PROGRESSIVE MODELLING FOR PARAMETRIC DESIGN OPTIMIZATION

An Example of How Parametric Design Optimization Can Support Reflection

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Abstract. The use of parametric design optimization should not be merely a solution for design challenges, rather, a medium of reflection. The research explores how to conceive feasible design schemas and formulate appropriate parametric models capable of fully exploiting potential performance improvements through an iteratively reflective design synthesis with parametric design optimization. Taking a courtyard design as a case study, the paper describes three alternative parametric models for natural lighting optimization. A comparative analysis of the populations is presented, showing that the alternative parametric modelling approaches have a progressive positive impact on the quality of design performance.

Keywords. Design optimization; parametric modelling; reflective conversation; courtyard; natural lighting.

1. Introduction

Parametric design optimization based on heuristic search techniques such as evolutionary algorithms has attracted much interest from architects for pursuing performative design. By defining parametric models for the building design and evaluative models for the building performance, designers are able to use optimization algorithms to explore a large number of design variants and identify solutions that best achieve a set of requirements or for improving an existing design. However, when parametric models are inappropriate, design optimization can become ineffective in improving design quality.

The parametric modelling approach taken by a designer will typically start with a design schema. The schema defines a set of design objectives and a design strategy that the designer believes can meet the objectives. Parametric modelling can be considered a process of transferring the design strategy into a parametric model. The process requires the strategy to be decomposed into parts with a set of constraints defining the associative relationship among these parts. Thus, a parametric model attempts to capture the design strategy by defining the design

Intelligent & Informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Volume 1, 383-392.

space to be explored, often containing infinite or near-infinite design alternatives (Woodbury and Burrow, 2006). Being constrained, the design space only includes a particular set of design alternatives from all possible design solutions.

The design schema and the associated design strategy are often inherited from designers' personal experience. The initial parametric modelling approach can therefore be quite subjective. This subjectivity can result in biases that favour certain design alternatives while discriminating the rest (Figure 1). This may result in the most optimal design solutions being excluded from the design space for optimization. This issue is highlighted by Rittel & Webber as follows: *"setting up and constraining the solution space and constructing the measure of performance is ... likely ... more essential than the remaining steps of searching for a solution..."* (Rittel & Webber, 1973).

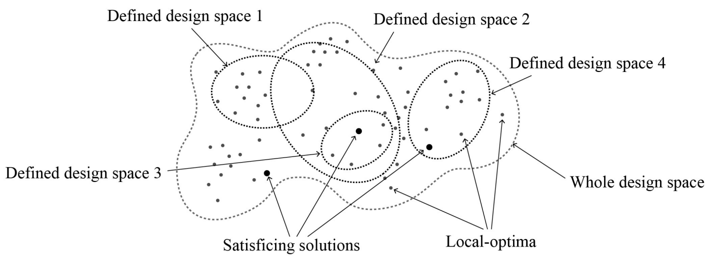


Figure 1. The relationship between the whole design space and constrained design spaces.

A weak or flawed design strategy will result in an inappropriate search space. However, even in such a search space, the design optimization process will most likely still discover improved design alternatives. A key problem is that the progress made by the optimization process will often give the designer a false sense of confidence with regards to the actual quality of the designs being evolved. From this point of view, we highlight the importance of developing appropriate parametric modelling approaches. Designers should become more adept at critiquing the design schemas and design strategies underpinning their parametric models and design optimization processes. Such a process of critical reflection can be part of the broader process of "reflective practice" (Schon, 1992).

2. From Schema to Parametric Modelling

Although parametric modelling can enable the creation of complex architectural forms, many designers are still strongly influenced by traditional paper-based design approaches when formulating their parametric models. One example is 3D parametric modelling approaches that are inadvertently based on 2D conceptual thinking. Such thinking is deeply rooted in the architectural design process, where building geometry is habitually defined by floor plans and floor height. Such parametric models are often unable to generate design variants that fully exploit potential performance improvements. Even when changes in the parameters result in significant changes in the building design, the impact of such changes on building performance may still be limited. For example, changes in a plan of a building may have a relatively limited impact on its ability to control the trade-off between solar irradiation or natural lighting. As the result, using an appropriate design schema and corresponding parametric modelling approaches is critical to achieving an effective design optimization process.

However, the wickedness of design problems makes it difficult to come up with feasible design strategies that are well suited to the performative objectives of the design task. In order to find a feasible design strategy or refine the current strategy, the design process is essentially a learning process through a series of moving-seeing-moving actions (Schon, 1992). In the past, designers could only manually generate and test a small number of design alternatives. This reflective process was constrained by the designers' human cognitive limitations, and as a result, the learning process was often inefficient, subjective, and inadequate. The use of parametric design optimization has the potential to accelerate and amplify this learning process.

The designer, with the help of design optimization, should be able to efficiently and effectively identify the weakness of the adopted design strategy in exploiting the potential improvement of performance and then conceive better strategies to overcome the weakness. As such, design optimization approaches, as Wortmann (2018) has argued, go beyond the technical solution for the design problems and become a "medium of reflection". This paper investigates this proposition and gives an example of such a reflection process through a series of parametric models for a courtyard design. With the case study, a progression of design schemas and their associated parametric modelling approaches are presented. This progression of schemas and approaches is driven by the overall aim of discovering ways of improving the performance objectives defined in the case study.

3. Case Study

The case-study focuses on the design of a quadrilateral courtyard space within a fixed low-rise building mass. Courtyards are widely applied in architectural designs to improve indoor lighting quality by allowing more natural light to reach the inner part of the building. Nevertheless, the performance of the courtyard can be weakened by problematic designs. The case-study demonstrates the progression of parametric modelling approaches and their impact on the quality of architectural design optimization process.

The size, proportion, and shape of the courtyard are commonly considered as the important factors influencing lighting performance (Muhaisen & Gadi, 2006). As the result, a designer may follow this idea to formulate a simple parametric model to generate alternative courtyard designs based on a parametrically defined 2D shape in plan. However, the improvement of natural lighting through optimization based on such a 2D-based approach may be limited due to the fact that changes in shape or proportion in plan cannot address challenges related to the courtyard section. These challenges include allowing more natural light to penetrate down to the lower floors and reducing the mutual shading among courtyard facades.

The challenge of natural lighting can be a "performative" factor driving the progressive transition from one design schema to the next. As an example of such progressive transitions, a sequence of three alternative parametric approaches is presented. The three parametric models are respectively referred to as the *plan-based model*, the *facade-based model*, and the *vertex-based model*. These names reflect the parametric modelling approaches used for the creation of the courtyard (Figure 2). These modelling approaches view the courtyard in conceptually different ways. In each case, the later design schema was conceived by considering the weakness of the earlier design schema. In each case, design optimization played a significant role in revealing these weaknesses. For example, for the plan-based model, the generated design alternatives all had similar natural lighting performance. Even when plan shapes differed significantly, the indoor area with sufficient natural daylighting remained relatively constant.

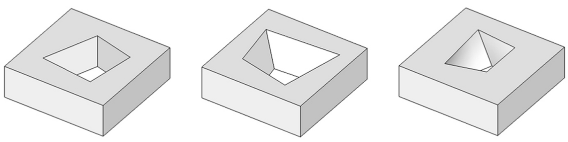


Figure 2. Examples generated by the three parametric models.

The fixed building mass consisted of a square building, 50m x 50m and an overall height of 16m, consisting of equal-height floors. The quadrilateral courtyard is to be inserted into the centre of this building mass. The objective is to find the courtyard design that maximizes the naturally daylit indoor floor area and minimizes the loss of floor area due to the insertion of the courtyard. In other words, the optimization process must search for courtyards that let in as much daylight as possible, but that are also as small as possible.

The fitness evaluation of the generated design alternatives considers both the floor area and natural lighting performance. For floor area, the target gross area of the building is set as 8,500m^2. Therefore, if the overall loss of floor area due to the courtyard is 1,500m^2, then no fitness penalty will be applied. (The total area of the building without courtyard is 10,000m^2.) For courtyards that reduce the floor area by more than 1,500 m^2 will have penalties applied.

For natural lighting performance, Spatial Daylight Autonomy (sDA) is taken as the performance indicator. The sDA fitness evaluation calculates the percentage of floor area that receives at least 300 Lux for at least 50% of the annual occupied hours (Sterner C., 2014). In addition, in order to focus on the effect of the courtyard on natural lighting, only the courtyard facades are defined as transparent and all outer facades of the building are opaque. This means that only light received from the courtyard is taken into account. The remainder of this section describes the three models and analyse the advantages and disadvantages of each of the models.

3.1. PLAN-BASED MODEL

The plan-based model (Model A) defines the courtyard volume principally by its plan layout, which is controlled by the positions of the four corner points. In order to make the courtyard have a reasonable shape and size, the four corner points are only allowed to move within one of four 10 by 10 meters squares on the plan (Figure 3). In addition, the movement is discretised into one-meter steps, thus each corner point has 121 $(11 \cdot 11)$ possible positions.

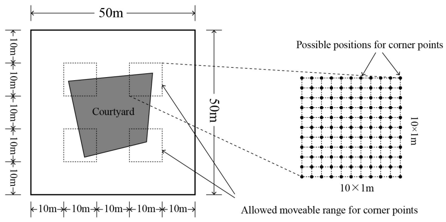


Figure 3. Possible positions of the four corner points.

This model is simple and straightforward. The most significant advantage of the model is that the design space defined is relatively small, which is $121^4 \approx 2.14 \cdot 10^8$. However, the disadvantage of the model is also obvious. Since the courtyard facades are extruded from the plan layout, only facade orientation can be changed, while facade inclination remains constant. As the result, for maximizing natural light, larger courtyards would be required.

3.2. FACADE-BASED MODEL

In order to allow the courtyard cross-sectional profile to also vary, the second model (Model B) uses a facade-based approach to define the volume of the courtyard. The approach decomposes the courtyard volume into four planar facades. Each facade can be rotated horizontally and vertically and moved alongside with x/y axis (Figure 4). The approach permits the vertical inclination angle of the facades to be changed so as to vary the cross-sectional profile. As the result, the courtyard volume has greater geometric freedom, which allows the courtyard to catch much natural light, especially for the lower floors. Compared with the next model, this model also has a significant advantage that the facades are planar and therefore relatively straightforward to construct. This would likely improve the economic feasibility of the designs.

The use of the facade-based approach results in a significant increase in the size of the design space. For each facade, the ranges of two rotation direction are all 30 degrees, which can be changed in a 1-degree step. The facade is also allowed to move horizontally in a 10-meter range (in 1-meter step). Therefore, the size of the design space is $(31 \cdot 31 \cdot 11)^4 \approx 1.2487 \cdot 10^{16}$, which results in a greater search difficulty for the optimization process.

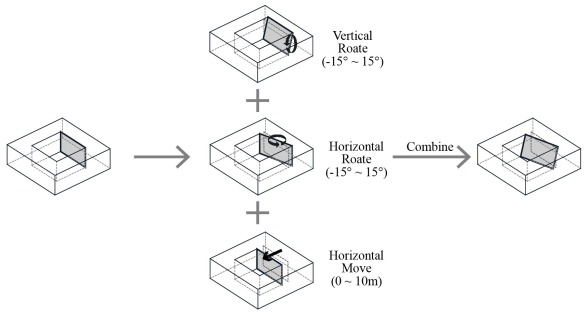


Figure 4. The generative procedures of the facade-based model.

An analysis of the generated design alternatives revealed that a weakness of using the facade-based approach was not able to respond flexibly to the different conditions of light and shade. The planarity of the facades meant that the model was not able to control the trade-off between, on the one hand, receiving more natural daylight and, on the other hand, avoiding being shaded. In light of this, further geometric freedoms in defining the courtyard volume were introduced.

3.3. VERTEX-BASED MODEL

The vertex-based model (Model C) treats the volume of the courtyard as a spatial entity. In essence, the volume of the courtyard is a hexahedron, thus it can be defined by the eight vertices. In this model, each vertex is allowed to move within a predefined area, similar to Model A. However, in this case, the lower vertices on the ground and upper vertices on the roof can move independently from one another. By moving these vertices, rich diverse courtyard volumes with twisted-surface facades can be generated. The twisted facades can be more effective in allowing natural daylight while also avoiding shade. In addition, from the architectural point of view, they are also able to create a more expressive space for the courtyard.

Using Model C comes with two major disadvantages. First, the twisted facade will be more difficult and expensive to construct. Second, the design space is further enlarged. The size of the design space is $121^8 \approx 4.5949 \cdot 10^{16}$, which is almost 4 times as big as that of Model B. In consideration of the disadvantages, it is necessary to evaluate whether the benefits of using Model C can offset the price of lower constructability and larger design space.

3.4. SUMMARY

The above three parametric models illustrate a progression of design schemas and parametric modelling approaches. However, it should be noted that the three models were not conceived at the same time, and the actual chronological order was also different. Model A and the Model C were based on two Masters research theses at the School of Architecture and Urban Planning at Nanjing University completed in 2015 and 2017. Model B was the last to be conceived, taking into account the design space size, constructability and economic feasibility, which were overlooked in Model C.

4. Result

The three parametric models were used to evolve populations of optimised designs. For running the evolutionary algorithms, the Galapagos component within the Rhino-Grasshopper platform was used.

For the evolutionary runs, the population size was set to 100 with an initial population (initial boost) of 200 individuals. In order to avoid the premature convergence, a higher mutation rate and a lower selection pressure were used (5% for *maintain* and 50% for *inbreeding*). The maximum number of generations was set to 60, and the maximum number of stagnant generations was set to 20. As a result, for each evolutionary run, there was a maximum of 6200 births.

For the performance evaluation, sDA (Spatial Daylight Autonomy) was simulated using DIVA (Jakubiec & Reinhart, 2011) based on the weather data of Nanjing, China. In order to ensure that the evolutionary process can be completed within a reasonable timeframe, the lowest quality settings were used. This resulted in each simulation taking 1 to 2 minutes, varying with the number of analysis grids. The overall running time for one evolutionary run with 6200 births took around 4 days.

A single-objective mode was used in the evolutionary design. The evaluation function multiplies the index value of sDA with a 0-to-1 coefficient, defined by how close the floor area of the design variant is to the target value (8500 square meters). The coefficient decreases exponentially with the decrease in the floor areas. Hence, the fitness of designs alternatives with lower floor areas is penalized more heavily. With this evaluation function, the evolutionary process is forced to search for design variants with floor areas close to the target value.

4.1. EVOLUTIONARY RUN

Figure 5 shows the fitness progress trendlines of the evolutionary process based on the three alternative parametric models. During each search process, the best two solutions found over time were recorded. The reason for recording the best two is that focusing only on the best solution can conceal the overall progress of the whole population. By recording the best two solutions, the improvement of the population is more clearly.

Among the three evolutionary processes, only the one based on Model A reached the stagnation threshold and was stopped at 25 generations. The fast convergence of the evolutionary process might result from the smaller design search space where a feasible design subspace and local optima are relatively easy to identify. However, the poorer fitness of the evolutionary result indicates that Model A can only provide a limited improvement on natural lighting.

In contrast, due to the larger design search space, the evolutionary processes based on the other two models were much longer. The two processes did not reach the stagnation threshold and all run through 60 generations. Despite the increase of time in evolutionary processes, the evolutionary results were significantly improved by the change of parametric modelling approaches. In comparison, the fitness improvement of Model C across the evolutionary process is more significant than that achieved by Model B. This confirmed that Model C, as expected, is more effective in exploiting better courtyard shapes to maximize natural lighting than Model B.

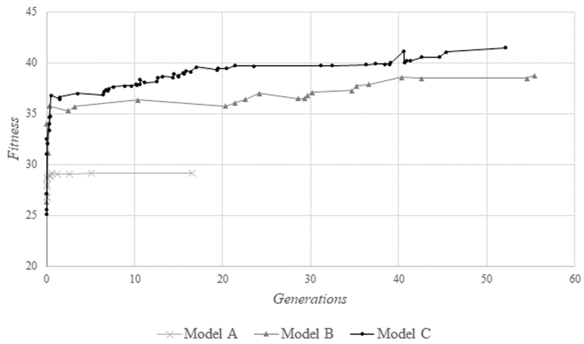


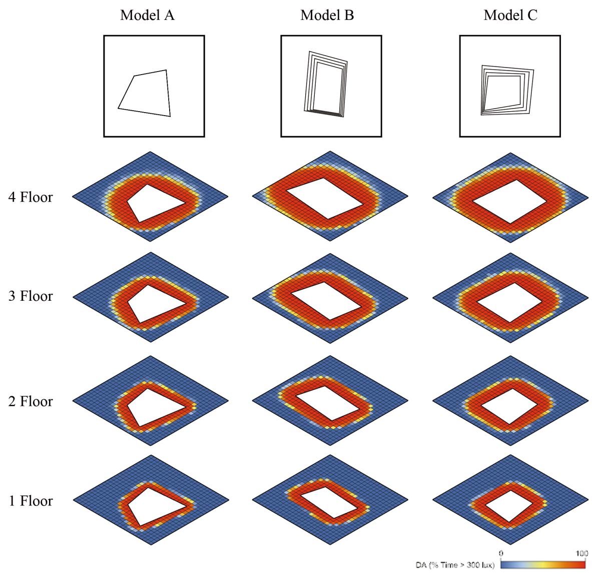
Figure 5. The fitness progress trendlines of the evolutionary processes.

4.2. OPTIMIZATION RESULTS

Figure 6 presents the best design alternatives found by the three evolutionary processes. Guided by the evaluation function, all three evolutionary processes ended up with a design variant with a similar floor area, a little bit smaller than the target value. This means that the volumes of the courtyards are similar and allows a meaningful comparison of the effectiveness of each model in exploiting natural lighting performance. Two features can be identified, accounting for the difference in natural lighting performance among the three designs.

In the first place, the inclined or twisted facade effectively enlarge the fully natural lit area (100% sDA), especially for the lower floor. For the design found across the evolutionary process of Model B and Model C, the width of the fully natural lit area on the ground floor is approximately double of that in the design found with Model A. Likewise, for the top floor, the fully natural lit area covers a markedly larger proportion of the indoor space of the design from Model B and Model C than that from Model A.

Second, as the form of the courtyard volume is increasingly liberated with the change in parametric modelling approaches, the designs have become more effective in controlling the trade-off between the loss of floor area and the improvement of natural lighting. It is clear that the natural daylight can reach deeper areas on the upper floors. Thus, the designs found by Model B and Model C tend to have a longer courtyard perimeter on the upper floors. The lengthened perimeter of the courtyard surface amplifies the advantage of the upper floor in receiving natural light. In reverse, the courtyard becomes smaller on the lower floors in order to offset the floor area lost on the upper floors, which also comes along with another advantage that the area with poor natural lighting is decreased.



	Model A	Model B	Model C
Fitness	29.1624	38.7197	41.4890
sDA(%)	30.3	41.2	43.1
Area(m2)	8356.00	8316.59	8356.31

Figure 6. The daylight analysis based on the resulting designs.

5. Discussion

The progression of parametric modelling approaches results in marked performance improvement of the optimization result. The optimization results reveal that Model A is significantly inferior to the other two models and, therefore, is not feasible for use for improving natural daylighting performance. However, the performance difference between Model B and Model C is relatively trivial. Hence, when using Model C, it is necessary to consider the advantages and disadvantages of the twisted facades. These considerations need to take into account the broader requirements of the project. When economic feasibility is the priority for the project, the extra marginal improvement achieved by Model C may become problematic. In this regard, the superiority of Model C is not absolute.

Another important finding uncovered by the optimization results is that the fitness distribution of the initial population approximately corresponds to the fitness value of the final evolutionary result. The fitness of the best individual found in the initial population of each Model is respectively: 29.1 (Model A), 35.7 (Model B), and 36.8 (Model C), while the corresponding fitness of final results is 29.1, 38.7, and 41.5. Since the initial population is a random sampling within the design space, this suggests that a random sampling survey can be a useful indicator for one to predict the result and compare the performance among different parametric models. Therefore, in real-world design scenarios, it is unnecessary for designers to run all parametric models for optimization, which may be impossible within typical design processes with tight schedules. Instead, designers can select a promising parametric model using random sampling and then run the evolutionary optimization process with only the selected model.

6. Conclusion

This paper explores the impact of design schemas and parametric modelling approaches on the quality of the design optimization. The result of the optimization process confirms Rittel's concern: that the definition of the design search space may be more decisive than the optimization process itself (Rittel & Webber, 1973). As optimization techniques become more accessible to practitioners, the conscious and reflective application of these techniques becomes ever more important. The case study example aims to shed light on how such reflective design optimisation processes might unfold.

The synthesis process of the three parametric models can be considered a "reflective conversation" between the designer and the parametric design optimization process. The process is strongly performance-oriented, where the performance of natural lighting plays a key role in driving the progression of parametric modelling approaches. The results of the optimization process can act as the catalyst for the designer to synthesize modified design schemas that are more appropriate to the performance objectives. In light of this, it is important that performative design research should not focus only on the algorithms themselves, but should also consider how such algorithms can contribute to the reflective conversation. With design optimization process, the final optimised design alternatives should be seen as a starting point for designers to launch explorations that are more likely to lead to the step changes required to achieve the best possible performance.

Acknowledgements

This paper was supported by the National Natural Science Foundation of China (51378248) and the China Scholarship Council (201706190203).

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