A Performance Based Generative Design System Methodology for Sustainable Design in Practice

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Abstract

In this paper, a Performance Based Generative Design System is implemented within a professional practice environment. The system is developed to assist architects, engineers and clients in designing intelligent and sustainable buildings. In the early design and conceptual phases of a traditional building design process, the design team can only present the client with a limited number of alternatives due to the long design iteration time needed to generate a single solution. Clearly, these design solutions represent a very small portion of the possible design space. The Performance Based Generative Design System methodology proposed comprises a generative system and an analysis system. The generative system is a rule based system that provides a powerful mechanism for breeding design alternatives while the analysis system provides the tools to asses these solutions. The symbiotic relationship between the generation and testing mechanisms would lead to a larger set of feasible solutions. If performance criteria such as daylight, solar heat or even real-estate preferences are established and solutions are modeled and analyzed, then the design team can compare design alternatives and develop a better understanding of the effects of different design decisions on the design output. This proposed methodology can help both the design team and the client in navigating the design space to identify intelligent, sustainable and superior designs. Furthermore, this methodology lends itself well to automation and high fidelity simulation implementation. The processing power of the computer can be utilized for better breeding capabilities, while the use of sophisticated analysis .tools and models would provide for more robust solutions

1. Introduction

To produce successful sustainable architecture is ultimately determined by the ability of this architecture to enrich the lives of current and future generations through high performing designs that can conserve energy and natural resources, enhance its surroundings, and provide healthy environments for its occupants.

The design of buildings is typically determined by the need to meet a set of minimum performance criteria, including budget and time constraints and functionality and energy requirements. This process typically produces buildings that just meet these minimum criteria. To achieve better performing and more sustainable buildings, the design team needs to work collaboratively in a focused effort.

As an architectural firm we have attempted to produce better performing and more sustainable architecture by developing a *Generative Performance Based Design* methodology that can assist us in handling design complexity to produce buildings that can perform highly among various performance criteria. Our methodology depends on the ability of generating solution variation through a generative system. The performance of the solutions produced can be analyzed using a set of analysis systems. By coupling generative and analysis systems we aim to achieve a better sustainable architecture.

In this paper we will describe our proposed generative performance based design methodology and its expected benefits. We will first start by providing a short brief on generative systems and their use in design. That will be followed by discussing analysis systems used in architectural design. We will then discuss our methodology. Finally we will demonstrate this methodology through an experiment that we carried out for designing an actual commercial building which has been recently constructed. We hope to explain the phases within the methodology and show how the methodology influenced our building design process.

2. Generative Systems

The concept of using generative systems in design is not new. Formal design patterns and design rules have been implemented throughout the history of architecture. Signs of such systems can be found in many historical examples of architecture.

Palladio, a fifteenth century architect, was influenced by both Greek and Roman architectures developed a process of designing that was based on such logical design rules.

Durand, a French architect in the eighteenth century, provided his students with a kit of shape rules and instructions on how to build architecture (Britt 2000). In the early twentieth century Sullivan demonstrated the construction process of ornament plates through a set of instructions and rules that were then given to the craftsmen to reproduce variations of the ornaments within Sullivan's design style (Twombly 2000). In the Modernist movement certain design rules that promoted the simplification of form and the elimination of ornament were also implemented.

Since the early 1960s Christopher Alexander has been arguing for the development of design rules in architecture and urban planning. He designed a set of rules and processes to offer solutions for various urban design contexts. Alexander's Pattern Language showcased several algorithms to solve urban design issues. These include topics such as street corners, street pedestrian view, public spaces, and access points among others (Alexander 1977).

In addition, many experimental architects like Peter Eisenman base their work on the assumption that architecture is based on an embedded design logic. Eisenman described (House X) in a series of "Transformational diagrams" to define the process of design. His design rules where expressed in how the design evolves (Eisenman 1983).

Fractal geometries and theories (Mandelbrot 2004) also had a large influence on architecture within the twentieth century and specifically on the development of the concept of generative systems in design. The relevant issue highlighted generally assumes the necessity to develop a design process that is more systematic.

In the 1970s Stiny and Mitchell were able to extract from Palladio's writings and work a set of shape rules and grammars (Stiny and Mitchell 1978). These grammars were capable of producing many variations of Palladio's designs. This work and many others that followed helped develop the Shape Grammars formalism as a Generative System.

Generative Design System exploits the principle of generating complex forms and patterns from simple specification in order to breed design solutions and complex variations that are hard to create through typical design approaches and methodologies (McCormack et. al. 2004).

This is achieved by the exploitation of the design concept's inherent rules and design algorithms. The development of a generative design system is only possible after identifying the design objectives and intent. This entails defining concepts, rules, relationships and algorithms.

In addition to Shape Grammars, there are currently a number of Generative Systems formalisms that have been borrowed from mathematics and computer science and applied within an architectural design context. These include formalisms such as Cellular Automata (Batty 2005), Fractals and L-Systems (Flake 1998). The solution that a Generative System eventually provides can be evaluated and compared with other alternative solutions using an analysis system.

3. Analysis Systems

An analysis system should facilitate the assessment of both quantitative and qualitative aspects of an architectural design. Quantitative aspects could be measured and are value driven and therefore can indicate an objective assessment of a design. Qualitative aspects on the other hand are not of a constant value and rather indicate a subjective notion.

The quantitative features in a building design include aspects such as economical requirements and the environmental and energy requirements. The economical features could include the building's construction initial cost, the building's running cost or even the building's return on investment in the case of commercial buildings. The environmental and energy features could include aspects like day lighting, thermal, indoor air quality, acoustics, and structure. The qualitative features in a building design are much harder to gauge or identify such as aspects affected by social requirements or aesthetics.

An analysis system in this sense infers certain behaviors from a design solution that are relevant to a specific discipline, and in doing so can play the role of quality control within the architectural design process.

4. Proposed Methodology

The key properties of our generative performance based design system can be summarized according to the following phases: Design Concept, Hierarchies and levels, and Generate and Test loops. However, these phases should not be treated separately because of how they affect each other and the inherent relationships that exist between them.

The initial step is the development of a design concept by the design team. After the concept is developed it is decomposed into a hierarchy and levels of development. Each level is then assigned one or more generate and test loops that include both generative and analysis systems (Figure 1). The following sections will describe each of these phases in more detail.

4.1. Design Concept

The first step in our proposed methodology is the development of a design concept. Developing a design concept is the initial step in any approach to design. A building's design concept is influenced by several aspects that include building program, social conditions, environmental considerations, and cost among others.

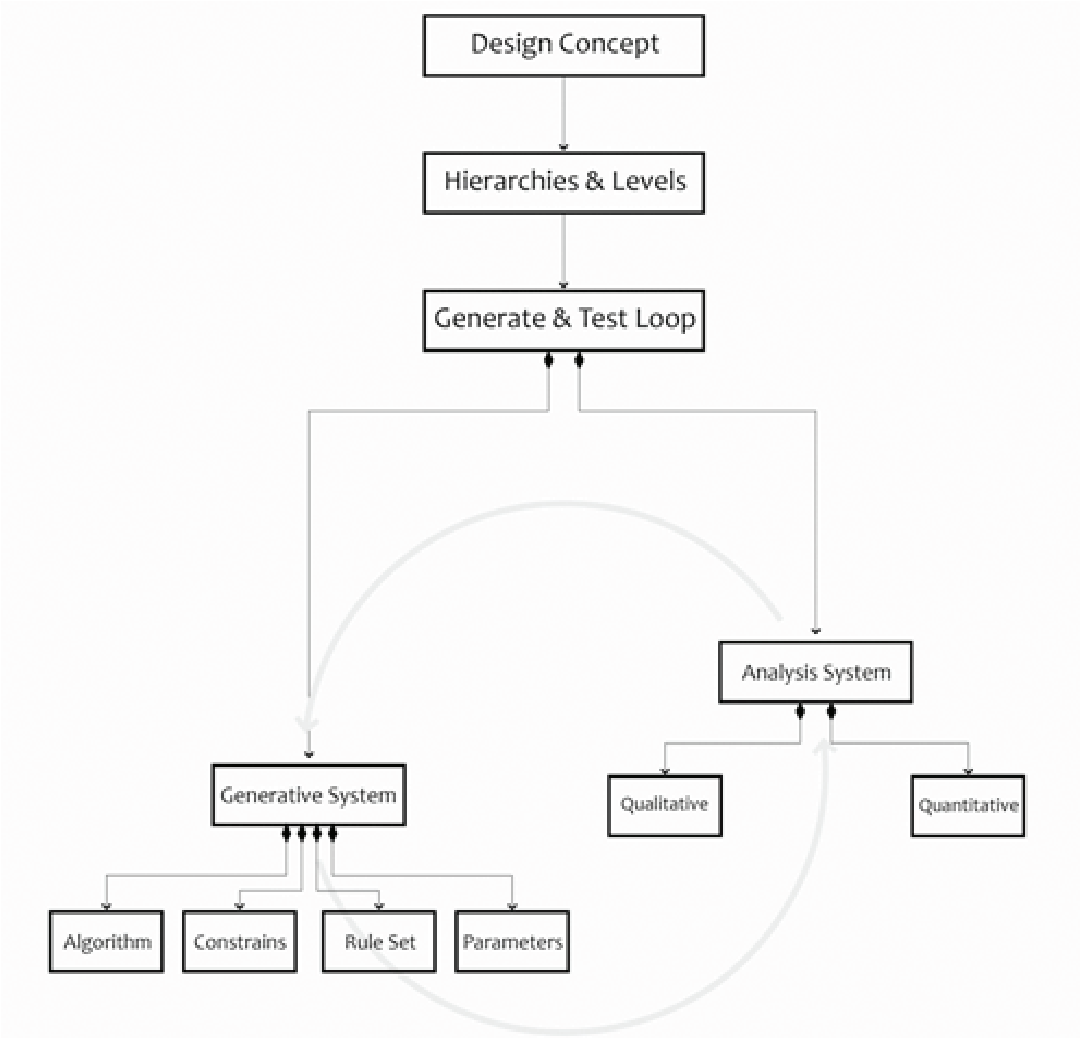

Figure 1: The Generative Performance Based Design System includes a design concept, hierarchies and levels, and generate and test loops.

Building program information such as functional program needs, public and private partitioning, commercial and service requirements are all important in developing a design concept. Social conditionings also help set the stage and should draw on both the contemporary norms and experiences of the past. Furthermore, environmental considerations and cost constrains present important factors that determine design strategies and goals.

4.2. Hierarchies and Levels

After the design concept is developed, the design is decomposed into a hierarchy of components and aspects that, as a whole, represent the design concept. A hierarchy defines a system as being composed of several subsystems, each of which can also have their own hierarchies. A hierarchy can also be seen as a collection of parts with ordered asymmetric relationships inside a whole. That is to say, upper levels are above lower levels, and the relationship upwards is asymmetric with the relationships downwards (Simon 1996).

The design concept developed by the design team can be broken into hierarchies and levels to handle design complexities and simplify the design process. Each level within the system includes one or more generate and test loops. The following section will discuss this loop further.

4.3. Generate and Test Loop

Within a design process, designers while seeking a design solution, typically first propose certain compositions and geometries and then reflect on the results and analyze and evaluate the solution. They then investigate certain modifications to the proposal that might present more potential and eventually repeat the process. This is what is referred to here as a Generate and Test loop (Rowe 1998). Therefore, the generate-and-test loop is in essence a trial-and-error process. However, the results of tests are explicitly used to guide successive attempts to generate solutions.

A generate and test loop is expected to produce part of the design concept at a certain level. Each loop includes both a generative system as well as an analysis and test system.

4.3.1 Generative System

The Generative System we are proposing includes the following elements: parameters (constants and variables), constraints, rule sets, and algorithms. Typically, after the system constants are set, the rule application is initiated based on the design algorithm, and the generation of solutions is restricted by the system constraints. The system variables will control the design variation. These elements work collectively within the algorithm to breed a design solution each time the algorithm is applied.

4.3.1.1. Parameters

A parameter is a measure or value on which something else could depend. Parameters include both constants as well as variables. Constants could be defined as expressing a property, quantity, or relation that remains unchanged under specified conditions. On the other hand, variables could be defined as something that can be changed and varied.

Based on the design intentions and goals, the architect and design team should define what sort of parameters can be expressed as constants within the design and what parameters are able to pass on as variables.

4.3.1.2. Constraints

A constraint could be defined as a restriction on the degree of freedom in the process of providing a solution. Each constraint has the potential to restrict our ability to deliver a solution. Therefore, each constraint must be carefully considered as part of the design planning process.

In our proposed methodology, constraints will be of two types, geometric constraints, and functional or performance constraints. The geometric constraints will control geometric attributes such as building height, internal spaces area, etc. The functional or performance constraints, on the other hand, will control the function and performance attributes such as the minimum illumination requirements for an internal space or the maximum solar intensity allowed on an external surface, etc.

4.3.1.3. Rule Sets

A set of shape rules must be first extracted from the design concept. The rules specify how each of the shapes in the grammar is replaced with another shape. The system begins with the axiom and replaces each of its shapes according to the shape rules to produce a new combination of shapes. This process of shape replacement continues until a certain shape rule is triggered terminating the process. These shape or design rules are the basis of the generative design system. The generated design alternatives fall within the design space generated by the rule set.

4.3.1.4. Algorithms

In general, algorithms describe a process or sequence to be followed in calculations or other problem-solving operations. This sequence should consist of unambiguous instructions for solving a problem and for obtaining the required output for any valid input in a finite amount of time. In our methodology, algorithms are not design products in and of themselves, but rather descriptions for building the design. These descriptions however require clearly defined objectives to generate the design language.

4.3.2. Analysis System

In our methodology the analysis system tests a generated solution in order asses it's behavioral and performance characteristics and measure how well it fits the objectives it is planned to assemble.

Here our focus is on quantitative aspects of the design. In doing so, the analysis system operates on the design solution data through laws of physics and geometry to produce the desired rating. It also depends on specialized disciplinary knowledge such as heuristics, formulae, or simulations to inform how this data is transformed into performance characteristics. Qualitative aspects on the other hand will be assessed for every solution independently by the design team.

5. Design Experiment

In this section we will demonstrate the application of our proposed methodology within a design experiment. The design experiment is an actual commercial building currently under construction in Riyadh, Saudi Arabia

5.1. Design Concept

The goal of this project was to design a unique office building that took into consideration the need to satisfy multiple requirements such as real estate and return on investment, internal work environment, and energy conversation among others.

The concept was developed to maximize rental spaces, and offer a variety of office sizes and spaces that could accommodate different tenant needs. The design concept provided expansion possibilities for offices as well as the capability of dividing large offices into smaller ones.

Several architectural aspects were taken into consideration while designing this building. Views to the outside from the offices were considered a priority. In addition, interesting internal views were provided within the building. Due to length of the building, different design approaches were implemented to break the huge building mass. In addition, the building design was unattached to any design style with a limited timeframe.

In regards to energy conservation, different approaches and strategies were implemented to provide high comfort levels for occupants without depending on the overkill of mechanical systems.

It was taken into consideration that the systems implemented should be easy to maintain, efficient, and long lasting. Finally, the structural system proposed was based on the commonly used post and beam system which is both economical and reasonably easy to implement.

5.2. Hierarchies and Levels

In this study the design concept was broken down into two design levels. The first design level handles the internal spatial zoning while the following level considers the external building skin and massing design solutions (Figure 2).

It should be noted however that while the design system in level two is developing solutions, it is also considering several factors from the previous design level.

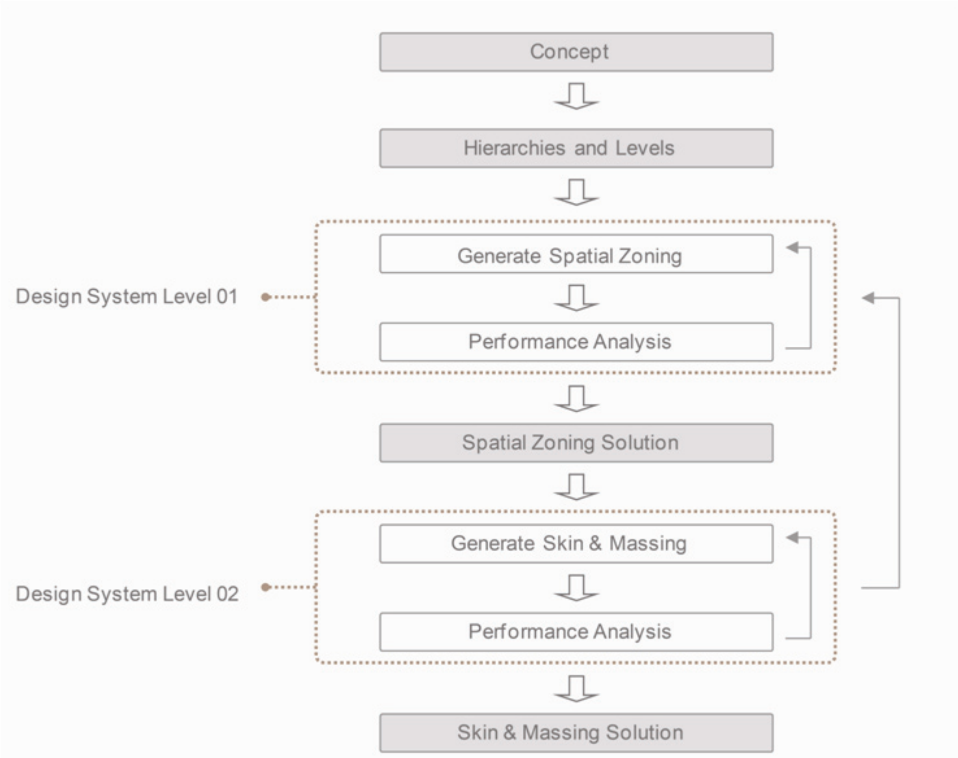

Figure 2: The design concept is decomposed into two levels.

5.3. Design Level One

As stated earlier, the first level of the design system is responsible for generating spatial zoning options that will be analyzed based on qualitative as well as quantitative aspects. Qualitative aspects include characteristics like quality of the internal space while quantitative aspects will include characteristics like real estate and lighting (Figure 3).

The feedback from the analysis system will then inform the generative system and a new solution will be produced. This generate and test loop will continue until we reach a satisfactory solution that can then be exported to the second level of our proposed design system.

5.3.1. Generative System

The generative system should produce different spatial zoning alternatives. The system will consist of parameters, constraints, rule sets and a design algorithm.

5.3.1.1. Parameters

The parameters of the generative system in level one are divided into constants and variables. The constants will include the location of the main entrance and main circulation spine. The main entrance represents the main access point to the building which is also connected to the main vertical circulation core. The main corridor is the main public access to office spaces and spans the building from north to south. It is also attached to the main vertical circulation core.

The variables in the system were chosen as the internal gardens cell locations on the boundary as well as the sub-corridor shape that connects between the main spine and the offices (Figure 4).

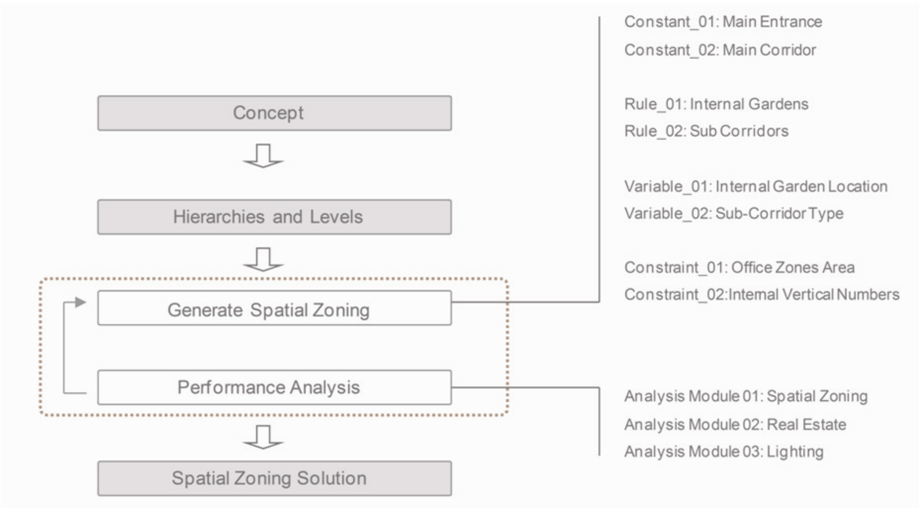

Figure 3: Generate and Test loop of level one

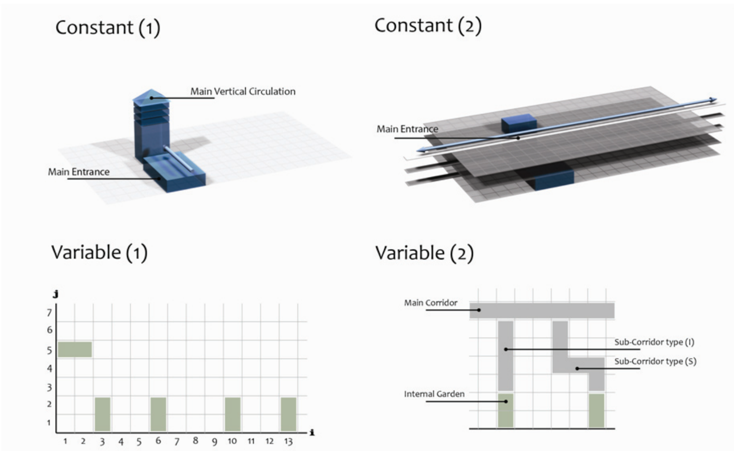

Figure 4: Constant and variable parameters of the generative system at level one

5.3.1.2. Constraints

Certain design constraints were imposed on this level. For instance, every office has to have a semi private corridor, and overlooks 2 gardens. The lower bound of office areas was set to 200 square meters and the upper bound was set to 600 square meters. Furthermore, every office larger than 400 square meters has to be dividable into 2 offices with 2 different entrances. In addition, the number of gardens in the east and west should be ≤ 4 and > 2. Due to the real-estate requirements the western offices were made smaller than the eastern offices. And since the western offices also have privacy code restrictions, the number of gardens in the west was constrained to be greater than or equal to the gardens in the east. The number of gardens in the south and north were set to range between 1 and 2 (Figure 5). Furthermore, gardens in different floors were not allowed to share any edges or vertices for massing and aesthetic reasons.

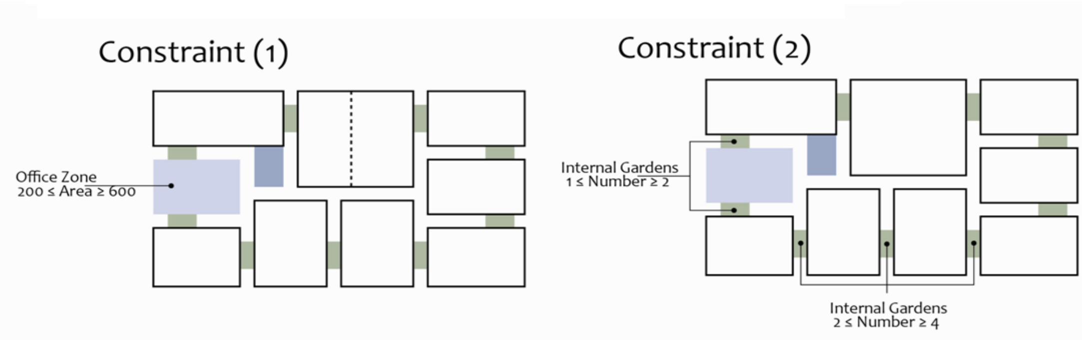

Figure 5: Some constraints of the generative system at level one

5.3.1.3. Rule Set

The rules applied in this level are mainly spatial zoning rules and will be related to the generation of internal gardens and sub corridors. The internal gardens will be located at different locations on the design grid.

The sub-corridors will provide a link between the main corridor and gardens. They offer a semi-private zone for the offices. Their shape also affects the shape of the offices.

Also each garden on a certain floor is related through the elevation to the gardens on the upper or lower floors. These gardens provide both view and lighting for the offices and corridors. They also provide a solution for the view code restrictions towards the surrounding residential buildings (figure 6).

5.3.1.4. Algorithm

After defining the system rules, we apply them in a sequential manner to generate a design alternative. Initially the system constants provide us with a layout that is only occupied by the main entrance and the main circulation elements (main corridor and main vertical circulation).

Since the internal garden coordinates on the floor are variable, the algorithm starts by locating the internal gardens on the floor boundaries using rule (1) while checking constraint (2) to maintain a satisfactory level of view and light to the office zones. Afterwards, the internal gardens are connected to the main corridor using the sub-corridors rule (2). However, the shape of the sub-corridor is subject to variation.

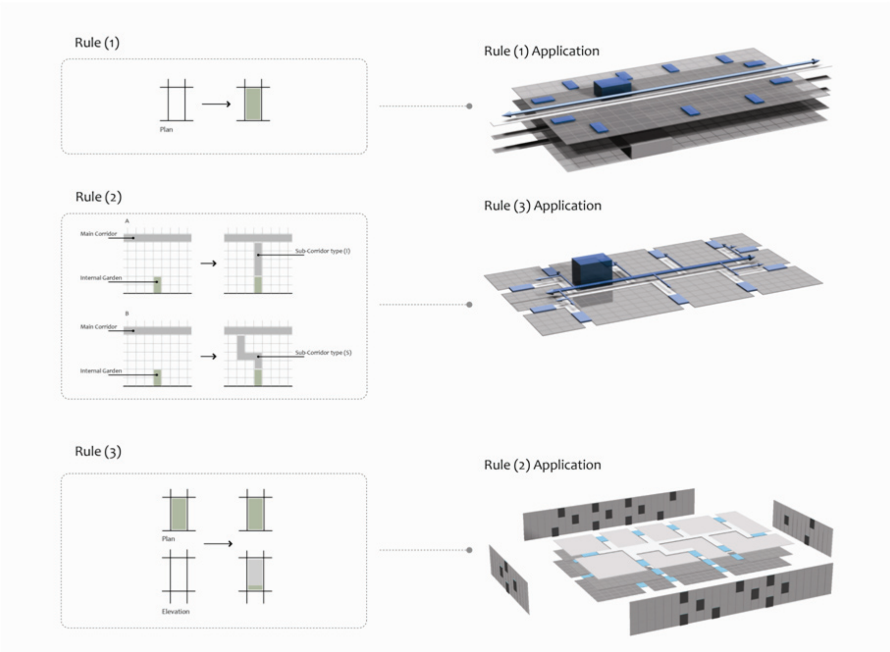

Figure 6: Rule sets implemented within the generative system at level one

This algorithm is repeated for each floor while checking that constraint (3) that relates gardens on different floors is satisfied. Applying the generative system produced a large number of solutions and alternatives. Each solution was then analyzed on the basis of certain aspects and performance criteria.

5.3.1.5. Analysis System

After a solution is generated by the generative system, the analysis system can be implemented. The analysis system at this level includes a spatial zoning, real estate, and lighting analyses. The spatial zoning is considered a qualitative aspect, while the real estate and lighting analyses represent quantitative aspects.

The spatial zoning analysis is used to assess the general arrangement of the floor plans with a focus on the architectural space features such as circulation ease through the horizontal and vertical circulation systems.

The real estate analysis will calculate the percentage of the rentable area and compare it to the built area, and will assess the expansion and the down sizing flexibility in the offices. Finally, the lighting analysis will be responsible for calculating the quality of lighting provided in each office space.

Each criterion discussed above will be given a certain weight. All criteria and weights will be combined to define the objective and evaluate a single solution (Figure 7).

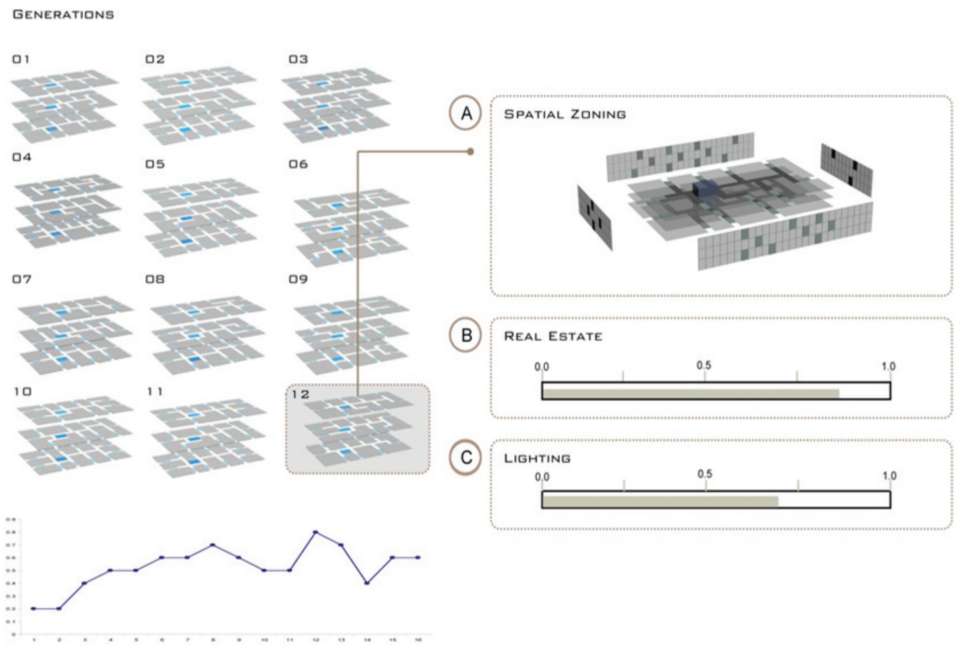

Figure 7: The outputs of the generative and analysis system of level one.

5.4. Design Level Two

The design system at level two will be responsible for generating the building massing and the external building features. The options generated from the generative system will then be analyzed based on qualitative aspects such balance and proportion, as well as quantitative aspects such as real estate and solar intensity on the façade (figure 8).

5.4.1. Generative System

The given solution from design level one will be current level starting point. As stated earlier, the goal of the generative system at this level is to produce an interesting building form by exploring the design space in search of satisfactory solutions. Solution variations will be produced after running the design algorithm with its elements that include parameters, rule sets, and constraints.

5.4.1.1. Parameters

The parameters of the level two generative system are divided into constants and variables. The level one design results and outputs are considered constants. In addition, the number of vertical divisions in each building elevation was chosen to be constant. The east and west elevations number of divisions was chosen to be 3, and the north and south elevations were set to 2 divisions. Also the number and location of horizontal breaks were set as constant. A maximum of one break in any mass was allowed. This break will be located between the ground and first floor. Furthermore, the floor heights were also considered as a constant because of building code requirements.

On the other hand, the variables in this level are the surface division line, the rotation angle (θ) of the surfaces deformation, the transparent surface locations, and the shading system location (Figure 9).

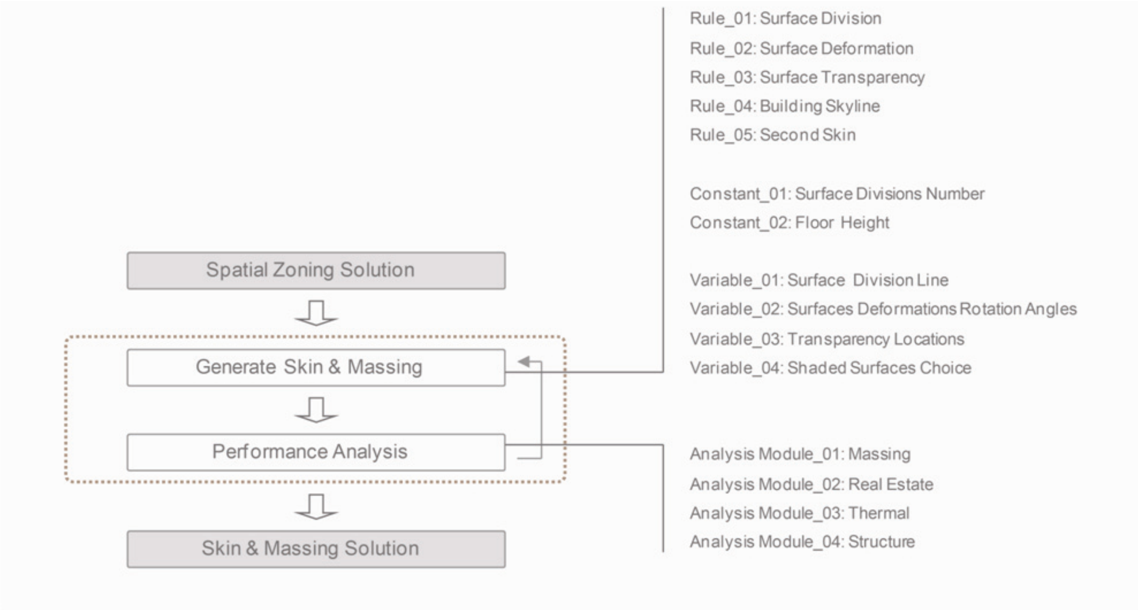

Figure 8: Generate and Test loop of level two

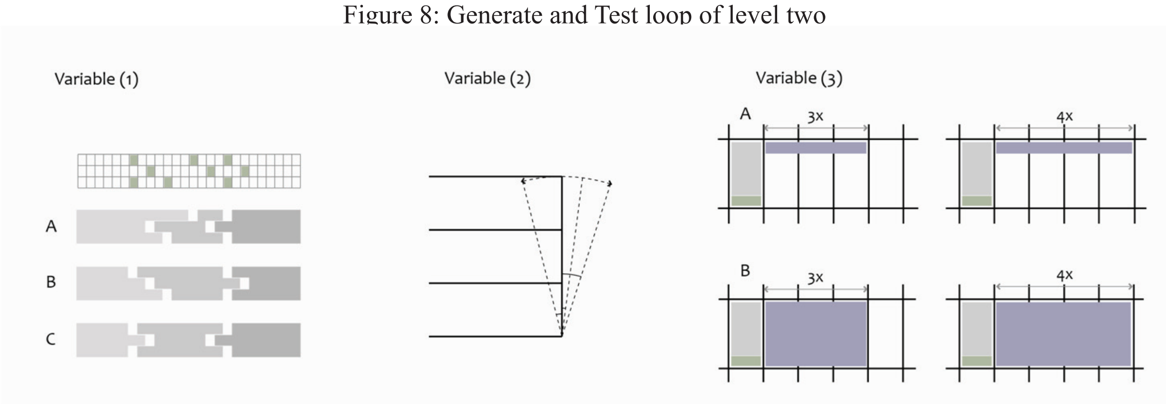

Figure 9: Variable parameters of the generative system at level two.

5.4.1.2. Rule Set

The rules to be applied in this system are mainly massing rules and will be related to the elevations treatments such as surface division, surface deformation, surface transparency, surface shading, and building skyline.

The building facade will be divided into vertical surfaces. This will help scale down the length of the building. The surfaces can only span between internal gardens. The first floor projection lines on the elevation can also divide the surfaces horizontally. The surface planes will rotate in two directions vertically and horizontally. This will provide a dynamic effect to the building's form and masses.

The transparent surfaces are two types: transparent surfaces that provide view and light, and transparent strips that can only provide light. Based on the location and internal need, one of the two types will be implemented. The surface shading system represents a second skin to the building. It acts as a filter allowing indirect light to penetrate the building, but prevents direct solar radiation. The skyline of the building will be allowed to deform to follow the surface division, conform to the massing breaks, and define important corners of the building (Figure 10).

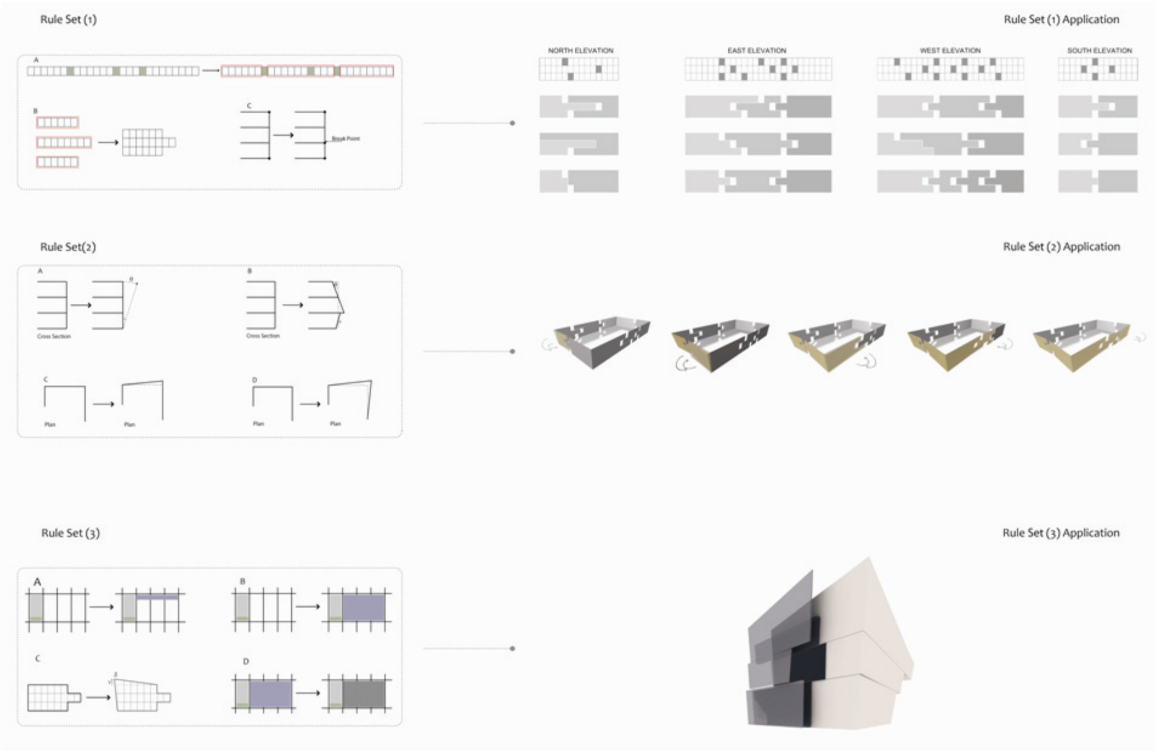

Figure 10: Rule sets implemented within the generative system at level two.

5.4.1.3. Algorithm

After receiving the spatial zoning result from level one, rules (1a) and (1b) are applied to divide the elevations into separate vertical surfaces based on the gardens locations. The division line will be defined through breaking the elevation of each floor separately, and then grouping the breaking results of each floor into one surface. Rule (1c) can also be applied to divide the generated surfaces horizontally.

After applying rule set (1), rule set (2) takes part in rotating the defined surfaces both horizontally and vertically according to variable angles (θ). Next rule (3) is applied to change surface transparencies. Rule (4) is then applied to generate the second skin on the building. Finally rule 5 is applied to change the building skyline.

5.4.2. Analysis System

After producing a solution by the generative system, the analysis system can be used to evaluate it. The analysis system will include a massing analysis that is based on qualitative aspects. In addition, real estate, thermal (solar intensity), and structural performance will be evaluated based on quantitative aspects.

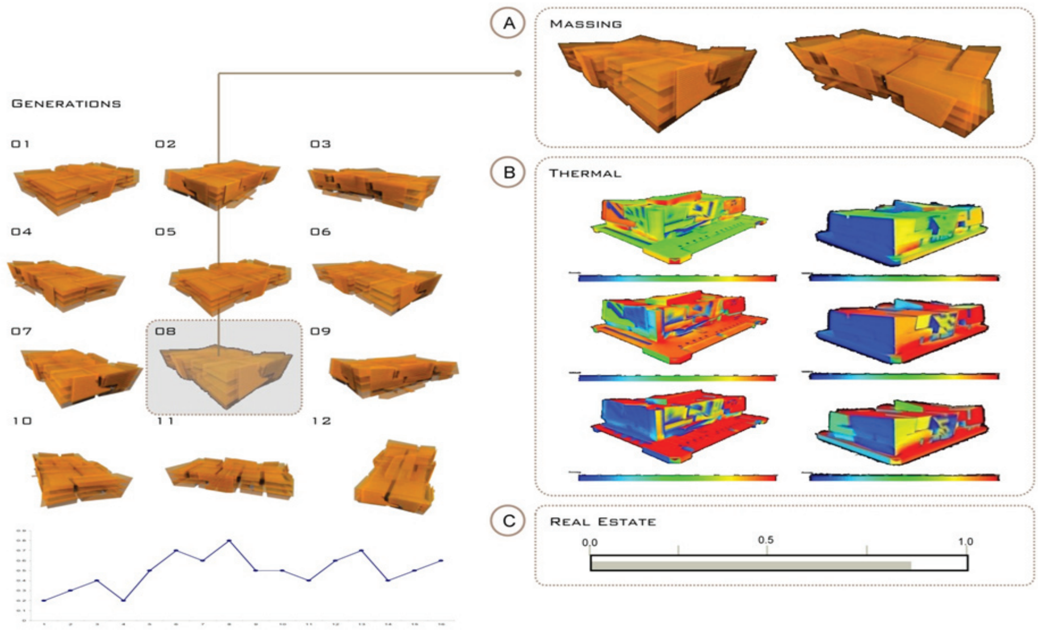

Figure 11: The outputs of the generative and analysis system of level two.

The massing analysis will evaluate balance proportion and aesthetics. The real estate analysis will re-evaluate the rentable area of the building to gauge the affect and change that occurred due to surface deformations. The thermal analysis will calculate the surface solar intensity and the affect of deformation on it. Finally, the structural system will be evaluated based on an estimate of construction cost and complexity generated by surface deformations (Figure 11).

6. Conclusions

In this paper we demonstrated a Performance Based Generative Design methodology that we applied in our practice (Figure 12). The methodology stars by identifying a design concept. This design concept is then broken down into different levels and hierarchies. Each of these levels includes one or more generate and test design loops in which a generative system produces a solution that an analysis system can test. The generative system includes parameters, constrains, rule sets, and algorithms. The analysis system tests for both qualitative and quantitative aspects. The system is fairly flexible and can allow the design team to maintain certain design intentions.

The methodology helped the design team generate solutions that have high performance levels. These performance levels should contribute to the building's sustainability.

Our objective in the development of this methodology was to provide a design system that can be included in early conceptual design phases. This proposed methodology can present both the architect and the client with a better understanding of the design space and the effects of different design decisions.

It should be noted that the design system proposed provides for emergent properties that are only identified through the integrated interactions of the design elements as a whole.

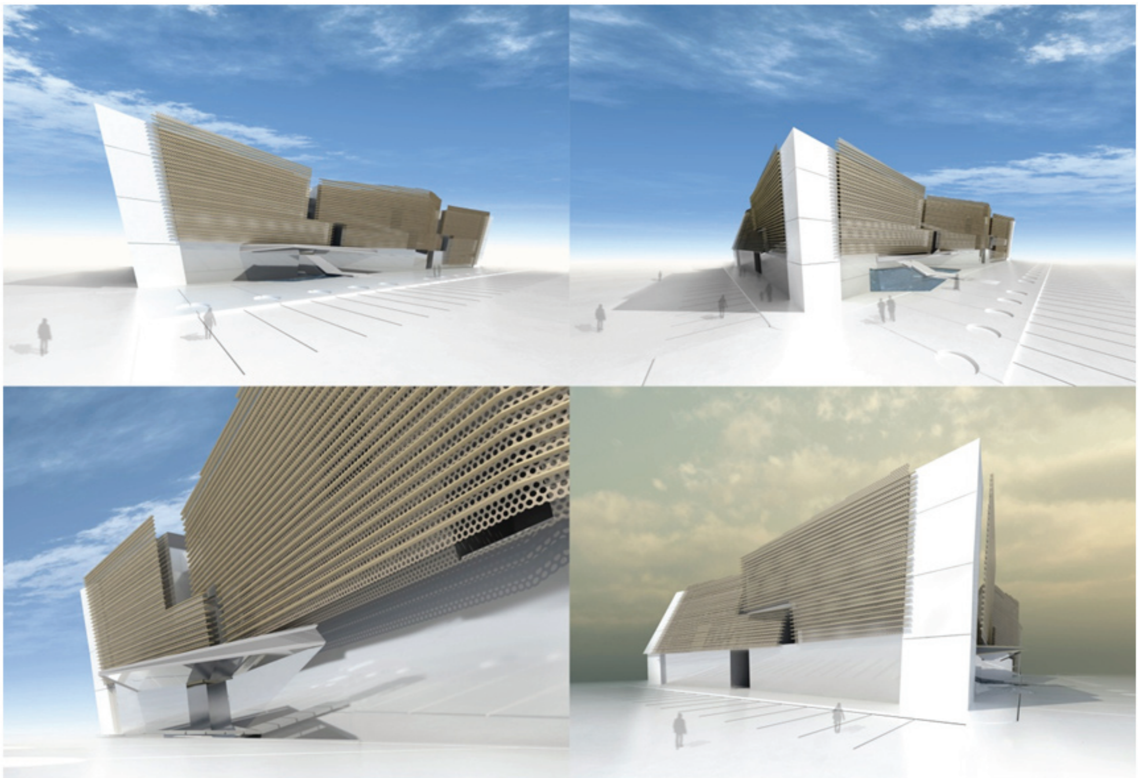

Figure 12: Final solution produced using the proposed methodology and system.

In addition, the design system methodology lends itself well to computational modeling and simulation implementation. Fully automating the process similar to Alfaris and Merello (2008) would provide for better breeding capabilities. Also the use of more sophisticated analysis tools would offer more robust solutions.

7. Acknowledgment

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منهجية تصميم في الممارسة المهنية لتوليد الحلول المستدامة اعتماداً على تقييم الأداء

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ملخص:

يتـم تطبيق المنهجية المقترحة لتوليد الحلول اعتماداً علـى تقييم الأداء في إطار الممارسة المهنية. وقد تم تطوير هذه المنهجية لتساعـد المعمـاري والمهندس وصاحب العمل علـى تصميم مباني ذكية ومستدامة في مراحـل التصميم المبكرة ومرحلة وضع الفكرة التصميمية في المنهجية التقليدية لتصميم المباني لا يستطيع فريق التصميم تقديم إلا عدد محدود من بدائل الحلول نسبــة للزمن المطلوب لاستكمــال المحاولات لوضع كل بديل بالتالي لا تغطي البدائل الحقـل الكامل للحلول الممكنة. والمنهجية المقترحـة هنــا تشمل نظامــين: نظــام لابتــكار الحلــول (Generative System) ونظــام لتحليل الحلــول (Analysis System) . نظام ابتكار الحلول مبني على أسس محددة لتوليد بدائل الحلول بينما يقدم نظام التحليل الوسائل لتقويم هذه البدائل. والتكامل الطبيعي بين نظامي التوليد والتقويم يؤدي إلى مجموعة أكبر من الحلول الممكنة.

يتــم وضــع معايير الأداء، مثل مستوى الإضاءة الطبيعية والأداء الحــراري أو حتى متطلبات الاستثمار العقاري ثم يتم نمذجة (modeling) الحلــول التصميميــة وتحليلهــا والمفاضلــة بينها، ويؤدي كل هــذا إلى إكساب فريق التصميــم معرفة أفضل بتأثـير القرارات التصميمية على مخرجات التصميم. تساعد هذه المنهجية فريق التصميم وصاحب العمل على تغطية كامل مجــالات الحلول الممكنــة لاختيار أفضل التصاميــم الذكية والمستدامة أضـف إلى ذلك أن هذه المنهجيــة ملائمة لاستخدام الحاسب لتمثيل الحلول بوسائل المحاكاة (Simulation) وبالتالي يتم الاستفادة من قدرة الحاسبات على معالجة البيانات لتوليد أفضل البدائل، بينما استخدام وسائل التحليل المتطورة تؤدي إلى الحلول الجادة والملائمة.