BUILDING MASSING OPTIMISATION IN EARLY DESIGN STAGE

A Performance-Driven Design Based on Total Sunlight Hours Evaluation

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Abstract. This paper proposes a performance-driven design workflow based on Total Sunlight Hours evaluation. The objective is to investigate an optimal solution of a building massing design meeting solar radiation criteria as early as in the conceptual design stage. In our paper, such a process is demonstrated through a case study on an Experimental Social Housing project. We illustrate how design constraints are encoded with the evaluation criterion, Total Sunlight Hours (TSH), through an integrated computational workflow. Alongside with such a computation-intensive process, we also experimented with the same design project using a conventional design approach. The advantages and disadvantages of using a performance-driven computational workflow over a conventional design process are discussed and presented. In particular, we examine how a performance-driven design workflow can be integrated within the iterative design process and how human designers interact with computation to investigate optimal design solutions.

Keywords. Performance-driven design; environmentally-conscious; parametric modelling; building massing optimisation; daylight performance evaluation

1. Introduction

Using optimisation to explore building design alternatives has been demonstrated since decades ago, e.g. optimising construction costs and building envelopes (Caldas and Norford, 2003; Radford and Gero, 1987). This paper shares the same interest in adopting an optimisation approach yet with a fo-
focus on the cohesion of computation and human interventions within the iterative design process. Central to this paper is to investigate solar impacts on buildings during the early conceptual design stage. This is, in particular, challenging to evaluate with limited information given at this early design stage using a conventional architectural design approach. Whereas simulation technology has made such environmental analysis possible, the extent to which the potential benefits can be gained is yet to be explored (Shi, 2010). For instance, to incorporate solar access analysis could facilitate nature daylight design and gain benefits, e.g. reduction in costs/energy for artificial lighting. Kim et al (2011) and Granadeiro et al (2013) expressed the same interest to introduce performance simulation in early design stage.

It is of great interest to building scientists and engineers to advance technology that better facilitates building performance simulation and evaluation (Zhou et al, 2011; Greenberg et al, 2013). However, for most designers and architects, understanding how buildings perform while facing the environmental challenges is essential. Technology serves as the basis to investigate viable environmental design solutions (Roudsari and Park, 2013). Despite the advancement in building simulation technology, there are currently very limited applications regarding how such technology can be applied at various scales during the design process (Chung et al, 2011; Park et al, 2012; Tang et al, 2012). As such, we propose to investigate the integration of building performance metrics into the development of design concepts and environmental strategies. We examine solar radiation performance as an active design actuator rather than a post design indicator. Particularly, we look at how performance evaluation can be synthesised with human interventions to improve the machine-controlled optimisation process.

A conventional design approach is mostly undertaken through a linear process, starting from ideation, development to evaluation. Among this process, post-design evaluation is often carried out too late and provides very limited flexibility for designers to improve their design with the simulation results. Through integrating performance into the early conceptual design phase, our intention is to ensure the building design is on the right trajectory from the outset and moves toward a desired environment-friendly solution.

1.1. CASE STUDY AND BACKGROUND

The chosen case study is an Experimental Social Housing project in Medellin Colombia, where the altitude is around 5,000 ft (1,500 m) above sea level and the city’s average annual temperature is 22 °C (72 °F). Because of its proximity to the equator, its temperature is constant year round, with minimal temperature variations. The project site is surrounded by complex
neighbouring buildings, with their heights varying from around 5 to 30 metres, as shown in Figure 1.

For most sites located in the Northern Hemisphere, the worst solar condition basically falls on the day of winter solstice. In this project, we have chosen time period, 10:00-15:00, for the preliminary site shadow analysis. Figure 1 shows the predominant influence caused by the buildings next to the south of the site.

![Figure 1. Site sun path illustration on the day of winter solstice](image)

The housing project aims to accommodate a variety of single-to-multiple housing types based on a modular unit (8m Length x 4m Width x 3m Height). We propose three modular units with various configurations, some of which were shown in Figure 2. The proposed design solution aims to provide 240~250 modular cells, equivalent to 100 modular units (10xA, 30xB, and 10xC) with communal spaces in-between. Based on preliminary calculation, a three-storey proposal is chosen; as it can provide required modular cells while keeping the minimum building height.

![Figure 2. Illustration of unit types formation](image)
2. Performance-driven design process

The performance-driven design process is structured with following three stages: (1) Ground unit cell layout configuration; (2) Building massing formation; (3) Housing unit allocation. The workflow diagram, shown in Figure 3, illustrates the evaluation results used at three stages. The first stage results provide indicative feedback to formulate the ground cells layout. During the second stage, the evaluation results further inform building massing generation while investigating optimal TSH performance. The third stage involves unit allocation with human intervention.

During the generative process, Genetic Algorithm (Michell, 1999) is chosen for massing optimisation with maximal natural lighting. A variety of tools, including parametric modelling, daylight simulation, and data analysis software packages, are integrated at various stages throughout the proposed performance-driven design process. Aiming at maximizing the building’s solar gain for better natural lighting, the fitness function is defined as the Total Sunlight Hours (TSH). For the demonstration purpose, we choose Ecotect for the TSH calculation.

Figure 3. Entire performance-driven design workflow

2.1. GROUND UNIT CELL LAYOUT CONFIGURATION

The first design stage starts from architectural element definitions, including (1) the predominant shadow from the south neighbouring buildings, (2) a frontage setback from the main road to shape a civic plaza, (3) two inner courtyards and the respective rotation angles, and (4) two circulations pass-
ing through the site. These elements are provided to meet public space requirements detailed in the project brief.

As shown in Figure 4, two courtyard rotation angles are flexible among four orientations, and the positions of two entrances are flexible among five options. These architectural elements are defined as design constraints while generating ground unit cells.

As the site is located in the Northern Hemisphere, southeast and southwest exterior surfaces are defined as indicative surfaces, as shown in Figure 4. During the evaluation process, variations of the courtyard rotation angles and entrance positions are evaluated against the summation of TSH values using Galapagos—a genetic algorithm solver provided by Grasshopper3D. The top three candidates with best TSH fitness values are chosen for further design development, as shown in Figure 5.

2.2. BUILDING MASSING FORMATION

On the basis of ground cells layout, the second stage initiates from the ground level refinement, which consists of following steps: (1) randomly reducing to 120 cells in total, (2) filling up unexpected voids, (3) removing isolated and neighbour-less cells. The objective is to refine the ground level configuration that could sustain the necessary housing unit cells. Randomisa-
tion is used to generate sample cells, which will act as the initial genomes for the genetic algorithm.

Among three steps mentioned above, identification of the void and isolated cells involves detecting local neighbouring relationships. We encoded connectivity constraints using Cellular Automata, which examines the unit cell fitness at a local neighbourhood scale. In Figure 6, each number represents the connectivity state of a cell in its local neighbourhood. For instance, an isolated cell is the one shaded in grey with zero neighbour cells, as shown on the left of Figure 6. The neighbour-less cells are those without directly connected neighbours, sharing the same boundary edges. These analytical outcomes serve as the basis to inform the generation of unit cells for first and second floors accordingly. Figure 7 illustrates a sample evolution from the ground level configuration to the massing formation.

Once ground cells were determined, this configuration will be used as the basis to generate the first level layout. The number of cells at the first level is constrained to be two thirds of the ground level. This aims to provide void spaces in-between cells to ensure better solar access. The second level cells are then generated on the basis of the first level. Similar to the ground level refinement, this process consists of following steps: (1) randomly reducing to 40 cells in total, (2) removing the isolated and neighbour-less cells. For each stages stated above, we carry out the TSH fitness evaluation to examine
cells propagated at each level. In total, 15 candidate configurations were chosen from the initial three strands of the ground level layout. Figure 8 illustrates the initial massing configuration with south-facing surfaces.

![Figure 8](image)

**Figure 8. (Left) Initial massing configuration; (Right) South-facing indicative surfaces**

During the second stage evaluation, the fitness function of the solar access optimisation is defined by combining the average TSH value (per indicative surface) with areas of indicative surfaces that have less than one hour TSH. The former constraint reflects the overall performance of indicative surfaces, while the latter represents cells not suitable for residential allocation.

### 2.3. HOUSING UNIT ALLOCATION AND ADJUSTMENT

![Figure 9](image)

**Figure 9. Unit cell connectivity analysis. (Left) Planar cell connectivity analysis; (Right) Axonometric cell connectivity analysis**

Unit cell connectivity is analysed among cells at each storey horizontally and vertically. Figure 9 visualises the analysis in a 2D planar configuration on the left and a 3D axonometric fashion on the right. These connectivity patterns serve as the foundation for housing unit allocation. For instance, unit cells that form an enclosed space can be allocated as a regular unit B, or unit C, where four or more adjacent cells are required. Alternatively, a zigzag cluster can fit a variant unit B. Figure 10 illustrates the housing allocation using various unit types, A, B and C.

During the process, the third stage involves manual adjustment, which is carried out interactively with the unit cell connectivity analysis; for instance, removing a superfluous cell or adding an extra one where appropriate while minimizing its influence to others regarding natural lighting.
3. Results

To compare conventional and computer-aided design processes, the first design proposal was conducted using conventional media. This preliminary study has helped a better understanding of the programming of the project and contributes to the computational principles implemented in this paper. Figure 11 illustrates the original proposal achieved via the conventional design process.

With the proposed refinement through encoding design constraints into generative procedures, we further analyse the differences between original design and computer-aided design alternatives. As shown in Figure 12, we illustrate the performance of the original design and chosen candidates, and how the optimal solution, B4, is further improved after manual adjustment. The TSH fitness value of B4 is improved from 3.363h to 3.405h, and indicative surfaces that have less than one hour TSH decrease from three to only one (B4'). Figure 13 shows the comparison of the solar access performance using TSH for both manual design and computer-generated alternatives.

In brief, the manual design proposal, which appears at the top left corner in Figure 12, shows a poor solar access performance and thus a lower TSH fitness value. The final proposed B4' outperforms the conventional design by
10.9% in terms of the TSH fitness value and demonstrates the positive impact of integrating performance evaluation into the early design stage.

Figure 12. Scatterplot of the top 15 solutions, including the adjusted optimal result and the manual design

Figure 13. TSH evaluation comparison among the manual design, the optimal solution and the adjusted massing result

4. Conclusion

In this paper, we present a computational workflow that consists of multi-stage optimisation. The objective is to examine a performance-driven design process and its potential influence on architectural design at an early design stage. We choose Total Sunlight Hours (TSH) evaluation as the main performance criterion and demonstrate how this constraint can be evaluated at various design phases throughout the case study development.

During the evaluation, TSH serves as a key indicator of the solar access performance. Through encoding this constraint with computable procedures, we automate the unit cell configuration while ensuring the anticipated solar access performance is maximised. Whereas in a conventional design process, such analysis are usually carried out after design solution was presented and by the time, the solar performance can only be provided as one of the design outcomes. In this paper, we demonstrate how performance evaluation can be integrated into an iterative design process during the early design stage and
showcase how such a performance-driven design process can be implemented in architectural practice.

Figure 14 illustrates the housing proposal derived from the performance-driven design process. This result exemplifies the potentials of the hybrid mode of digital and conventional design process, where computation and human interventions were harmonised to produce the satisfied optimal solution.

Figure 14. Unit allocation layout by floor

References


