EVOLUTIONARY DESIGN OF RESIDENTIAL PRECINCTS

A Skeletal Modelling Approach for Generating Building Layout Configurations

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Abstract. This paper presents a ‘skeletal’ parametric schema to generate residential building layout configurations for performance-based design optimization. The schema generates residential building layout configurations using a set of ‘skeletal’ lines that are created based on various design elements and coincident with factors such as walkways, spacing, and setback requirements. As such, the schema is able to generate diverse and legitimate design alternatives. With the proposed parametric schema, a case-study optimization is carried out for a Singapore Housing Development Board (HDB) project. The case study considers a set of performance criteria and produces results with higher practical referential value. The case study demonstrates that the optimization with the parametric schema can improve the overall quality of the design and provide designers with various design options.

Keywords. Parametric Modeling; Building Layout; Performance-based Design; Algorithmic Design; Design Optimization; SDG 11.

1. Introduction

In Singapore, 80 percent of the population lives in public housing precincts, constructed by the Housing Development Board (HDB) (Cheong, 2019). The design and construction of these public housing precincts can have a great societal and environmental impact on sustainable city development. In this regard, novel and efficient design methods and techniques are being explored for improving the overall performance of HDB precinct designs with respect to various liveability criteria. Over the past decades, a number of studies have been conducted to integrate techniques such as parametric design and computational optimization into the design for HDB precincts (Chen et al., 2017; Chen & Norford, 2017; Janssen & Kaushik, 2013; von Richthofen et al., 2018). These studies demonstrate the potential of computational optimization and performance-based design in assisting architects in their design of HDB precincts. Despite this, there are still certain barriers making it difficult to apply computational optimization to HDB precinct designs.
Considering real-world design scenarios, a decisive factor in the utility of evolutionary optimization workflows is their ability to incorporate a set of constraints relating to various design rules for the precinct typology (Wang et al., 2018a, 2018b). The challenge is therefore to develop generative algorithms that are capable of generating designs with both adequate variability and feasibility. For variability, design variants need to differ significantly. For feasibility, design variants need to adhere to the constraints. This challenge also explains why it is difficult to use existing design optimization workflows for HDB projects in practice.

In these existing generative and optimization workflows, the parametric schema for design generation is often either over-constrained or under-constrained. The over-constrained case results in a lack of designs that vary significantly. Using this approach, buildings are typically placed over a predefined grid, thus resulting in a barracks-like building layout configuration (Chen & Norford, 2017; von Richthofen et al., 2018). In contrast, the under-constrained case results in a lack of designs that are deemed feasible, as buildings are typically placed arbitrarily within a predefined boundary (Chen et al., 2017; Janssen & Kaushik, 2013). Both cases can ultimately defeat the purpose of applying the optimization algorithm in the first place.

In response, this study presents a novel parametric schema for middle-scale HDB precinct design generation, in which a skeletal modeling approach is adopted. To overcome the lack of design variability and feasibility, we use the “skeletal” line as the organizational device for generating building clusters in this study. These skeletal lines allow design constraints to be more easily handled. In addition, by varying the position and direction of these skeletal lines, solutions with a wide variety of building block arrangements and orientations can be created. Hence, the parametric schema can achieve both variability and feasibility. With this parametric schema, this study establishes an optimization workflow for evolving high-performing precinct designs for HDB development projects.

Following this section, the skeletal modeling approach is first elaborated. A case study is presented for the generation and optimization of designs for an existing HDB project. The result of the case study demonstrates that the parametric schema is able to generate practical solutions that are in alignment with a wide range of constraints applicable to HDB projects. Meanwhile, the variations in position and direction of the skeletal lines also allow the optimization to identify design solutions that outperform existing designs created without the support of an optimization system.

2. Method

2.1. SELECTED PROJECTS

To extract the design logic, we investigate several recent and ongoing housing development projects and select two representative projects for further analysis (Figure 1). These two projects, Tampines GreenGlen and Punggol Northshore Edge, consist of 649 units and 388 units respectively. As displayed in Figure 1, both projects have a parking block building and several tower clusters, each comprising of two to four residential building towers. The towers in each tower cluster are connected by walkways on the ground or air bridges on certain floor levels. In each tower, there can
be two to four units (apartments).

With a clear spatial structure of precinct configurations, these two projects are ideal for the initial implementation of the proposed parametric schema. Furthermore, their similarity to other projects will allow the parametric schema to be future upgraded at a later date to cover more complex precinct configurations. Based on these two projects, we first identify the underlying dependencies of the design elements constituting the precinct configuration and then schematically represent the dependencies as a series of generative steps. Finally, the generative steps are encoded as a multi-stage algorithm and implemented in one integrated parametric model.

2.2. UNDERLYING DEPENDENCIES OF DESIGN ELEMENTS

Based on the two selected projects, a hierarchical dependency among different elements that constitute the precinct design can be identified (Figure 2). First, the parking block plays a critical role in determining the overall precinct configuration in both projects. The parking block functionally connects the exterior city road network to the interior circulation system of the precinct, which, as a result, defines the main entrance of the precinct. Hence, in these two projects, the parking block is always placed along the site boundary where there is an existing road. The block is positioned either parallel or perpendicular to the boundary.

The second-level element defining the precinct configuration is a set of organizational lines that determine the overall spatial structure within the site. These lines connect the parking block and tower clusters and coincide with walkways and air
bridges. These lines also serve as the connection between different adjacent tower clusters as well as the internal link among the buildings in one cluster. Thus, in the proposed parametric schema, these ‘skeletal lines’ are used as the primary organizational device for generating the building layout.

The direction and length of skeletal lines play a decisive role in determining the orientation and density of the residential towers. For the direction, all the skeletal lines are roughly parallel or perpendicular to the edge of the parking block, while the skeletal lines also serve as the axis to create tower clusters. The length of each line defines the number of towers in the cluster (Figure 3). Moreover, skeletal lines can include small turnings, which can help to accommodate more towers or prevent the end tower from being too close or crossing the site boundary of the site.

The last level of elements is tower clusters. In each tower cluster, there can be two to four towers, depending on the length of the skeletal line. In addition, each tower can have two to four apartments, resulting in square towers, L-shaped towers, or slab towers. As shown in Figure 3, the different tower shapes allow for configurations that allow towers to be positioned closer to one another. The solid-void pattern is stable and in relation to the number of towers in the cluster (Figure 4). Moreover, vertical circulations (elevators and fire escape stairs) are shared by the towers in the same cluster. Constrained by the fire evacuation requirements, the number of towers in each cluster is limited to a maximum of four towers.

To summarize the dependent relationship, even though the parking block is the first-level design element, the second-level element of skeletal lines play a more critical role in defining the spatial structure of the precinct.
2.3. GENERATIVE STEPS

Based on the hierarchical dependencies among the design elements, six steps are defined, as shown in Figure 5. The first step generates a rectangle-like parking block at one of the corner points along the site boundary. The second step generates a set of skeletal axes oriented parallel or perpendicular to the two inner edges of the parking block. The third step generates a set of skeletal lines along each skeletal axis. Each skeletal line hosts one cluster of towers. The fourth step adjusts the positions and orientations of the skeletal lines in response to the site boundary. The fifth step subdivides the skeletal lines into smaller segments, where each segment will host one tower. The last step generates tower clusters along each skeletal line. The floor plan of each tower is created according to the pre-defined solid-void pattern.

![Figure 5. Six generative steps](image)

2.4. PARAMETRIC SCHEMA

Based on the generative steps, we encode these steps into a parametric schema with four sub-algorithms. The four algorithms generate 1) the parking block, 2) the skeletal axes, 3) the skeletal lines, and 4) the tower clusters. These four algorithms are executed as a sequence of steps. The output of each algorithm will serve as the input for the next algorithm.

The first algorithm defines the position of the parking block (Figure 5 - Step 1). It uses a position parameter to select one point on the site boundary. This point is then used to generate a rectangle for the parking block (Figure 6). The rectangle is roughly parallel to the occupied segment of the boundary. Additionally, the width and length of the rectangle are self-adjusted to ensure that the area of parking is sufficient for the predefined parking capacity.

![Figure 6. Different parking block positions and the corresponding subdivision of sub-regions](image)
The third algorithm corresponds to the generative steps 3 and 4 in Figure 5. For axes capable of hosting just one tower cluster, a skeletal line with a single segment will be directly created from the axis. For axes capable of hosting more than one tower cluster, the skeletal line is divided into multiple skeletal lines (Figure 5 - step 3). In addition, the length of each skeletal line will be adjusted to satisfy setback and spacing requirements to the site boundary or adjacent skeletal lines. For those skeletal lines close to the boundary, the line orientation will be adjusted to make these lines tend to be more parallel to the boundary (Figure 5 - step 4). Moreover, when a line is too close to the boundary, this line will be moved backward to satisfy a setback requirement.

The last algorithm generates tower clusters. The algorithm first calculates the number of towers in each cluster according to the length of the input skeletal line and then subdivides this line into smaller segments. In most cases, these segments are co-linear if the original skeletal line is parallel or perpendicular to the parking block. For those skeletal lines that have been rotated with respect to the site boundary, each segment will be self-adjusted, and the straight skeletal line will become a segmented line with several turnings (Figure 5 - step 5). After the segments are adjusted, the floor plans of the towers are generated based on each segment (Figure 5 - step 6). The floor plan of the apartment configuration of each tower is determined according to its position in the cluster and the pre-defined solid-void pattern as shown in Figure 4.

Figure 7 illustrates a randomly generated set of precinct configurations using the parametric schema. On the one hand, these designs display high design variability in terms of the building layout configuration, which overcomes the barrack-like layout using over-constrained schemas. On the other hand, the proposed schema effectively eliminates invalid designs, thus facilitating the optimization to focus on searching for high-performing solutions. In contrast, when using under-constrained parametric schemas that arbitrarily place multiple buildings within the boundary, the design solution space can be dominated by invalid designs, including overlapping buildings or layouts that do not meet the setback or spacing requirements. As a result, the optimization can be overwhelmed by the task of identifying legitimate solutions among a vast number of invalid designs (Wang et al., 2018a, 2018b).

3. Case Study

The proposed schema is applied within a case-study optimization, where precinct
configurations are evolved for a housing typology based on the Tampines GreenGlen project. Design solutions are evaluated against three performance metrics: 1) solar irradiation, 2) unobstructed views, and 3) accessibility. It should be stressed that the main focus of this paper is on design generation rather than on design evaluation and optimization. Hence, the purpose of the case study is to demonstrate that the proposed parametric schema can produce designs maintaining the organizational features of the existing residential precinct typology. Hence, the evaluation metrics are simplified.

3.1. EVALUATION METRICS AND CONSTRAINT

The first design objective is to minimize annual solar radiation (ASR) received by the facades of all residential buildings. As Singapore has a tropical climate, lower ASRs mean less solar exposure, which can enhance passive cooling. Second, the accessibility and unobstructed views are included in the optimization to improve residents’ convenience, health, and well-being. Finally, for residential precinct design, land-use efficiency is also important, and designs normally need to be close to the plot ratio defined by the urban design code. For the evaluation, ASR and unobstructed views are simulated using the Ladybug Grasshopper plugin (Roudsari & Pak, 2013), while accessibility and land-use efficiency are assessed by two ad hoc algorithms.

To evaluate the accessibility, we develop an algorithm to create a circulation network that connects all the skeletal lines back to the parking block, which constitutes the entrance to the site (Figure 8). The algorithm generates various additional connection lines between the disconnected skeletal lines. With all skeletal lines connected, the accessibility metric is evaluated by adding up the distance from each tower cluster to the parking block. The optimization objective is to minimize the sum of these distances. In future research, we envisage that the circulation network can include other destinations apart from the parking block, such as bus stops or footbridges, but in the case study, we simplify the system with one destination.

For land-use efficiency, another algorithm is developed to allow the number of floors to be varied for each tower cluster, which further differentiates the design solution by varying building heights. At the same time, the number of floors is constrained to ensure the generated solutions have the gross floor area (GFA) close to the target area defined by the plot ratio. Figure 9 shows a set of randomly generated designs subject to this requirement. In this case study, we set a plot ratio of 2.0 and a height limit of 50 meters (or 16 floors with a 3-meter floor height). As shown, the inclusion of building heights can further differentiate the mutual shading effect and the unobstructed views among different design variants.

Figure 8. Examples of the generation of connection lines between skeletal lines or the parking block

Figure 9. Examples of randomly generated designs subject to a plot ratio of 2.0 and a height limit of 50 meters.
3.2. DESIGN OPTIMIZATION

For evaluating designs, three evaluation metrics are formulated. While it would be possible to apply a multi-objective Pareto optimization approach, previous research has shown that such approaches often undermine the efficiency and effectiveness of the optimization (Wortmann & Fischer, 2020). In this research, the decision was therefore taken to combine these evaluation metrics into a single weighted objective function.

A hybrid algorithm, called Steady-State Island Evolutionary Algorithm (SSIEA) (Wang et al., 2020) is used to evolve the design population. In comparison with other optimization algorithms in Grasshopper, such as Galapagos, EvoMass is embedded with an island-based model that divides the population into multiple subpopulations, and, thereby, the search of each subpopulation is guided to focus on a different region in the design space. By focusing the optimization on different regions, SSIEA is capable of providing optimization results with a variety of solutions and avoids the optimization ending up with a family of homogeneous designs.

4. Result

The SSIEA was used to run the optimization process. In SSIEA, five islands (subpopulation) were defined, each with a population of 30 design variants. A total of 2100 designs were evolved. In the final design population, we select four high-performing design options, each with a distinct building layout configuration. Figure 10 shows these selected options from the optimization result as well as the existing configuration for comparison.

By comparing each of the options based on the three metrics of evaluation, different strengths can be identified. The first two options show similar performance, while the parking block is located at two entirely different positions. For the third option, it outperforms the first two in terms of unobstructed views but comes with a downside of higher solar exposure, as indicated by ASR. The fourth option is inferior to the first two options. In comparison to the third option, although it has lower solar exposure, the corresponding accessibility and unobstructed views are inferior. Lastly, all four options have a GFA that is closely similar to that of the existing one. With different advantages and disadvantages, the four options offer different alternative trade-off solutions.
associated with the three objectives, which provides designers with room for choice in early-stage decision-making.

![Figure 10. Optimization result.](image)

To further validate the proposed parametric schema and the utility of the design optimization, we also created an additional design based on the existing building layout configuration (the last one in Figure 10). In comparison, the existing design has higher solar exposure than the evolved designs, and its accessibility is also worse than most designs except for option 4. In addition, option 3 outperforms the existing design in all aspects, while it is noticeable that the layouts of option 3 and the existing design are similar. In contrast, the existing design offers a better view than options 1, 2, and 4 and surpasses option 4 in terms of accessibility. The comparison highlights that the existing design already incorporates a building layout with relatively competitive performance. Nevertheless, the optimization approach is still able to discover alternative high-performing design options.

5. Discussion and Conclusion

As the study demonstrates, the skeletal parametric schema provides a viable method to generate building layout configurations for residential precinct projects. The wide variation of skeletal line configurations offers sufficient variability and diversity, while the organizational arrangement of buildings also maintains a desirable spatial order. In comparison to other existing parametric schemas for building layout configuration generation, the proposed parametric schema avoids generating invalid design variants without having to resort to over-constraining the layout configurations.

From the practical perspective, the study highlights that the skeletal parametric schema can generate designs that are typologically consistent with the existing projects. In other words, the proposed parametric schema is able to capture the design knowledge derived from existing projects. Hence, it enables the computer to generate human-like designs in an automated way. The optimization algorithm then enables a rapid assessment of the performative potential of the selected housing typology. Such optimization-based design exploration can free the designers from the tedious trial-and-error design processes of manually seeking desirable design solutions, which, in turn, also reduces human errors and bias. As such, the designers will be able to devote more time and effort to design ideation and conceptualizing innovative solutions to challenge
the computed optima.

To conclude, the paper presents a skeletal parametric schema based on a Singapore public housing project. The parametric schema can be incorporated into design optimization processes to provide rapid feedback and meaningful design solutions. By offering practical examples, the optimization, on the one hand, can be directly applied in future projects to help reduce the time and effort spent on routine design tasks. On the other hand, the optimization results can become a benchmark for decision-making. It enables designers and other stakeholders to evaluate design proposals in comparison to evolved solutions based on existing housing typologies. Future research directions include testing the parametric schema with other public housing projects and further developing strategies for refining performance metrics to guide the optimization process to produce more balanced designs. In addition, more detailed design elements, such as apartment types and circulation cores will be further embedded into the schema, which can allow for a more thorough design evaluation.

References


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