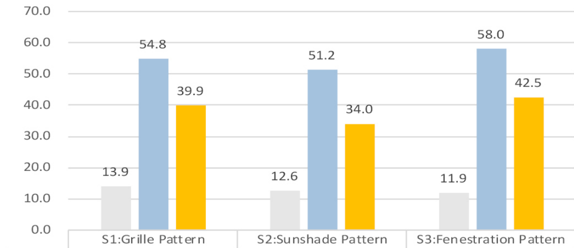


Figure 4. Five highest-ranking design variants(elites) from the three optimization results of the case study (Total number of tests:3150 for each).

For optimization S2, the elites show a tendency of self-shading with a greater depth in the floor plan than those in S1. It reveals that the triangular shading element is relatively weak in blocking SI, while reducing the adverse effect on daylighting. Thus, the weaker shading effect, in turn, requires the building massing to play a greater role in avoid over-heating. Thus, it also results in a significant compromise on daylighting than in S1 indicated by the average sDA value.

For optimization S3, it gets the lowest average fitness. The elites feature scattered and separated massing, and the massing in the north are generally higher than those in the south to achieve a mutual blocking of sunlight. This is to compensate for the incompetence of the shading effect, for this pattern can only respond to SI through varying the wall-to-windows ratio. However, it achieves the best average sDA due to less daylight obstruction when there are no extra shading devices.

Table 1. The average of each indicator of the elites from optimization S1, S2, S3 (SI:×10^6kWh).



	S1:Grille Pattern	S2:Sunshade Pattern	S3:Fenestration Pattern
fitness	13.9	12.6	11.9
sDA	54.8	51.2	58.0
SI	39.9	34.0	42.5

5. Comparison study

The optimization results show different compromises between SI and daylighting when using different façade schemes. It raises the question of how the design responds to the environment without these adaptive building skins, and whether the facade-integrated design process has an advantage over the non-integrated one. In light of this, a comparison study is conducted to test out whether the integration of the façade development would make a difference in the optimization.

Firstly, an optimization process (C0) is carried out to optimize the design without any self-adjusted façade generation scheme but with the same settings as the case study, which serves as an example of the conventional facade-separated design process to be the control group for the former experiments (Figure 5, S1, S2, S3). Since SI is the main influencing factor, the elites from the control group (C0) show concentrated shapes in the south with a large depth, to minimize the heat gain by taking advantage of the shadow created by the high-rise building in the south.

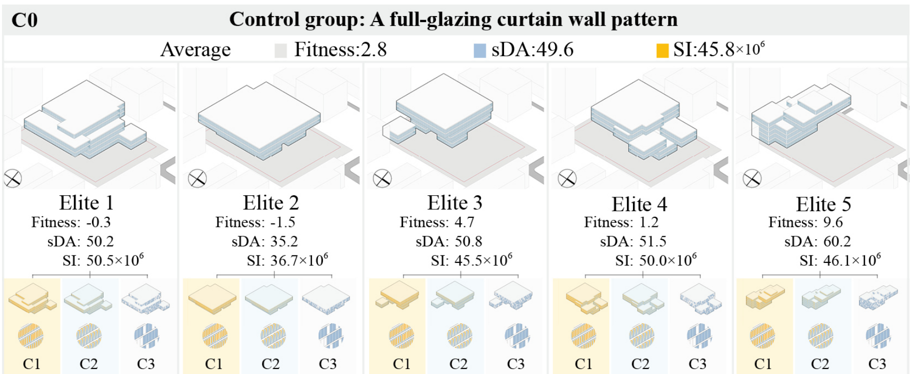


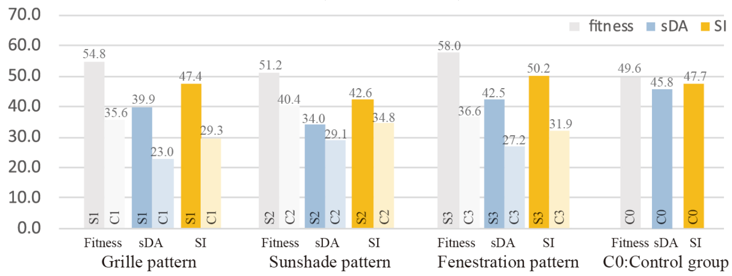
Figure 5. Optimization C0's result and groups of the generative results (C1, C2, C3) with façade scheme 1 to 3 respectively.

According to the results of these four optimizations, demonstrated in Table 2, elites from facade-integrated design processes (S1, S2, S3) significantly outperform those in the C0. Additionally, the building massing demonstrates distinctive differences, as shown in Figure 4 and Figure 5. Both become evidence of the great influence of façade design on building performance.

Next, the five elites' building massing designs from C0 are also incorporated with the three façade schemes, resulting in 15 final designs, which are marked C1, C2, C3 to present 3 groups of the results with Schemes 1 to 3 respectively. This generative step simulates the conventional design processes, where facade design is being scheduled after the building massing is finally determined.

As shown in Table 2, the average fitness of S1, S2, S3 generally outperforms the ones from C1, C2, C3, which further validates the efficacy of the proposed generation workflow. By comparing the average of sDA and SI, it is notable that integrated ones (S1, S2, S3) unexpectedly outperform in sDA but underperform in SI, it may be because that building massing in C0 contributes more to SI reduction than façade. Lastly, the separated design process drives the optimization search for solutions in one direction and results in one type of building massing design, thus killing the diversity of the final results. In contrast, with different design schemes, the proposed approach diversifies the optimization searching direction and, thereby, stimulate architects' design exploration..

Table 2. The average of each indicator of the elites in optimization S1, S2, S3, C0, C1, C2, C3, showing the difference between the façade-integrated design processes and the non-integrated ones (SI:×10^6kWh).



6. Discussion and conclusions

The results of the case study demonstrate that with different façade schemes, the produced optimal building design shows different characteristics in terms of the building form and performance. In addition, the comparison study also highlights the necessity of the proposed integrated design workflow based on the Evo-Devo approach comparing with the non-integrated one. Thus, incorporating façade design into the performance-based building massing design is rewarding.

With the proposed workflow combining EvoMass, architects can make an early-stage design exploration of different façade schemes by comparing the feature of design variants, from which, they can extract information about façade and building massing design. For façade design, this exploration helps to reveal underlying performance implications about different façade schemes and their impact on building massing design. This can inform architects' decision-making when considering other design concerns such as aesthetics and cost. For building massing design, this exploration discloses how the building responds to the environment with different skins. Consequently, such exploration provides architects a larger picture of the design problem and stimulate design ideation.

Beyond its implication of practical applications, this study also promotes research on the façade design's impact on building performance. This topic is not new in research, and there have been many studies that consider façade design as an important factor influencing building performance, such as Lee's research of façade shading (Lee 2017). However, the limitation is that they typically use rooms as the analysis unit, rather than from the perspective of the whole building to compare the advantages or disadvantages of different facade designs. This may be misleading when considering the overall design.

To conclude, this paper proposes an integrated building design optimization workflow that can synergize the strengths of building massing and façade design at the same time. The advantages will encourage architects to apply design optimization exploration to the early-stage design and make architecture become a more responsive and adaptive agent in shaping our future built environment. Future research will consider more factors in the optimization objectives, such as ventilation, cost, and energy consumption, to meet the requirements of complex real-world design scenarios. Furthermore, more detailed and sophisticated façade schemes can be considered in the façade development step, including varying sizes, orientations, angles, materials, which will increase the practicality and enhance performance improvement.

References

Frazer, J.: 1995, *An Evolutionary Architecture*, AA Publications, London,UK.

Hensel, M., Menges, A. and Weinstock, M.: 2013, *Emergent technologies and design: towards a biological paradigm for architecture*, Routledge.

Jakubiec, J.A. and Reinhart, C.F.: 2011, DIVA 2.0: Integrating daylight and thermal simulations using Rhinoceros 3D, Daysim and EnergyPlus, *Proceedings of building simulation*, 2202-2209.

Janssen, P., Basol, C. and Chen, K.W.: 2011, Evolutionary developmental design for non-programmers, *Ecaade 2011*, **Respecting Fragile Places**, 245-252.

Lee, K.S., Han, K.J. and Lee, J.W.: 2017, The impact of shading type and azimuth orientation on the daylighting in a classroom–focusing on effectiveness of faccade shading, comparing the results of DA and UDI, *Energies*, **10**(5), 635.

Navarro-Mateu, D. and Cocho-Bermejo, A.: 2020, Evo-Devo Strategies for Generative Architecture: Colour-Based Patterns in Polygon Meshes, *Biomimetics*, **5**(2), 23.

Wang, L., Chen, K., Janssen, P. and Ji, G.: 2020, ALGORITHMIC GENERATION OF ARCHITECTURAL MASSING MODELS FOR BUILDING DESIGN OPTIMISATION - Parametric Modelling Using Subtractive and Additive Form Generation Principles, *CAADRIA 2020*.

Wang, L., Janssen, P. and Ji, G.: 2020, SSIEA: a hybrid evolutionary algorithm for supporting conceptual architectural design, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, **34(4)**, 458–476.