ALGORITHMIC GENERATION OF ARCHITECTURAL MASSING MODELS FOR BUILDING DESIGN OPTIMISATION

Parametric Modelling Using Subtractive and Additive Form Generation Principles

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Abstract. Using performance-based optimisation to explore unknown design solutions space has become widely acknowledged and considered an efficient approach to designing high-performing buildings. However, the lack of design diversity in the design space defined by the parametric model often confines the search of the optimisation process to a family of similar design variants. In order to overcome this weakness, this paper presents two parametric massing generation algorithms based on the additive and subtractive form generation principles. By abstracting the rule of these two principles, the algorithms can generate diverse building massing design alternatives. This allows the algorithms to be used in performance-based optimisation for exploring a wide range of design alternatives guided by various performance objectives. Two case studies of passive solar energy optimisation are presented to demonstrate the efficacy of the algorithm in helping architects achieve an explorative performance-based optimisation process.

Keywords. Parametric massing algorithms; performance-based optimisation; design exploration; solar irradiation.

1. Introduction

Parametric modelling incorporating evolutionary optimisation has been widely considered an efficient approach to facilitating architects to address complex energy optimisation challenges in sustainable building design. While this approach can technically solve performance-based building design problems by evolving design guided by various energy criteria, it also allows for an exploration of unknown design space, which may facilitate the discovery of unexpected

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design solutions. The latter exercise can be referred to as *optimisation-based design exploration*, and its relevance in enhancing early-stage design ideation and overcoming design fixation has been increasingly acknowledged and upheld over the last decade.

Despite many successful applications in the literature, achieving a design exploration with meaningful and informative feedback from evolutionary optimisation is still challenging. Apart from the tedious optimisation process, the limited design space for the optimisation process to search often accounts for the unsatisfying result of such optimisation-based design exploration. The design space is limited as the result of the lack of diversity in the design space defined by the parametric model. Although there are a few complicated algorithms for parametric modelling to generate building design with higher differentiation, the implementation of such algorithms is often too challenging and time-consuming for architects to handle on the fly for each project. In order to address these challenges, it is essential to develop algorithms that can not only generate diverse building design alternatives but also be readily re-used to different design tasks. To this end, we propose two algorithms based on the additive and subtractive form generation principles (Simitch & Warke, 2014) for generating building massing design alternatives with high topological variability. Because these principles are the two most generic massing strategies in architecture, they can be adapted to different building design tasks with minimal customization. In this way, the algorithms can address the two requirements simultaneously.

To place this research in the context, we first discuss the progress that has been made related to the algorithms for parametric building design before going on to describe the proposed algorithms and present design scenarios demonstrating the efficacy of the algorithm. We conclude by discussing the effectiveness of the algorithm in supporting optimisation-based building design exploration.

1.1. ALGORITHM FOR PARAMETRIC BUILDING DESIGN

Describing design with explicit rules and parameters, parametric models can generate a large number of design variants by varying parameters. Sheikholeslami (2010) defines two types of design variant outcomes from parametric models. The first one is referred to as *design alternatives* which represent designs with “structurally different geometries”. The second one is referred to as *design variations*, in which the topological configuration of the generated building design remains fixed to the change in parameters. Most massing algorithms can be categorised into the second type of parametric models. Such algorithms are often used for representing a specific design concept. For example, a building block with a central internal courtyard is widely adopted in the building design optimisation for daylighting or passive solar energy. However, for the sake of design exploration, the invariant topological configuration of the building design variants significantly confines the scope of the design space, and, thereby, the opportunity of exploring other competitive design concepts is lost.

In order to widen the design space for exploration, a few researchers have developed algorithms for generating building massing design beyond a fixed topological configuration. The first approach is to include multiple parametric schemes in one parametric model, and each scheme describes design with different topological configurations. The parametric model switches the schemes each time according to a regulatory parameter and generates solutions according to the selected parametric scheme (Chen, 2015). The second approach creates building massing by combining multiple smaller mass units. The mass unit typically has fixed or similar dimensions and shapes (Wang, Janssen, & Ji, 2019). Thus, the building design generated by this approach typically appears to be cellular-like massing. By arranging and re-arranging the mass units, the resulted building massing differs dramatically in terms of topological configuration, but it often comes with a large number of chaotic designs (Wang, Janssen, & Ji, 2019).

However, applying these two approaches in practice is time-consuming and technically challenging. The former requires the laborious creation of many parametric schemes, and the latter involves complicated constraint handling to ensure the generated design is feasible and legitimate. Furthermore, as the development of these algorithms is often subject to a large amount of task-specific knowledge, the re-usability of these algorithms to other design tasks is limited.

The task-oriented parametric modelling largely accounts for the lack of versatility and the limited re-usability of parametric models. Thus, peeling off the task-specific intentions while preserving generic domain knowledge and expertise into adaptable algorithms for repetitive tasks can allow for the generation of a broad range of preliminary design alternatives and, thereby, enable re-utilization. A relevant method is meta-modelling (Bernal, 2016; Harding & Shepherd, 2017), which captures the rules of parametric associative design. Recent efforts on meta-modelling aims at the automated generation of the parametric association of the nested sub-functions for differentiated design creation. However, due to the absence of architectural design knowledge, human intervention is still necessary, else the parametric model, randomly generated by computers, can be illegible.

Alternatively, we have proposed a parametric modelling approach to abstracting generic architectural massing strategies and developed an algorithm based on the subtractive form generation principle (Wang, Janssen, Chen, Tong, & Ji, 2019). The algorithms do not have a modifiable parametric association as other meta-modelling approaches do but can derive various versioning parametric models by specifying a set of user-defined parameters. Partly constrained by the user-defined parameters set by the architect, topologically varying building massing designs are generated according to different design settings while still complying with the subtractive form generation principle. In this study, we extend the research by including the additive form generation principle and compare the effectiveness of these two algorithms in supporting design exploration through performance-based optimisation.

2. Proposed Algorithm

2.1. PARAMETRIC SCHEMAS FOR ARCHITECTURAL MASSING STRATEGIES

In architecture, the additive and subtractive form generation principles are the two most commonly-adopted massing strategies, and most building designs can be described by either of these two principles. Examples of the subtractive form generation principle include Simmons Hall at MIT in Boston, USA and Administration Building at XJTL University in Suzhou, China. For the additive form generation principle, examples include Ftown Building in Sendai, Japan and New Museum of Contemporary Art in New York, USA. Furthermore, these two principles also have a tight connection to many sustainable design strategies, such as courtyards, atriums, stilts, self-shading, and solar envelopes

The versatility and the connection to sustainable design strategies make these two principles suitable as generic parametric schemas for the performance-based optimisation in various design settings. The algorithm can delineate the design space reflecting the different sustainable design strategies through various design variants. By exploring the design space and evaluating the design variants against the performance criteria, the optimisation process, in fact, compares these strategies against one another and screens out the high-performing strategy. At the same time, architects can adjust the overall building features simply by defining the number and size of subtractive or additive massing elements and the behaviour of the elements when interacting with other elements. Thus, the algorithms satisfy the requirement listed in the previous section and can be re-usable in different design contexts.

2.2. GENERATIVE PROCEDURE OF THE ALGORITHMS

The research develops two algorithms respectively based on the two principles, and the core of the algorithms is to avoid commonly unwanted features, increase the diversity in the generated building massing design, and facilitate customisation by the architects. The core procedure of the two algorithms is similar. Thus, we first introduce the algorithm based on the subtractive form generation principle (*subtractive algorithm*) in detail. For the algorithm based on the additive principle (*additive algorithm*), only the major differences to the subtractive algorithm are pointed out.

2.2.1. Subtractive Algorithm

The subtractive algorithm creates building massing design by removing several parts from a maximal mass (Figure 1). The element defining the part being removed is referred to as the subtractive element (SE). By manipulating multiple SEs in different sizes and spatial positions, the maximal mass subtracted by these SEs can show vast different topological configurations. In this algorithm, the architect first defines the dimension of the maximal mass. By varying the dimension, the maximal mass can appear in different types of buildings such as high-/low-rise and deep-/thin-plan buildings. With the maximal mass defined, two types of SEs are defined. The first type is vertical SEs, and the second type is horizontal SEs. The vertical SEs tend to be tall and slender, which is aimed to cut through the maximal mass vertically to ensure features such as courtyards and atriums appearing in the building massing design. In contrast, the horizontal SEs are aimed to create features, such as stilts and stepped roofs. The architect defines the number of these two types of SEs, which can control the configurational complexity of the generated building massing.

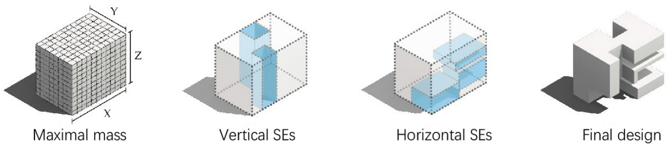

Figure 1. Relationship between the maximal mass and the two types of SEs.

Using parametric approaches can result in arbitrary size and placement of the SEs. First, the size of the SEs can be too large or too smaller, which may lead to infeasible building massing. Thus, the algorithm requires the architect to specify the size constraint to define the upper and lower size limits of the two types of SEs (Figure 2). In order to diversify the appearance of the parts removed from the maximal mass, two different operations are activated when the size constraint is violated. When the original size of a SE exceeds the upper size limit, the upper size limit is assigned to the SE. In contrast, when the original size is below the lower size limit, the SE is deactivated, and the corresponding part is not subtracted from the maximal mass.

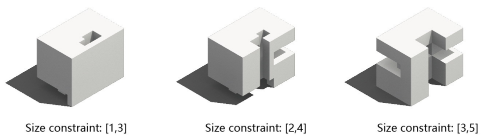

Figure 2. Size constraint.

Another problematic feature resulting from the arbitrary placement of SEs is that two SEs can be too close to one another or partly overlaps. When two SEs are close but not attach, it creates a space between the two SEs that may be too narrow to be of any use. This problem can also happen when a SE is close to the face of the maximal mass. Thus, the closest parallel faces of the two SEs or the face of the SE and the maximal mass are aligned to be co-planar (Figure 3-a,b). With the faces aligned, the two SEs are merged into a larger subtractive void in the maximal mass, or the SE creates an open void in the maximal mass. When two SEs partly overlap, it may create a subtractive void with small jagged faces. Thus, the algorithm also aligns the face of two overlapping SEs if they are close to one another to avoid this (Figure 3-c).

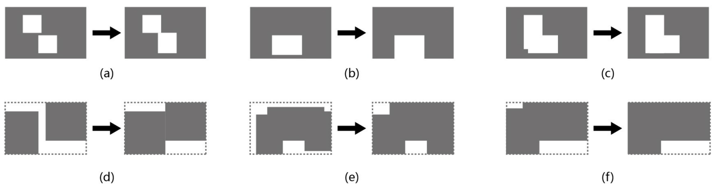

Figure 3. Alignment constraint.

With the size and alignment constraints, the algorithm can generate building massing with a broad topological variability from a building without any part removed to that with the largest number of parts permitted removed. In addition, the alignment constraint also enriches the diversity of the generated building massing. When two or more small SEs are merged into one large subtractive void, the algorithm can generate building massing either with several small parts removed or with one large part removed. Such diversity can reveal rich performance-related architectural implications. For example, the generated building massing can have a large courtyard or several smaller courtyards or light/air wells (Figure 4).

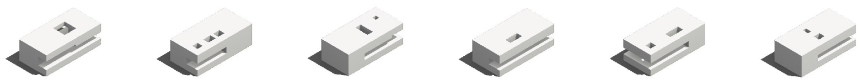

Figure 4. Example designs (randomly generated).

Lastly, the implementation of the algorithm also considers the gross area of the generated building massing as it is an important functional requirement in architectural design. As the accumulating occupied area by the SEs changes with varying parameters, the gross area of the generated building massing varies accordingly. It is important to ensure the gross area of the generated building massing satisfies the required value. Thus, this algorithm incrementally increases or decreases the dimension of the maximal mass in order to create the building massing with a gross area close to the required value (Figure 5-a).

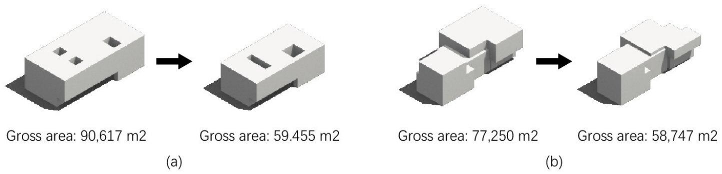

Figure 5. Gross area constraint (target area is 6,000 m2).

2.2.2. Additive Algorithm

The additive algorithm creates the building massing by accumulating several mass elements, which are referred to as *additive elements* (AE). The generative procedure can be viewed as the inverse operation of the subtractive algorithm. The maximal mass in the subtractive algorithm becomes a maximal volume (spatial boundary) in this algorithm to confine AEs. Similar to the subtractive algorithm, the size and alignment constraints are also applied in this algorithm to regulate the AEs for ensuring the rational space and geometric diversity in the generated building massing (Figure 3-d,e,f). Except for these shared procedures, there are two major differences in the additive algorithm from the subtractive one.

First, compared with the arbitrary behaviours of SEs, the arbitrary placement of AEs is more likely to create chaotic designs such as floating masses and huge overhanging structures. In most cases, all AEs are floating when using the parametric approach. Thus, the algorithm iteratively lays down one of the floating AEs to the ground until half of the footprint of the predefined maximal volume has been occupied (Figure 6).

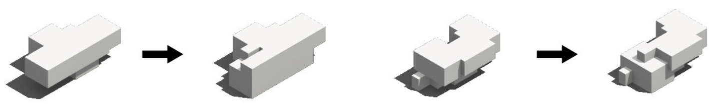

Figure 6. Floating constraint.

Second, the development of the additive algorithm also considers the requirement of the gross area but adopts another approach to adjusting the building massing. For the additive algorithm, all AEs are iteratively scaled up or down by 5% until the gross area of the building massing cannot get closer to the target value (Figure 5-b). At the same time, the maximal volume remains fixed, which is unlike the unchangeable maximal mass in the subtractive algorithm.

2.3. IMPLEMENTATION

The two algorithms were implemented in the Rhino-Grasshopper environment as two independent plug-in components. The components are integrated into an evolutionary design toolkit which also includes a diversity-guided evolutionary algorithm - SSIEA (Wang, Janssen, & Ji, 2020). The implementation in the Rhino-Grasshopper environment allows the two components as well as the component of SSIEA to be easily connected to other performance evaluation tools such as *DIVA* and *Honeybee*. As the two building massing generation components can be re-used in different design tasks, it also makes the established optimisation workflow re-usable as long as the performance criteria remain the same.

A graphic user interface (GUI) was also implemented in the algorithm components to facilitate the architect to input the user-defined parameters. In the GUI, the architect can specify the number of SEs or AEs and the constraints such as size limits. After inputting the user-defined parameter, the architect can generate several sampling design variants and receive timely visual feedback of the change in the user-defined parameters. As such, the architect can exclude the unwanted building features by parameter tuning before running the optimisation process.

2.4. CASE STUDY

For demonstrating the efficacy of the algorithms, two case studies of performance-based building design optimisation are presented (Figure 7). The design objects of two case studies are a high-rise slab type building and a middle-rise deep plan building located at the campus of Nanjing University in Jiangsu Province, China. This region is characterised as *cold-winter-hot-summer* climate, which results in heavy heating and cooling loads in winters and summers due to inadequate and excessive solar irradiation received. In this regard, the optimisation is aimed to optimise the utility of passive solar energy by minimising incident solar irradiation in summers and maximising it in winters.

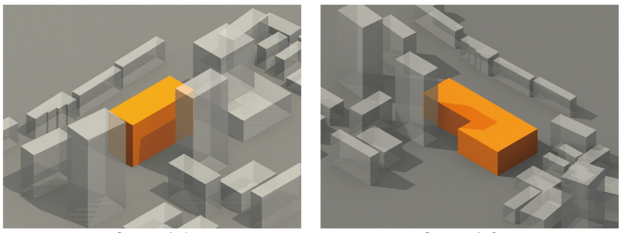

Figure 7. Case study design settings.

The objectives of minimising and maximising incident solar irradiation are formulated into a single-objective fitness function. The fitness is calculated by subtracting the amount of incident solar irradiation on facade surfaces in winters from that in summers. It is because the solar irradiation received in summers is always higher than that received in winters. Thus, for high-performing design variants, these variants receive lower solar irradiation in summers, while receiving higher of that in winters. Therefore, the difference between the two values tends to be small. In contrast, the design variants receiving unfavourite higher solar irradiation in summers and lower solar irradiation in winters have a large difference between the two values.

In addition, 45,000 m^2 and 100,000 m^2 are set as the target gross area of the building for the two case studies. The factor of the gross area is considered a penalty function in the fitness evaluation, which scales up the difference between the values of the incident solar irradiation received in summers and winters. As a result, the design variant that cannot satisfy the gross area requirement is punished by enlarging the difference of the incident solar irradiation values.

3. Result

3.1. CASE STUDY 1

Figure 8 shows the results of the optimisation processes based on the two algorithms. The evolutionary algorithm used in the case study allows for yielding several distinct high-performing design variants. In this case study, the six highest-ranking design variants from each optimisation process are retrieved. Revealed by these variants, the optimisation process primarily identifies the building massing can achieve better solar avoidance in summers. It is because the building is surrounded by several high-rise buildings, which reduces incident solar irradiation in both seasons on the one hand. On the other hand, as the sun in summer afternoons can be on the north-west side of the target building, the building still receives intense incident sunlight on the summer afternoons, which can heat the building and increase the cooling load.

From the design variants generated by the subtractive algorithm, we can notice that these variants have a large stilt in the upper part of the building massing, which self shades the facade to prevent overheating of the building (the first row in Figure 8). In contrast, the design variants generated by the additive algorithm typically have a narrow west facade which reduces the exposure to the fierce incident sunlight on summer afternoons. The narrow west facade also makes the design variants generated by the additive algorithm have better average fitness. The reduction in the gross area due to the narrow west facade is compensated by several overhanging structures or podiums which also self shade the building (the second row in Figure 8).

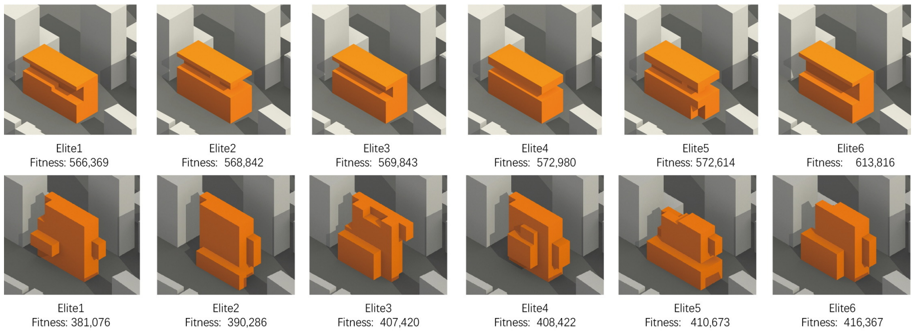

Figure 8. Optimisation result of case study 1.

3.2. CASE STUDY 2

Figure 9 shows the optimisation result of the second case study. The architectural implication related to the passive solar energy utility is similar to that unveiled in the first case study. Stilts and overhanging structures are the dominant features appearing in the design variants generated by both algorithms. Compared with the design variants of the first case study, the design variants generated by the two algorithms in this study share more similarities with regards to the strategy of self-shading. In addition, narrow west facades also appear in the design variants generated by the additive algorithm, which makes the average fitness of the design variant generated by the additive algorithm more desirable than those generated by the subtractive algorithm.

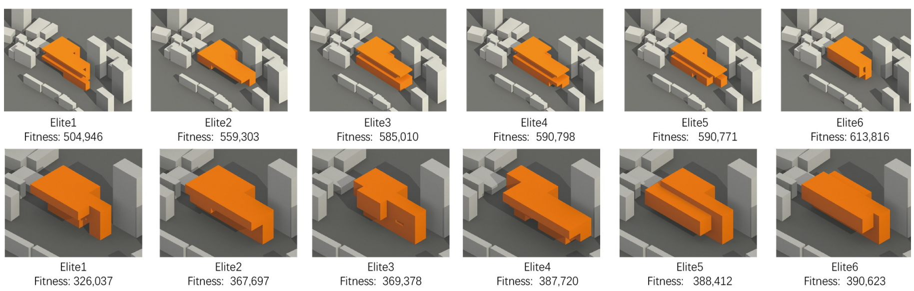

Figure 9. Optimisation result of case study 2.

4. Discussion and Conclusion

The results of the optimisation based on the two algorithms unveil the architectural implication related to achieving good passive solar energy utilistion. The design variants have illustrated the appropriate and site-specific application of the self-shading strategy for the case study. However, due to the difference in the form-making procedure, the design variants generated by the two algorithms show different building features. In addition, in comparison with the two algorithms, the optimisation result based on the additive algorithm has design variants with higher design differentiation. The implication of self-shading shown in the optimisation results also provides a less conventional way to improve passive solar energy utilisation. Contrarily, this problem is typically addressed by adding external shading on buildings' facades. The case study highlights the potential of combining the proposed algorithms and performance-based optimisation for achieving an optimisation-based design exploration. Such exploration helps architects free from design fixation and stimulates design reflection and ideation, which makes the design of buildings become a more responsive and adaptive agent in shaping our future built environment.

To conclude, this study proposes two parametric massing algorithms to generate building massing with higher topological variability. The development of the algorithms aims to facilitate explorative performance-based optimisation in the early design stage of sustainable building design. The two case studies show that the algorithms can be adapted to different design settings with minimal customisation and generate task-specific solutions, which underlines the re-usability of the algorithms to various design tasks. The future research will consider providing higher geometric freedom in building massing generation in order to increase the versatility of the algorithms.

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