Performance-Based Design:

From Form Making to Form Finding

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.

Extended Abstract

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1 Introduction

Since the invention of the profession, architecture has been through several changes[1]. It started off as a craftsmanship and then changed to a more intellectual activity. In recent years, we have been observing the emergence of CAD (Computer-Aided Design) tools and, with them, both parametric and building analysis tools. The parametric tools allowed the discovery of new shapes and non-euclidean geometry[2]. As for the analysis tools, they are a reflection of concerns about building performance. The combination of parametric design, analysis tools, and optimization processes can potentially lead architecture to a new phase.

Since parametric tools allow the designer not only to achieve new forms, but also making faster changes in the design, the combination of analysis tools and parametric tools allow us to test different designs rapidly. However, the usage of optimization methods could potentially allow designers to not only find more results but find better results.

The use of optimization processes means the use of both parametric model and analysis tools in an automated way. For this to happen, the parametric model needs to be connected to the analysis tools, and the versions of the design should be sorted and ranked by an optimization algorithm.

This approach requires the designer to be aware of not only the conceptual and aesthetic premises of the design, but also which factors influence the performance of the various criteria that require analysis. The result of this approach is Performance-based Design [3]. Performance-based Design, as the name suggests, is when a building is designed to meet specific requirements in regards to environmental impact, structural performance, and energy consumption, amongst others. Designing according to these requirements is what results in *form finding* over the traditional process of *form making*[4].

The research purpose of this thesis is to find a mechanism to generate design options, that will be combined with optimization processes to inform and support the choice of an optimal design.

2 Background

2.1 Importance of Parametric Tools

The need to have means of representation in architecture was originated in the renaissance period. It was during this time that architecture developed as an intellectual profession that was distinctly separate from craftsmanship. The social consequences of this change in the information flow was that only those who could read, namely the most wealthy and intellectual layers of society, were the ones that could be allowed to practice the profession. In order to study and understand buildings, architects started using technical drawings, plans, elevations, sections, and scale models [1].

It could be argued that architecture is presently going through another transition phase. With the transition of architecture to a digital environment, and the implicit change of support, the process of architectural thinking is evolving yet again[3], namely with the Computer-Aided Design tools. CAD tools helped to develop the architectural drawings more rapidly as well as building 3D computational models. Nevertheless, when using CAD tools a simple change in the 3D model can cause some disruptions and, sometimes, require a rebuild. By parametrizing certain parts or elements of the model these changes become effortless. The parametric design works by using declared parameters to generate a form, turning it into the main design exploration method [5].

2.2 Building's Performance

Engineers and architects developed metrics and formulas to evaluate the performance of a building. These formulas not only feature structural calculations, but also thermal performance, humidity, acoustics, among others. These calculations are very extensive and most of them need the additional information contained in auxiliary documents. This information regards thermal coefficient and reflectance, associated with certain materials, regional climate, and others.

These calculations are now embedded in software tools, that by reading the 3D model, with the addition of material and location, save a considerable amount of time when analyzing the building's performance.

By combining the analysis with the parametric tools, it is possible to rapidly change the design and look for performance improvements. Nevertheless, the number of options that the designer is willing or has time to try is limited, and finding the best performance is not always a trivial process. Using an optimization algorithm it would be possible to search through the possible solutions and find the best one.

2.3 Optimization

Optimization can be defined, from a mathematical, computational, and operations research point of view, as the best option from a set of different solutions, according to a certain criteria/criterion. This solutions can be found using mathematical methods that can be calculus-based, as developed by Nemat and Lagrange, or iterative methods, as developed by Newton and Gauss.

In an architectural context, in order to do an optimization process, a parametric model is required. The reason for this is because the parametric model can process different ranges of values or information, and re-shape the model according to it.

Since the terms to describe an optimization in this context are not well defined in the literature, for a better understanding of this document, there is a list of definitions bellow.

Independent Variables. As the name suggests, these are the parts of the design that can be changed. The different values of the variables of the design will produce different design results.

Dependent Variables. These are variables that are not directly modified, but they vary because they are linked to the independent variables.

Objectives. The objectives are what is intended to be optimized. Usually, these objectives are translated into *objective functions*. These *objective functions* are a mathematical approach formula where each one of the different values will produce different results that the user intends to minimize, maximize, have within a certain range, etc. After the values are produced, the software will evaluate and rank how close they are to the objectives.

Constraints. The constraints express the boundaries of values. These boundaries are commonly established to avoid results that do not have a connection to reality or that do not follow certain standards. By establishing these boundaries, there are certain designs that are automatically excluded from the optimization process.

3 Performance-Based Design

3.1 Evaluation

In this section, we choose a case study and evaluated if, in fact, we can find better solutions in less time using optimization processes. We used two different approaches: parametrically, and by optimization processes. We compared the results in terms of UDI percentage, how many building iterations were produced and how much effective work time it required.

Figure 1: Dougong.[1]

Previously, we built the hypothesis that **using optimization methods is less time consuming than the parametric and manual methods, and achieves better performance results when designing a building**.

To evaluate this hypothesis we used an office building located in Shanghai. The building has three floors: the first floor contains offices with different sizes, the canteen, a coffee shop, restrooms and several service areas. Both the second and third floor are mainly occupied by open space office space, having a few conference rooms and pantries. The dimensions of the building are 99.6 by 33.6 meters, and a total height of 13.5, with a height of 4.33 meters per floor. A new façade was designed for this building.

The new design is inspired by the dougong (figure 1), an element of the chinese traditional architecture.

In parametric terms, what varies is the wavelength amplitude of the façade: the maximum distance between the edge of the stacks and the building border. By changing this wavelength different UDI (Useful Daylight Illumination) results are expected. Useful Daylight Illuminance is a range of illuminance across the work plane considered "useful" by occupants, measured within an annual timeframe [6]. The reason behind this choice is because the case study is an office building, and this metric considers useful values of light to perform work. Afterwards we maintained the wave amplitude but changed the materials, still optimizing for the UDI.

[1] source:https://en.wikipedia.org/wiki/Dougong

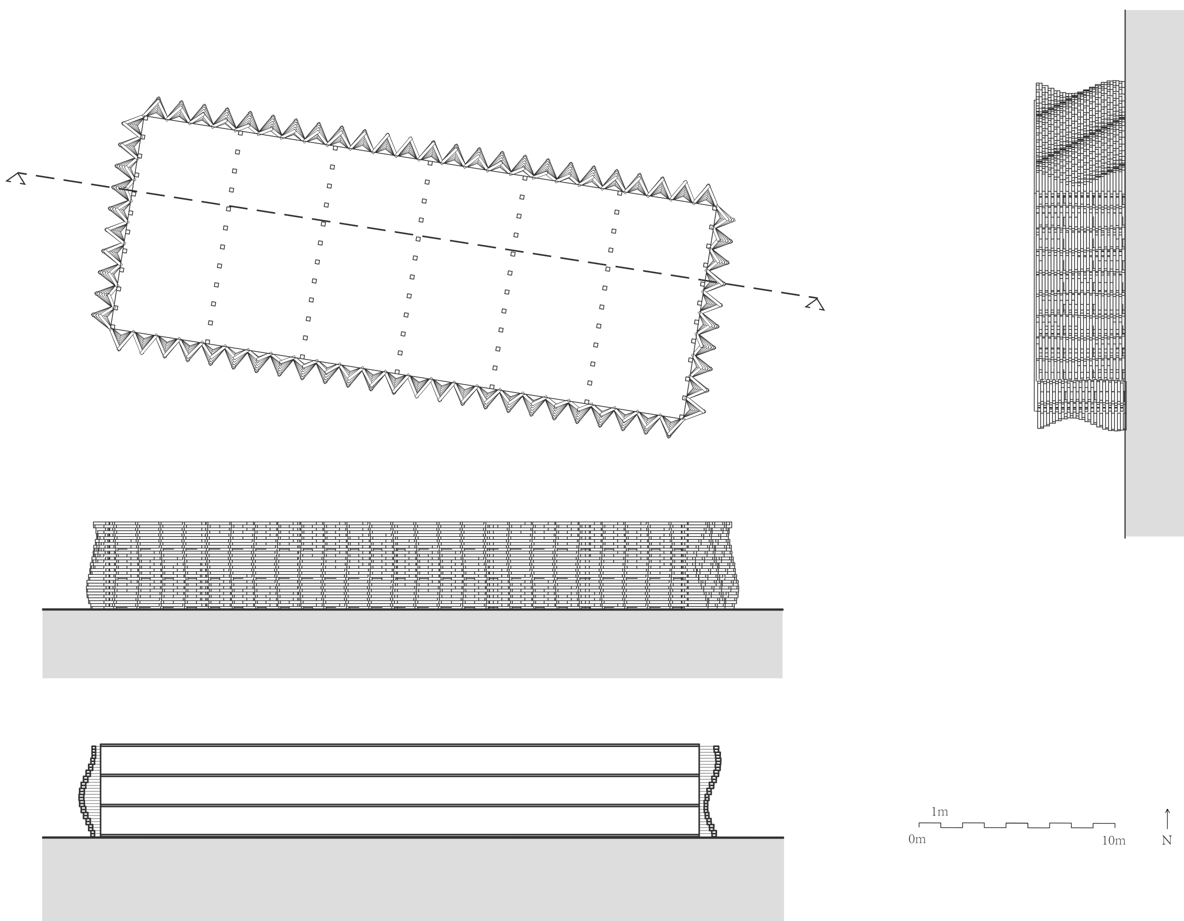

Figure 2: Plan and elevations of the case study.

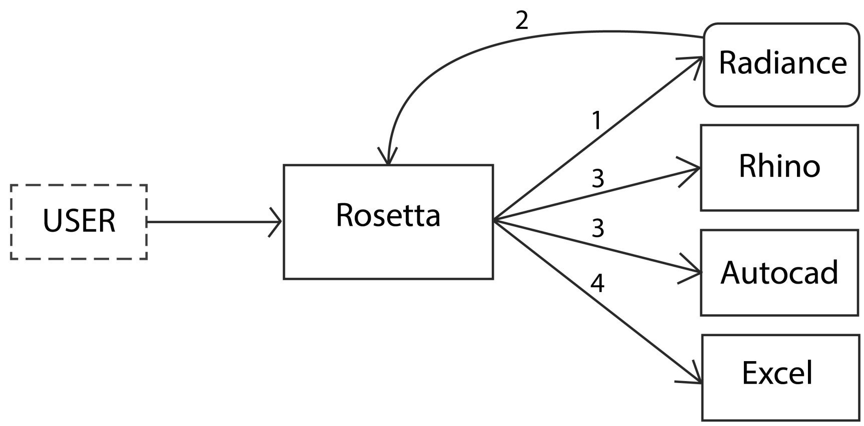

Figure 3: New backend's data flow

3.1.1 Algorithmic-Based Analysis

During the early stages of this research, when experimenting with different analysis tools and performing various types of simulations, we quickly realized that there are often many exportation errors when transferring the model built in a CAD or BIM environment to the various analysis software. These exportation errors occurred due to the various formats that different programs require. Furthermore, the 3D models built for design purposes frequently contain far more detail than required for analysis. This means that, in some cases, the architect needs to rebuild a simplified version of the model, containing only the relevant information for analysis. Both the exportation errors, and the use of simplified versions of a model can make the analysis results unreliable. As a result, building a new model or correcting errors becomes necessary, which is time-consuming.

To overcome these problems we introduced a new backend to Rosetta. Figure 3 illustrates the data flow introduced by this new back-end: the user models his design parametrically in Rosetta with no concerns regarding the analysis tools' requirements and then (1) Rosetta sends to the simulator only the necessary information for the analysis to be performed. After the simulation is concluded, the analysis results are retrieved (2) and the results can either (3) be displayed in the 3D modelling back-ends, e.g., Rhino or AutoCAD, or (4) exported for further processing, for example, in Excel. With this tool, most of the process of analysing and ranking of design solutions happens at an *algorithmic level*, only showing the results when an optimal solution is found or the optimization is stopped. We call this approach **Algorithmic-Based Analysis** and we claim that this method reduces the loss of information or misinterpretation of the model, making the results more trustworthy.

3.1.2 Framework

The framework of this optimization can be explained in terms of inputs, variables, constraints, and outputs. The inputs for this optimization are the shape of the building, the location, and materials. The variable is the wave

Table 1: Iterations, amplitudes and respective UDI values.

Iteration Number	Amplitude	UDI
0	1415	78%
2	1616	80%
13	1868	81%
49	1776	82%

Table 2: Materials and respective UDI values

1. White Enamel Paint	75%
2. Gray Paint	75%
3. White Paint	79%
4. Light Wood	72%
5. Dark Wood	76%
6. Translucent Plastic	78%
7. Metal Sheet	82%

amplitude: the distance between the edge of the stacks and the borders of the building façade. The constraints are the range of values between which the amplitude can vary, in this case between the values of 500 and 2000. These values do not have an exact unit of measurement, but they influence the wavelength. The expected output for this optimization is the UDI: Useful Daylight Illumination [7].

3.1.3 Optimization

Once the algorithm is running and finding design iterations the optimization process starts. While this process takes place there is no need for interaction between the architect and the model, the process is fully automated. In case the design space is finite, the architect can wait for all options to be generated. In case it is infinite the designer can set a time limit for the search and stop it within that time frame.

The optimal amplitude value found by the implemented algorithm is 1776, with a UDI of 82%, belonging to the 49th iteration of the building.

Table 1 shows the best four optimal values obtained and their iteration number.

Using the same the method we optimized for the materials in order to understand the impact that these materials have on the UDI and find the one that offers the best results. The materials from 1 to 7 are white enamel paint, grey paint, white paint, light wood, dark wood, generic translucent plastic and metal sheet. The material that increases the UDI inside the building is the metal sheet with the UDI value of 82% (see table 2).The better performing material is the metal sheet, but making a trade-off between aesthetics and performance we chose the translucent plastic as the material for the final design.

Table 3: Comparison between the two methods (changing the wave amplitude).

	Parametric	Automated
Number of Iterations	4	49
Total Time per Iteration	2,5 hours	0,175 hours
Effective Work Time	4,5 hours	2 hours

4 Conclusions

To develop our conclusions two methods were compared: parametric and optimization. When comparing these two optimization processes it is important to distinguish the time that the software requires when generating the model, as well as the time that the designer must spend interacting with the model/software. This distinction is important because if the designers are merely waiting for the program to finish an analysis, then they are free to perform other tasks. In the table 3 we can compare the two methods described on the previous sections.

If we consider effective work as a measure of effort, it is verifiable that less effort is required when using the automated method. This method produces a more significant amount of iterations, in less time, and with less effort.

This thesis intends to test if it is possible to find better architectural design solutions, in less time, by combining parametric design tools, analysis tools, and optimization algorithms. This can be done without jeopardizing the design intent, reaching a new and contemporary version of the *form follows function* principle: *form follows performance*.

Figure 4 is a render of how the building would look like. Figure 5 is a schematic representation of the final design.

The relevance of this research is not only connected with the advantages it brings from a practical point of view, but also to the contemporary panorama of thinking and creating architecture.

The emergence of optimization methods will certainly have an impact on how architects think their designs, but they are also a reflection of the whole society's evolution, in the way that there is an increasing search for methods that will make our buildings more sustainable.

The most significant problem of optimization processes is the difficulty in validating the results. As it is well-known, analysis software, mainly the ones connected with thermal and lighting efficiencies, are not necessarily accurate [8]. Another limitation found was the extreme difficulty of exporting the data generated by these software into useful information that the optimization algorithm could use.

In a more architecture-related context, the biggest concern when implementing this methodology is that this method, if used without care, has the potential to turn architecture into senseless nouvelle shapes, forgetting that it should consider context, cultural background and should have some statement or concept. Architecture is also about preserving a certain urban or historical context, otherwise, we risk cities being transformed into a set of

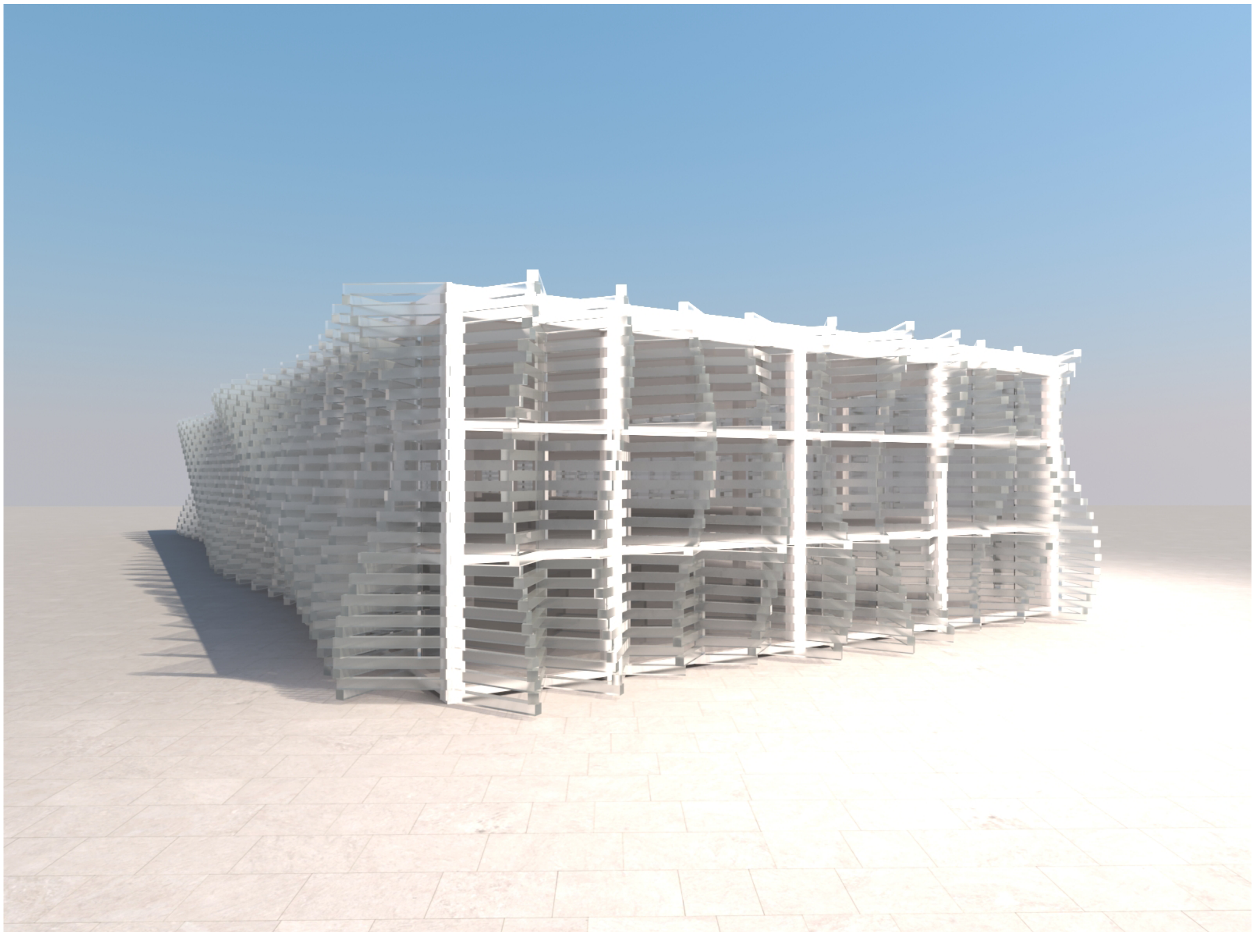

Figure 4: Exterior Render

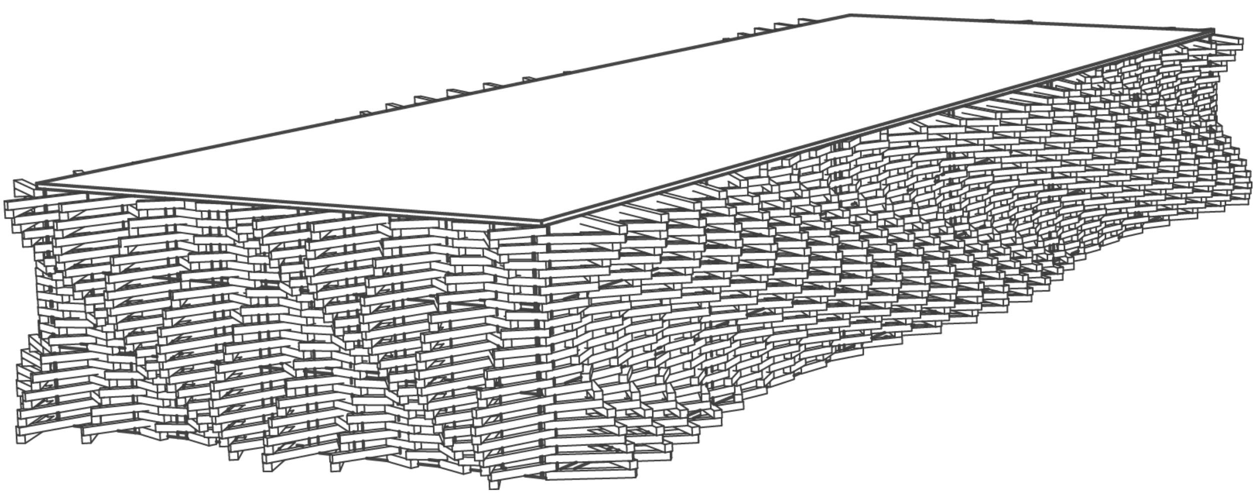

Figure 5: Final Design Scheme

complex shapes without any relationship with each other, or with the cultural context in which they are placed. In addition, architecture throughout history has a social and political statement role, and should be connected to a temporal context. To preserve the design intent, it is imperative that the conceptual phase is clear in the designer's mind.

This thesis proves that optimization processes reduce the environmental-related costs as well as the time needed to achieve better performing designs. Furthermore, it proves that this approach can help the designer to adapt and find form.

The contribution of this thesis is a direct link between the analysis tool and parametric model, which facilitates the optimization process, leaving a pathway open for multi-objective optimization.

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