ENABLING OPTIMISATION-BASED EXPLORATION FOR BUILDING MASSING DESIGN

A Coding-free Evolutionary Building Massing Design Toolkit in Rhino-Grasshopper

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Abstract. This paper presents an evolutionary design toolkit for performance-based building massing design optimisation. The toolkit is aimed to assist architects in exploring a wide range of building massing design alternatives guided by various performance objectives, thereby encouraging architects to incorporate evolutionary design optimisation for enriching design ideation at the outset of the design process. The toolkit is implemented in the Rhino-Grasshopper environment and includes components of a diversity-guided evolutionary algorithm and two pre-defined parametric models capable of generating a wide range of massing designs. The evolutionary algorithm can yield diverse design variants from the optimisation process and present more informative results with higher design differentiation. The pre-defined parametric models require minimal customisation from the architects. By using the toolkit, architects can readily explore high-performing building design with performance-based design optimisation with ease, and the coding-free optimisation workflow also streamlines the design process.

Keywords. Evolutionary design; building massing design; performance-based design; design process; design exploration.

1. Introduction

Over the last few years, there has been a focus shift from design optimisation to design exploration when using evolutionary design in architecture. Instead of purely maximising the performance of the design, the value of the information extraction from the optimisation and its role in boosting a performance-aware design process has become increasingly relevant to achieving a step change toward sustainable architectural design. Despite the increasing availability of

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 1, 255-264. © 2020 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

relevant know-how and tools related to evolutionary design, conducting such optimisation-based design exploration is still not trivial for most practitioners. On the one hand, parametric modelling of the design is typically time-consuming and technically challenging, which often results in an interruption to the design process (Nault, Waibel, Carmeliet, & Andersen, 2018). On the other hand, the feedback retrieved from the optimisation result is often limited due to the lack of design diversity in the result of optimisation (Wang, Janssen, & Ji, 2020).

In response to these challenges, we propose a coding-free evolutionary design toolkit to enable architects to undertake performance-based design optimisation and collect feedback from the optimisation result particularly for building massing design. The toolkit consists of two components. First, there are two pre-defined parametric models capable of generating a wide range of building massing designs beyond fixed topological configurations, which free the architect who carries out the performance-based optimisation from tedious parametric modelling. Second, the toolkit also includes a diversity-guided evolutionary algorithm that is aimed to enhance the design diversity in the optimisation result by increasing the genotypic differentiation in the design population. The two components allow the architect to quickly set up a task-specific evolutionary design system for performance-based design optimisation and exploring high-performing design solutions for design ideation and concept development.

To place this research into context, we first discuss the progress that has been made related to the evolutionary design tools. Then, we describe the proposed evolutionary design toolkit and present some design scenarios and associated results. We conclude by discussing the relative advantage of this toolkit and the possibilities for increasing the utility of optimisation-based design exploration in architecture.

1.1. EXISTING TOOLS FOR EVOLUTIONARY DESIGN

In the last decade, several evolutionary design and optimisation algorithm tools have been developed for performance-based building design optimisation. Popular tools include Galapagos, Octopus, and Opossum in Rhino-Grasshopper and Optimo in Revit-Dynamo. By using these tools, architects can set up a performance-based design optimisation system to search for high-performing solutions. However, establishing an optimisation system requires the architect to build up a parametric model for describing the design before running the optimisation process. For many architects who are not familiar with programming and coding, parametric modelling can be technically challenging and require considerable effort in setting up the parametric model. This technical barrier can to some extent be addressed by using visual programming tools for parametric modelling such as Grasshopper and Dynamo, which can free architects from coding. Even so, it is still challenging to use these tools to build up parametric models capable of producing substantial design differentiation over continuous design variations (Wang, Janssen, Chen, Tong, & Ji, 2019). As a result, the parametric models that get created are often only capable of generating very limited design differentiation, which makes the result of the optimisation predictable and less informing.

In order to address the challenge mentioned above, other researchers have proposed more integrated evolutionary design tools or workflows in recent years. Such evolutionary design tools and workflows typically integrate an evolutionary algorithm and pre-defined parametric models for generating simple building massings such as slab-/tower-type buildings and buildings with different footprint shapes (Natanian, Aleksandrowicz, & Auer, 2019; Nault et al., 2018; Xu et al., 2019). To use these tools or workflows, architects only need to customise the pre-defined parametric model by inputting constraints and preferences. These evolutionary tools and workflows do not require parametric modelling and associated coding and programming. As a result, the evolutionary design process based on these tools can be greatly streamlined. These tools and workflows are primarily aimed at the performance-based urban design optimisation, and the pre-defined parametric models are capable of generating diverse urban forms by varying permutations and combinations of different forms over multiple buildings.

Such coding-free and non-disruptive evolutionary design processes can also be used for performance-based design optimisation at the individual building level. However, for building design optimisation problems, the usage of these above-mentioned evolutionary design tools and workflows is limited. It is because the pre-defined parametric model embedded in these tools and workflows is typically unable to generate diverse building massings, which significantly confines the scope of design solutions for the optimisation process to explore (Nault et al. 2019). In order to address this issue, it is critical to develop pre-defined parametric models capable of generating diverse building designs with higher topological variability. Thus, we have proposed a parametric algorithm describing building design based on the subtractive form generation principle, which has proved to be effective for generating diverse building designs (Wang, Janssen, Chen, et al., 2019).

While the design process can be streamlined by providing pre-defined parametric models in the design tool, another problem is the lack of design diversity in the optimisation result. The evolutionary design tools and frameworks mentioned above are typically based on simple genetic algorithms. Such algorithms are typically poor in search efficiency and are only able to yield optimisation result within a family of similar solutions due to the genotypic similarity (Wang, Janssen, & Ji, 2020). This can undermine the type of design information and feedback that can be gained from the results. In order to enhance the information extraction, multi-objective optimisation is widely considered a means to reveal the trade-offs and compromises of the design problem by different design contestants. However, using multi-objective optimisation typically results in the reduction of search efficiency, and the contestants in the optimisation result are often too many. This can be overwhelming for architects, making information extraction very difficult (Yousif & Yan, 2018). In addition, with multi-objective optimisation, design variants must respond to multiple performance criteria. This can make the architectural implication related to each performance objective unclear.

To overcome the above weaknesses inherent in many evolutionary algorithms, we have proposed a hybrid evolutionary algorithm that can explore different regions in the design space while only focusing on one performance objective (Wang, Janssen, & Ji, 2020). With the algorithm, the result of the optimisation can include a range of design variants that are both high-performing and that are also highly differentiated. This helps to clarify the architectural implications related to the performance factors and to enhance the feedback gained from the evolutionary design process (Wang, Janssen, Chen, et al., 2019).

2. Proposed toolkit and its implementation

2.1. OVERVIEW OF THE TOOLKIT AND APPLICATION WORKFLOW

The toolkit is developed to facilitate architects to carry out an explorative performance-based optimisation of building massing design aimed at various performance factors such as daylighting and passive solar energy while without additional programming required. The toolkit consists of the components of an evolutionary algorithm and two parametric models for generating building massing design. The toolkit was implemented in the Rhino-Grasshopper modelling platform to facilitate ease of use. In this platform, architects can establish an optimisation system by connecting the components of the parametric model (with the default colour scheme to Grasshopper components) and the evolutionary algorithm (with the same colour scheme, pink, to Galapagos component) to various building performance simulation tools such as *DIVA* and *Honeybee* (Figure 1).

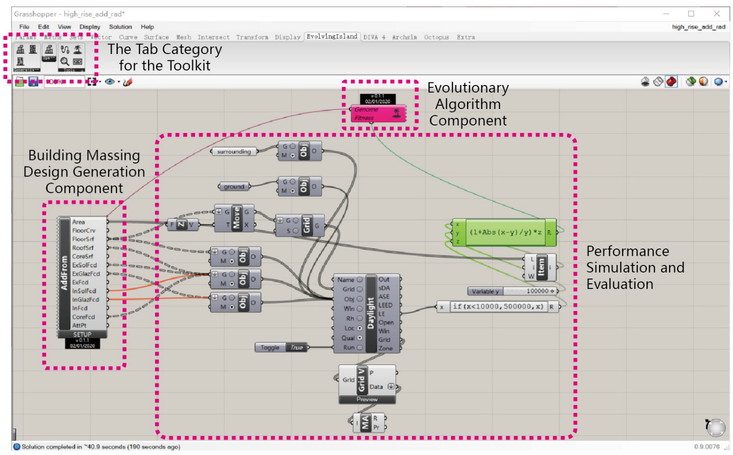

Figure 1. Example of a building massing design optimisation system established based on the toolkit.

With the system established (Figure 1), the architect first needs to adjust the selected parametric model via several user-defined parameters to generate building massings that satisfy the design setting. Second, the architect set the evolutionary algorithm and the simulation tool before running the optimisation process. While the design process is streamlined as no parametric modelling is required, the optimisation system also has the merit of re-usability for different projects. For different projects, architects are only needed to adjust a few parameters to customise the set-up of the system as long as the performance criteria and the associated simulators remain the same.

2.2. PRE-DEFINED PARAMETRIC MODELS

The toolkit includes two pre-defined parametric models based on additive and subtractive form generation principles. As the two principles can schematically describe many passive building design strategies such as courtyards and stilts, the building massing generated by the two parametric models can help architects understand the performance implications related to those passive design strategies. The two models are also embedded with the rule abstracted from common architectural manipulation on the building massing design such as element regulation and alignment to ensure the generated design is feasible and meaningful. In addition, the architect can use several user-defined parameters to control the overall geometric features of the generated building massing design. Hence, the parametric models can play as a meta-model, which can derive various versioning task-specific models to generate satisficing building massing design simply by varying user-defined parameters.

For the parametric model based on the subtractive principle, it defines several cubic subtractive elements and creates the building massing design by removing the parts of these elements from a predefined maximal mass. The architect defines the dimension of the maximal mass, the maximum number as well as the size constraint of the subtracting elements. With different arrangements of the subtracting elements, the subtracted massing appears diverse topological configurations. In reverse, the one based on the additive principle creates the building design by accumulating and merging several cubic massing elements. Likewise, the architect defines the maximum number of massing elements, the maximal volume (spatial boundary) confining the massing elements, and the size constraint of the massing elements (Figure 2).

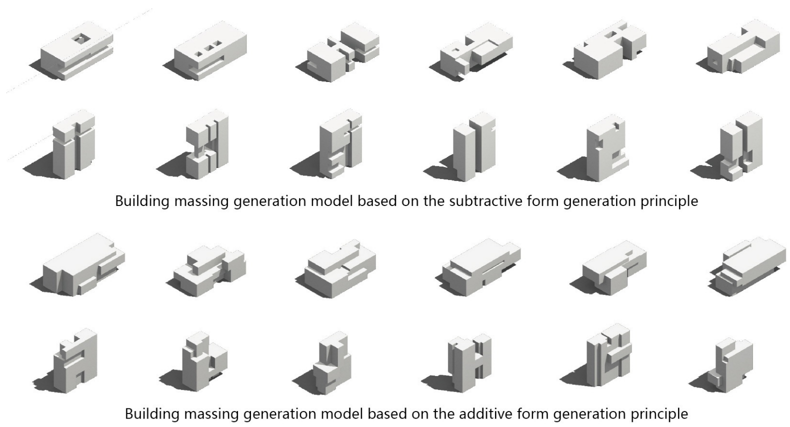

Figure 2. Examples of building massing design generated by the two parametric models.

2.3. DIVERSITY-GUIDED EVOLUTIONARY ALGORITHM

The toolkit includes an evolutionary algorithm integrating an island-model approach and a steady-state replacement strategy into a standard evolutionary algorithm, named SSIEA, for increasing diversity in the design population and improving the search efficiency. The island model allows the algorithm to launch multiple parallel search processes to evolve several "niching" subpopulations. Each subpopulation is guided to focus on a non-neighbouring region in the design space. The separation and multitude of subpopulations counteract the exploitative natural inherited in standard evolutionary algorithms and prevent the optimisation from ending up a set of neighbouring design solutions due to the genotypic similarity. In addition, the steady-state replacement strategy speeds up the optimisation process by increasing the evolutionary pressure on the whole optimisation process. Using the evolutionary algorithm can retrieve several high-performing solutions while having rich design diversity due to genotypic differentiation (Wang, Janssen, & Ji, 2020). The diversity in the result enhances the feedback from the optimisation, which facilitates architects to discover underlying compromises and trade-offs characterising the design problem.

2.4. SHOWCASE

In order to demonstrate the efficacy of the proposed evolutionary design toolkit, we first applied the toolkit into a case-study design task for exploring the building massing design responding to daylighting performance. In addition, the toolkit was used by two students in their design studio to design a 12-class kindergarten project, which allows the examination of the toolkit in a design scenario closer to reality.

For the first showcase, the design task describes a slab-type high-rise building surrounded by several high-rise buildings, and the quality of daylighting is set as the performance criteria to be investigated. As the surrounding buildings block a large amount of daylight from reaching the building, it presents a challenging design setting for achieving good daylighting performance (Figure 3). With the toolkit, we undertook optimisation based on the two parametric models to investigate how building design will be evolved to maximise the daylighting performance. The annual lighting energy consumption (LE) is taken as the performance indicator, which is calculated by DIVA, and the fitness evaluation is aimed to reduce LE. Moreover, 45,000 m^2 is defined as the target gross area of the building. In response to the requirement of obtaining an acceptable gross area, the difference between the gross area of the generated building design and the target value is set as a penalty function in the fitness evaluation. The penalty function proportionally scales up the value of LE to punish the design variants failing to satisfy the gross area requirement.

For the optimisation process, we adopted six subpopulations to make the optimisation process to explore more regions in the design solutions space. In addition, the initial population was 300 (50 for each sub-population), and 130 generations were set for each optimisation process. In each generation, 36 offspring individuals were created and compared against their parents, and the total iterations of design generations and performance evaluations for the optimisation process were 4,980.

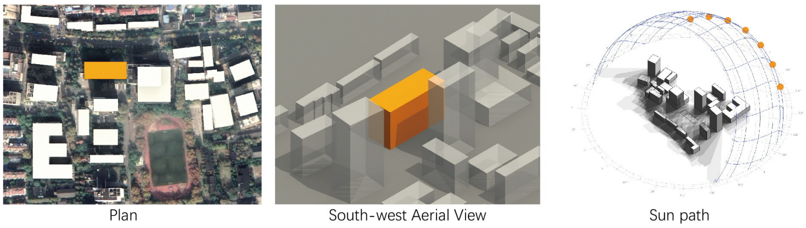

Figure 3. Design setting of the first showcase.

The second showcase is a 12-class kindergarten design (Figure 4). In this showcase, only the parametric model of the additive principle was applied, as the subtractive one is not suitable for generating design solutions with separated massing entities of classroom clusters. The gross area of the kindergarten is 2,500 m^2, and the design was required to consider the arrangement of the classroom clusters, the outdoor playground, and other facilitates such as kitchens and entrances. Two students chose the toolkit to explore design solutions in regard to the performance criteria of daylighting and passive solar heating. The students had no prior knowledge of computational design and building performance.

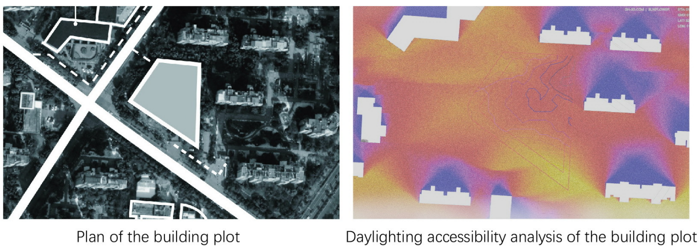

Figure 4. Design setting of the second showcase.

The period for the students to undertake the design optimisation lasted for three weeks (the overall period of the studio was eight weeks). As the students had no prior knowledge, we briefly introduced evolutionary optimisation and building performance to them while helping them to set up the optimisation system based on the toolkit in the first week. In the second and the third weeks, when the students became familiar with the toolkit and evolutionary optimisation, they began adjusting the setting of the parametric model and performance evaluation criteria according to the feedback from the previous optimisation result. After several trials, they extracted information from the optimisation result and developed their design concept based on the information.

3. Result

3.1. SHOWCASE -1

The first row in Figure 5 shows the elite design solutions found by the evolutionary process based on the building massing generation model of the subtractive form generation principle. According to these solutions, three passive energy-saving strategies can be identified. These strategies can be effective in achieving good daylighting performance in this design setting. First, stilts appear in the Elite1 and Elite4. This strategy can help reduce the area on the lower floor levels, which is naturally poor in daylighting quality due to the daylight obstruction by surrounding buildings. Second, Elite2, Elite5, and Elite6 appear to be a high-rise tower-type building, which means that increasing the total height of the building can also improve daylighting performance. The increase in the building height can increase the proportion of floor area with fewer daylight obstructions by other buildings. In essence, these two strategies indicate that raising the major building mass in the vertical direction can improve the daylighting quality due to the reduction of the indoor space in the unfavorite under-daylit position close to the ground. Third, all elite solutions have jagged floors. This improves daylighting by increasing the facade surface and by creating gaps between the target building and other surrounding buildings.

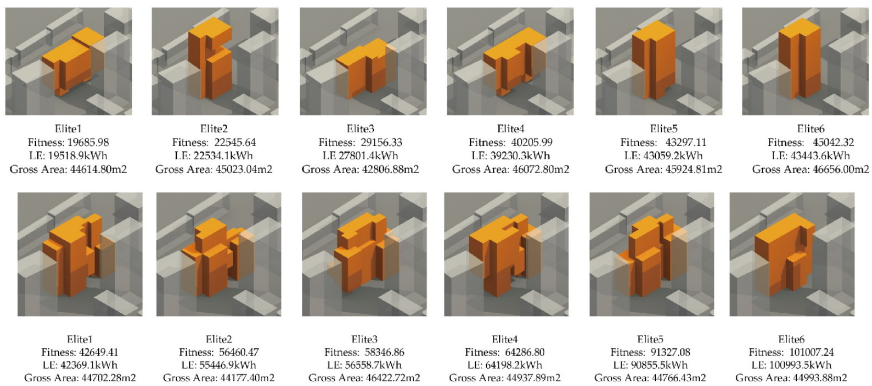

Figure 5. Elite design solutions in the optimisation result.

The second row in Figure 5 shows the elite design solutions found by the building massing generation model based on the additive form generation principle. Compared to their counterparts based on the subtractive form generation principle, these elite solutions share less similarity in the geometry. In general, Elite2, Elite3, and Elite4 show a stepped massing where a smaller mass sitting on a massive podium. Besides, stilts and jagged floor plans are also found among these elite solutions. These features also indicate the strategy in line with the strategy shown in the design variants based on the subtractive form generation principle that the building massing should be heightened to reduce the daylight obstruction by other surrounding buildings.

The reason why the result based on the additive generation model is different from the result based on the subtractive generation model is primarily due to an optional constraint imposed in the additive generation model. This constraint requires the building massing generated with at least half of the footprint to be occupied by the additive mass elements. The purpose of this constraint is aimed to avoid too many floating masses in the generated design. As a result, most of these elite solutions tend to have a large podium-like mass at the lower part of the building massing.

The above result shows that both parametric models can create diverse building massing designs to allow the architects to undertake an explorative performance-based optimisation. In addition, it should be mentioned that the effort and time required to establish the optimisation system for both optimisation processes are minor, as the two optimisation processes share most of the components in the system. The simple system establishing process may help architects focus on the optimisation process and exploring design solutions more deeply for solving the design problem.

3.2. SHOWCASE -2

In this paper, we present one student's in-progress optimisation work and the corresponding final design in Figure 6. The general goal set by this student was to maximise daylighting performance. The student first examined two different orientations to generate the building massing of classroom clusters. By comparing the average daylighting quality, the student decided using a 45-degree rotated grid system as it can have a better average performance than that based on the north-south direction. Thereafter, the student selected several high-performing solutions and extracted the information from these. The student found the jagged massing and spacing are helpful for improving the daylighting performance (Figure 6-1). On this basis, the student re-arranged the mass elements taking other requirements into accounts, such as circulations and geometric order (Figure 6-2).

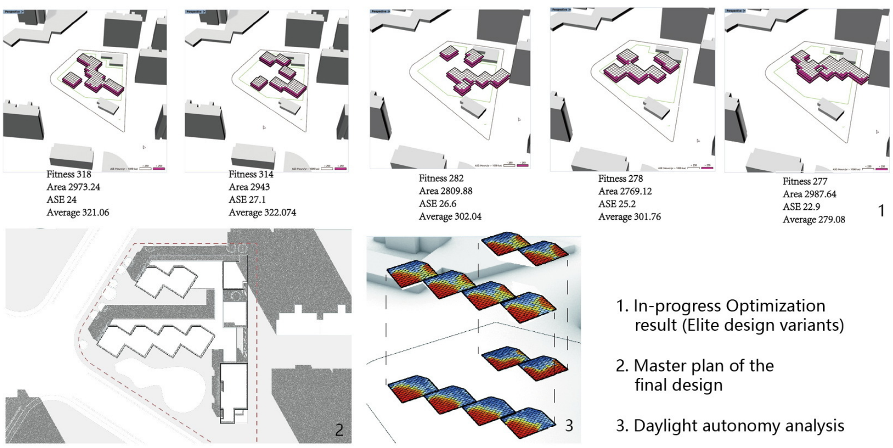

Figure 6. Elite design solutions in the optimisation result and the final design.

It may be noticed that the final design has marked differences from the optimisation result, which also points out a limitation of the toolkit. Indeed, the parametric model is primarily designed to generate single-entity building massing designs rather than the layout of multiple massing entities. Thus, the embedded rules and constraints may not be well suited to the kindergarten design. For such layout designs composed of predefined building massing entities, the building massing entity is typically not required to change in size, and the merging of two entities is also not appropriate.

4. Conclusion and Discussion

This research proposes an evolutionary design toolkit aimed at optimisation-based design exploration for encouraging architects to collect feedback for enriching design ideation on the outset of the design process. By minimising the technical demand of utilising evolutionary design, the toolkit allows computational novices to undertake design optimisation with simple instructions. The two parametric models capable of generating adequate topological variability allow evolutionary optimisation to explore a broad range of design alternatives. Additionally, the feedback of the optimisation is enhanced by the genotypic differentiation obtained by using the hybrid evolutionary algorithm (SSIEA). The two showcases demonstrate how architects can extract useful information by using the toolkit, and how the information can positively affect the trajectory of the design process towards a desired environmental-friendly solution. Furthermore, while the optimisation system established by the toolkit yields entirely different result for the two showcases, the system used in the two showcases is *de facto* the same. Thus, this may open up a possible standardised approach to applying evolutionary design in conceptual architectural design, which architects can use in many routine design tasks for the initial concept development and design ideation.

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