EvoMass + GH_Wind

An agile wind-driven building massing design optimization framework

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The complex interactive relationship between wind flow and building design poses a great challenge in architectural design. Recent research has been conducted to combine Computational Fluid Dynamics (CFD) and computational design optimization to solve the problem. However, due to the time-consuming simulation process and the assertion-oriented computational optimization application, such CFD-based design optimization frameworks are not easy to integrate with architects' early-stage design exploration. To address these issues, this paper proposes an agile wind-driven building massing design optimization framework incorporating EvoMass and GH_Wind in the Rhino-Grasshopper environment. EvoMass is an integrated evolutionary building massing design tool, and GH_Wind is a simulation tool embedded with a Fast Fluid Dynamics (FFD) solver. Combining these two tools allows for fast wind-driven design optimization, thereby enabling architects to apply it to early-stage design exploration. To demonstrate its efficacy, a case study is presented to illustrate how the proposed design optimization framework can provide architects with useful design information and, thereby, facilitate more performance-informed design for early-stage architectural design.

Keywords: *building massing design, performance-based design, design exploration, wind-driven design, Fast Fluid Dynamics, design optimization*

INTRODUCTION

Performance-based design optimization is becoming a popular application of computational design in architecture, which combines parametric modeling, building performance simulation, and computational optimization. Recent research has demonstrated that performance-based design optimization can be an efficient and powerful tool assisting architects in build massing design and provide pertinent performance-oriented information useful to future design and construction. While performance factors such as daylighting, solar irradiation, and energy consumption have been widely investigated in relevant research (Negendahl & Nielsen, 2015; Likai Wang, Janssen, Chen, Tong, & Ji, 2019; Yi & Malkawi, 2012), studies focused on wind-related factors are relatively rare. It is because conducting a wind-driven design optimization is challenging and demanding both for researchers and practitioners. However, considering wind-related performance into architectural design can be of great significance in environmental-friendly and sustainable architectural design, which highlights an urgent need of developing applicable computational design optimization methods and tools both for research and design practice (Kabošová, Katunský, & Kmet, 2020; Kormaníková, Achten, Kopřiva, & Kmeť, 2018; Likai Wang, Tan, & Ji, 2016).

For wind-driven design optimization, the popular simulation method, Computational Fluid Dynamics (CFD) simulation, is too time-consuming to be applied in practice. Moreover, the current practice of performance-based design optimization cannot provide results with sufficient information feedback for architects' early-stage design exploration and synthesis. As Østergård stated, the existing black-box algorithms either produce the best result only or provide incomplete variations in a limited time (Østergård, Jensen, & Maagaard, 2016). Besides, the linear and assertion-oriented nature of computational optimization often separates performance-based design optimization from architects' early-stage design exploration. It is because current techniques and design tools are typically offered to measure the actual building performance or polish the design's predetermined shape instead of providing information or inspiration for architects' design ideation and concept development.

Considering these limitations, this paper proposes an agile wind-driven building-massing design optimization framework for early-stage architectural design. The framework integrates with an evolutionary building massing design tool - EvoMass (Likai Wang, Chen, Janssen, & Ji, 2020b), and a Fast Fluid Dynamics (FFD) simulation solver - GH_Wind (Waibel, Bystricky, Kubilay, Evins, & Carmeliet, 2017). On the one hand, EvoMass is an integrated design tool enabling rapid building massing design prototyping and design optimization. It is designed to allow architects to leverage performance-based design optimization as a means for design exploration and information extraction. On the other hand, GH_Wind is a fast but less accurate wind-related performance simulation tool. With the use of EvoMass and GH_Wind, it is possible to achieve a wind-driven optimization process that can be completed within a reasonable timeframe, while the optimization results also show clear and rich performance implications in relation to building massing design. Incorporating these advantages makes the framework support a rapid wind-driven design exploration that allows the architects to inspect various possible directions at the outset of design, thereby making design optimization an integral part of architects' design ideation and synthesis.

To place this study into context, we first discuss the progress that has been made in the related fields before elaborating the details of the proposed design optimization framework. Afterward, a case study for wind-related design optimization and the corresponding result is presented in order to demonstrate the efficacy of the proposed optimization framework in early-stage architectural design. We conclude the paper by discussing the implications for architectural design and pointing out the limitations.

Background

Over the past decade, wind-related performance has been gaining attention from researchers, and studies have been carried out to investigate the interactive relationship between building design and wind-related performance such as wind pressure and pedestrian wind comfort by using computational design optimization frameworks. Technically, CFD simulation is still prevalent in wind-related design optimization research due to its accuracy. However, the time-consuming simulation process of CFD makes such wind-driven design optimization unlikely to be used in the practice. To speed up the optimization process, FFD is becoming increasingly popular (Chronis, Turner, & Tsigkari, 2011).

FFD can be understood as a simplified CFD simulation with a faster solving speed but less accuracy.

The utility of FFD in wind-driven design optimization has been verified by a number of studies since its introduction (Chronis et al., 2011; Waibel et al., 2017; Zhang, Waibel, & Wortmann, 2020). The fast simulation speed makes FFD very suitable for early-stage design exploration as a part of the computational design optimization framework, and the conclusions drawn from the optimization with FFD are sufficient for architects to identify promising design directions.

While using FFD can potentially provide valuable information for architects' decision-making, it is still challenging to integrate such simulation-based design optimization into early-stage architectural design exploration. For the early design stages, most existing design tools offer an asserted-oriented calculation solver and system of the simulation data, rather than continuous guidance from initial parametric modeling. In order to address this challenge, some researchers have proposed design tools that can be used for design exploration, such as UrbanSOLve (Nault, Waibel, Carmeliet, & Andersen, 2018) for urban design problems and EvoMass (Likai Wang et al., 2020b) for building massing design problems. These tools primarily provide design optimization frameworks that can be easily customized and adapted to different design settings and are aimed to allow the architect to extract information from the optimization result as opposed to merely providing them with a specific solution, thereby enabling a performance-informed and performance-aware design.

This study continues the research on EvoMass regarding the issue in relation to optimization-based design exploration. Due to technical limitations, previous studies focused only on performance factors such as daylighting and solar irradiation. Thus, the recent implementation of GH_Wind enabling FFD simulation in Rhino-Grasshopper provides us with an opportunity to synergize the strengths of FFD and EvoMass for solving complex wind-related design problems, and investigate how such wind-driven design optimization can be incorporated into early-stage architectural design exploration.

METHOD

In order to overcome the existing limitations, this paper presents an agile wind-driven building massing design optimization framework based on EvoMass and GH_Wind. The design optimization framework allows early-stage design exploration on various design directions, thereby, providing rapid and valuable design feedback to the architect and helping them become more performance-informed and -aware in their decision-making and design synthesis. This section elaborates on the details of the proposed design optimization framework and presents a case study to demonstrate how the proposed design optimization framework can be incorporated into early-stage architectural design exploration.

Design Optimization Framework

The proposed design optimization framework comprises design generation, performance simulation analysis, and computational optimization based on EvoMass and GH_Wind (figure 1). On the one hand, EvoMass is applied to generate building massing design variants and evolve the design population for performance improvement with its embedded evolutionary algorithm, Steady-State Island Evolutionary Algorithm (SSIEA) (L. Wang, Janssen, & Ji, 2020).

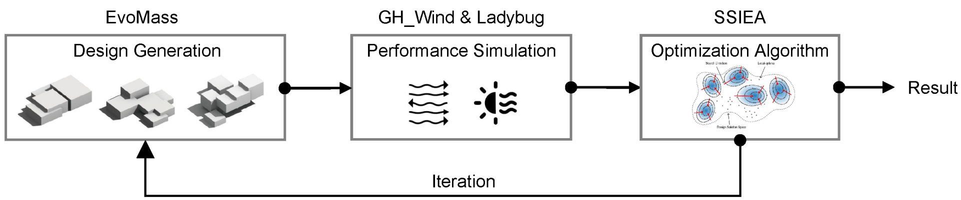

Figure 1
The design optimization framework incorporating EvoMass and GH_Wind.

On the other hand, GH_Wind is used to evaluate the wind-related performance of the design variant generated by EvoMass. The proposed design optimization framework can also be extended with other simulation tools to address architectural design's additional performance concerns. For example, in this study, we also combine the Ladybug tool into the optimization framework for sunlight-hour simluation as shown in the figure 1.

EvoMass is a design tool that can be tailored to different building massing design settings. It is aimed to enable architects to achieve a rapid optimization-based design exploration and to facilitate them to extract information from the optimization result. Herein, the priority of the development of EvoMass is not to directly provide architects with a solution but to use optimization results as a medium of design reflection and exploration. In addition, EvoMass can be customized for various design purposes. Using EvoMass allows for design exploration guided by different design directions, which also helps the architect understand the trade-offs and compromises characterizing the design problem and overcome design fixation and preconception.

Design Generation

For the massing generation, we used an additive algorithm in EvoMass to generate different building massing design variants (Likai Wang et al., 2020a). The additive algorithm creates the building massing by accumulating several mass elements (figure 2). The additive algorithm can be configurated and customized according to different control parameters. In addition, the varying combinations of multiple mass elements result in a wide variety of building massing designs with distinct topological configurations, thereby resulting in great design diversity and variability. The design diversity broadens the design solution space and allows the optimization process to explore a wide spectrum of design alternatives. In contrast, the conventional parametric models often limit the optimization to subtle design variations of a specific and predetermined type of design solutions.

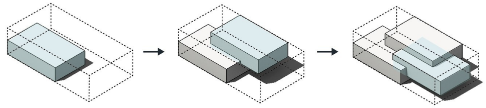

Figure 2
The generation process of the additive algorithm

There are three major constraints in the additive algorithm that allow the users to control the features in the generated design. These constraints serve as hyper-parameters of the additive algorithm, which will remain constant throughout the optimization process. The first constraint is the maximal volume that defines the spatial boundary of the generated design. The maximal volume is determined by the number of column grids (bays) in the X and Y directions as well as the number of floors in the Z direction (The dotted bound volume displayed in figure 2). Users can use this constraint to customize the building typology of the generated design such as high-rise towers or slab-type buildings. The second constraint is the number of mass elements that compose the generated design, which alters the topological configuration and complexity of the generated design. Larger numbers of mass elements tend to create building massing with complex interlocking volumes. The last constraint is the size constraint which determines the dimensions of each mass element by its ranges of column grids and floors. Using these three constraints, the additive algorithm can be customized to generate massing design variants with distinct architectural features. Additionally, the additive algorithm also allows users to specify the target gross area of the generated design, which can ensure the generated design can meet the functional requirement in architectural design.

Performance Simulation

For the wind-related performance simulation, GH_-Wind is applied to the proposed optimization framework. GH_Wind is implemented in the Rhino-Grasshopper environment, thus making it ready to be connected to EvoMass. GH_Wind allows users to define several parameters including the wind speed, step size, dimension of the simulation space. In addition, GH_Wind comes with a component that automatically discretizes input building volumes and transforms them into voxels. Although FFD is not as accurate as CFD, it can still generally differentiate the high-performing design variants from the bad ones. Since early-stage design exploration is more focused on identifying a promising design direction than offering a specific design solution, a degree of inaccuracy is acceptable. Lastly, due to the fact that computational design optimization typically involves hundreds or thousands of design generations and simulations, parameters need to be adjusted to achieve a feasible compromise between simulation time and accuracy when using FFD in design optimization.

Exploratory Design Optimization

To support the optimization-based design exploration, EvoMass provides users with SSIEA to obtain optimization results containing high-performing solutions with rich design diversity. On the one hand, SSIEA adopts an island-based approach to subdivide the design population into several 'niche' subpopulations, and each subpopulation is guided to focus on a different region in the design solution space (figure 3). As a result, the separation of design subpopulations allows for an "implicit" clustering during the optimization process. Therefore, SSIEA can prevent the optimization from convergent into a single region in the design solution space, thereby, decreasing the possibility for optimization results in yielding similar and homogeneous design variants. The design diversity in the optimization result helps to clarify the architectural implications related to the performance factors and enhances the information feedback.

On the other hand, SSIEA applies the steady-state replacement strategy to speed up the evolution of the design population. In contrast to the conventional generational replacement strategy, the steady-stage replacement strategy is designed to replace a small portion of individuals in the design population every generation. This allows the newly-found elite design individuals can affect the whole design population more promptly. On the contrary, using the generational replacement strategy only allows the elite design individuals to influence the design population after all other design individuals in the current generation are evaluated, which can significantly slow down the optimization speed. Accordingly, the use of the steady-state strategy can speed up the design optimization process by increasing the evolutionary pressure, thereby ensuring the optimization can exploit desirable high-performing solutions even when the computational resources allocated to each subpopulation are relatively limited. As a result, using the steady-state replacement strategy prevents SSIEA from making a significant compromise on search efficiency for design diversity.

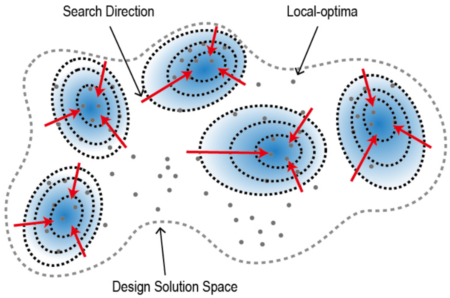

Figure 3
The search mechanism of SSIEA

Case Study

To demonstrate the efficacy of the optimization framework, a hypothetical case study is presented. The case study describes a building design in Nanjing, Jiangsu Province, China. The urban area of Nanjing commonly suffers from unpleasant winters due to the cold winds from the north and the lack of sunlight caused by the dense urban fabric. Hence, it is crucial to mitigate these two negative effects in building design to create a comfortable and pleasant urban environment. In this regard, several design parameters of building massing can affect the wind speed and sunlight in its building plot and the peripheral area, such as the projected area and the porosity with respect to the windward direction and the surrounding mask effect. Considering these, we conducted an optimization-based design explo-

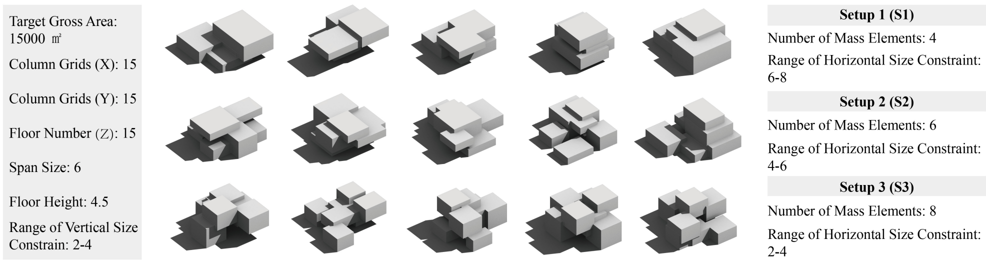

Figure 4
The parameter setups and the corresponding random sampling design variants

ration to investigate how building massing design with different formal traits can affect pedestrian wind comfort and sunlight accessibility in winters.

We focused the case study on the performance implications of building massing design respectively characterized by a smaller number of large mass elements or a larger number of small mass elements. For each set of design, we differentiated the formal features by the parameter setup including the number of mass elements and its size constraint (figure 4). Figure 4 displays the random sampling design variants generated using these three parameter setups. It can be noticed that the design variants in S1 tend to be bulky, whereas those in S2 and S3 become more flexible in terms of the topological configuration. In addition to the above-mentioned parameters, the three sets of design all had the maximal volume with 15*15 column grid units in the X (East-west) and Y (South-north) directions with a 6-meter sized span. In the Z direction, there were 8 floors of 4.5 meters in height each. Lastly, 15000 square meters were set as the target gross area.

For the performance evaluation, both pedestrian level wind speed and sunlight hours were chosen as the main performance indicator (figure 5). To measure the pedestrian level wind comfort, an average wind speed in a predefined area surrounding the target building is used. As high wind speed causes unpleasant human comfort in winters, the goal was to minimize the average wind speed. Based on the meteorological data of Nanjing, the wind direction was set blowing from north to south with an initial wind speed of 3.6 m/s. For the sunlight hours, the average sunlight hours on the winter solstice were used as the performance indicator. To increase sunlight accessibility, the objective was set to maximize the average number of sunlight hours in a peripheral area. The sunlight hour metric was calculated by using GH_Ladybug. Moreover, the gross area of the building was used as an additional penalty function in the fitness evaluation to ensure the optimization result can have desirable architectural feasibility.

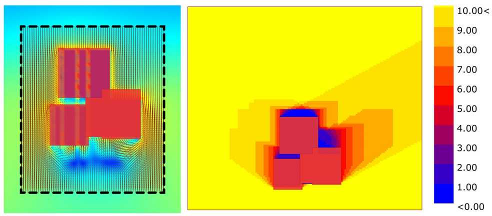

Figure 5
An example of wind-flow simulation and sunlight-hour simulation

The above performance metrics were formulated into a single-objective design optimization problem. While it is possible to use multi-objective optimization (MOO) to incorporate with these objectives, using MOO often results in compromise on search efficiency, and there can be also too many options that are difficult to analyze. In contrast, using SSIEA can achieve a good balance between design diversity and fitness improvement. For the setting of SSIEA, five subpopulations were applied, each with 30 individuals. Considering that each FFD still lasts for approximately 5 minutes based on our parameter setup, the optimization process went through 1050 iterations, with 30 successive generations after the initial generation. Each optimization process lasted around 4 days based on an i7 desktop computer.

RESULT

To analyze the result of the case study, we used the elite design variant in each of the subpopulations as the results of the conducted optimization processes. Figure 6 summarizes the results of the case study. Statistically, the elite design variants from S1 stand out compared with those from S2 and S3 regarding the average fitness. If we a closer look at fitness evaluation item-wise, we can find that the elite design variants in S1 generally have a lower average wind speed than those of S2 and S3. In contrast, it should be stressed that the average wind speed of S2 is only marginally higher than that of S1. On the contrary, the elite design variants from S3 can achieve a more desirable average sunlight accessibility than S1 and S2, although the advantage is less insignificant. The result implies that there is a trade-off between achieving favorable pedestrian wind comfort and sufficient sunlight accessibility in the given design setting.

In terms of the formal features, the design variants in S1 tend to lay more mass elements on the ground as seen in figure 5, which can lower the height of the overall building volume so as to decrease its surrounding mask effect, which increases the sunlight accessibility for its adjacent area. In contrast, S2 and S3 can achieve a more compacted building volume that further reduces the surrounding mask effect by taking advantage of more flexible topological configurations. However, its compacted building volume, in turn, weakens its ability in blocking the wind flow through the targeted area.

Figure 7 shows how the elite design variant affects the pedestrian wind flow. For S1, due to the fact that the building massing has a large projected area in the windward direction and elongates along the east-west direction, it results in a large wind shadow area. In contrast, the smaller mass elements in S2 and S3 can allow more wind to flow through the gap between those mass elements, which increases the average wind speed and reduces the wind shadow area. While the design variants generated by S2 and S3 are not desirable in winters, these design variants may produce better wind flow than those generated by S1 in summers because the sparse building volume at

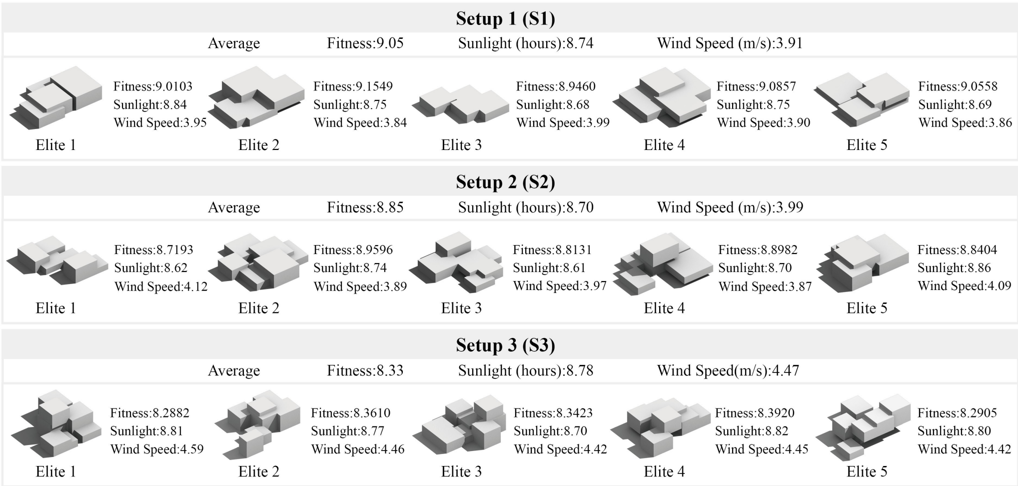

Figure 6
The result of the conducted optimization processes (elite design variants and performance indicators)

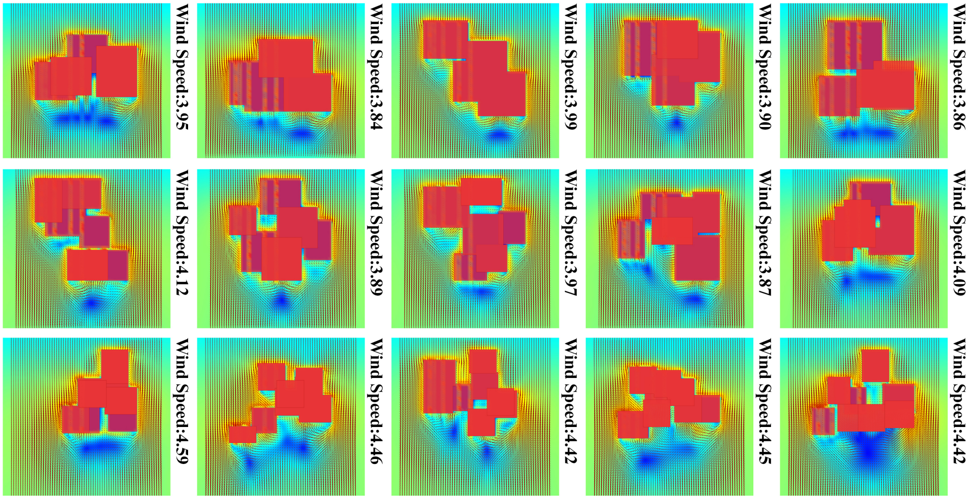

Figure 7
Wind-speed analysis based on the elite design variants

the ground floor can allow more wind flow through the building and increase the wind speed.

Figure 8 demonstrates the relationship between elite design variants and sunlight accessibility. As indicated in figure 5, the differences in sunlight hours among these design variants are relatively insignificant. However, the shaded area remarkably differs from one another. For S1, the large mass elements produce a larger area with severely poor sunlight accessibility (dark blue area) compared to those of S2 and S3. On the contrary, the elite design variants tend to be more compacted and have a smaller footprint. This tendency results in a smaller shaded area even though some of these design variants can produce a long shadow as shown in figure 8 bottom row. However, since the absolute size of the shadow is smaller, these long shadows, indeed, have an insignificant effect on the overall sunlight accessibility. Lastly, as shown in figure 5, the flexible topological configuration of S3 and S2 enables the elite design variants to have some mass elements hidden in the shadow cast by mass elements on the south, thereby reducing the overall surrounding mask effect. This tendency is also in agreement with the passive design strategy of solar envelopes.

As a summary of the case study, the result of the optimization provides valuable information about the design problem in regards to wind-related performance and sunlight accessibility. The three assigned building massing design generative setups enable the optimization process to explore three distinct design solution spaces. The three parallel optimization processes allow for a thorough and systematic investigation of the trade-offs and compromises among different building massing design alternatives in terms of the two performance factors. Furthermore, it is noteworthy that using the proposed optimization framework is not primarily aimed to offer architects a direct solution for the design task. Instead, the architect is recommended to extrapolate the design tendency reflected by the optimization result and conceive novel design schemes that can challenge the "computed optimal" provided by the optimization.

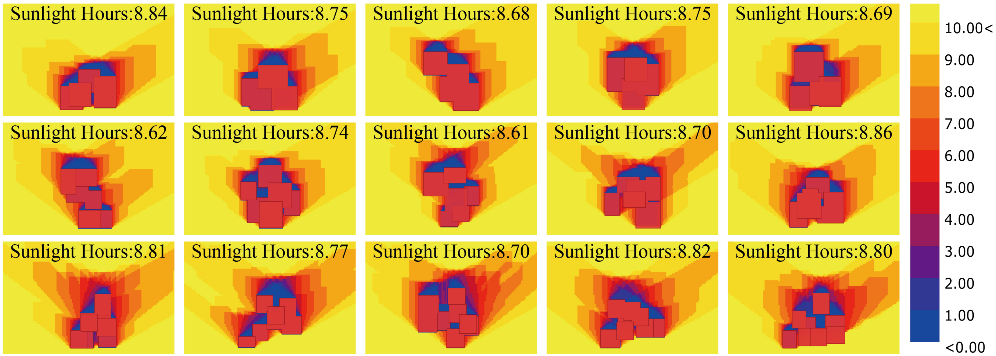

Figure 8
Sunlight-hour analysis based on the elite design variants

DISCUSSION AND CONCLUSION

This study demonstrates the efficacy of the proposed wind-driven design optimization framework using EvoMass and GH_Wind. By speeding up the optimization process by using a less accurate simulation, the proposed wind-driven design optimization can be more practical for use in early-stage architectural design tasks. Even though FFD only provides a coarse simulation on wind flow, it can differentiate the wind-related performance of different design variants, thereby allowing the optimization process to screen out promising design candidates for architects. Additionally, the application of EvoMass enables architects to conduct a fast investigation towards different directions at the outset of design, and the optimization result provides essential information about the performance implication with respect to different design directions. Considering the frequent data-poor situations encountered by architects during the early design stages, the revealed information offers them an opportunity to promptly understand the design problem. Last but not the least, the proposed optimization framework also has the advantage of easy to use. Without the requirement of parametric modeling, architects can establish the framework in a plug-and-play fashion on the Rhino-Grasshopper platform, and the framework can be readily extended to include more performance evaluation by incorporating other simulation or evaluation tools.

As the first attempt at combining EvoMass and GH_Wind, this study also bears certain limitations worth mentioning. First, in the case study, we did not consider urban environments in the wind flow simulation. As including surrounding urban environments will require expanding the computational domain, this can significantly prolong the simulation and make optimization more time-consuming. Second, the case study only considered one season. The optimization result implies that while using larger mass elements can be more advantageous in winters, it is reasonable to assume that they may have counter-effects in summers, for example, the large mass elements cause a greater resistance to wind flow. Thus, including the design problem in relation to summers in optimization can provide architects with a broader view and a more comprehensive understanding of the design problem. Lastly, the building skin was not considered in this study. However, it has been demonstrated to have a significant impact on the building massing design (H. Zhang, Wang, & Ji, 2021), thus incorporating it into the framework can make the result with greater practical value. Meanwhile, while using four days to complete one design optimization process using FFD is much shorter than those using CFD, it is still not ideal for practice. As a result, parallel computing or cloud computing can be used in future research to further accelerate the running speed of the optimization process, which may also allow for larger numbers of iteration to ensure the accuracy of the optimization result.

To conclude, as displayed in the case study and the result, the incorporation of EvoMass and GH_-Wind allows for a more engaging and pertinent application of wind-driven design optimization in early-stage architectural design. In contrast to the conventional assertion-oriented design optimization approach, the proposed wind-driven design optimization can produce more informative results and help architects in design ideation and overcoming design fixation. As a result, the application of the proposed optimization framework not only allows the architect to achieve a more performance-informed and -aware design process but also makes the wind-related performance more readily a driving force in architectural design.

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