INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

Generative Design Systems: Towards Integrated Digital Design Tools

Application to a Case Study: The Patio House of the Medina of Marrakech

Luís Filipe Batista Silveira dos Santos

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SUMMARY – English Version

Contents

1. Background and Objectives

This paper discusses about the paradigm and the issue of the methodological question of design conception using computer applications, featuring Generative Design Systems (GDS) as the most integrated and viable digital design tools for an exploratory, reasoned and sustained approach to architectural design. This work is also an extension, a consolidation and a deeper discussion of the results from a research project in architecture, POCTI/AUR/42147/2001, sponsored by FCT that aimed the integration of Shape Grammars with Generic Algorithms (GA). The project developed generative methods that reflected the urban complexity of the Medina of Marrakech (Morocco) and integrated shape grammars as generative process for the Gene_Arch (Caldas, 2006), a GDS that proposes the optimization of thermal and lighting performances throughout it's generative process.

The thesis has two main goals: the first one consists of a deepening and a synthesis of theoretical and conceptual issues related to designing with the computer; the second intend to apply the theoretical concepts developed, in order to consolidate to the Gene_Arch (Caldas, 2006) the analytic parameterization methodology of a specific architectonic *corpus* – the Moroccan Patio House of the Marrakech Medina. The first objective implies gather and perform a critical synthesis about the state of the art in order to identify the problems inherent to the development of architectural design with digital tools, and predict its solution: the application of GDS. The second objective proposes to prove the transposition of a coherent architectonic set (or stylistic *corpus*), vernacular and complex, for a generative process which will be incorporated in Gene_Arch. The application of this generative process also intends to prove the contribution of this GDS as an expansion tool that wide the search for solutions of the thermal and lighting multi-criteria problem in architecture, towards the improvement of the solutions sustainability.

2. Preview: Problem and Solution

The application of digital design tools, CA(A)D[1] and BIM[2], permit the automation of the arduous and time-consuming manual drawing methods, making more easier the study of different solutions and the introduction of changes in later phases of the project. The use of these software is important in contemporary architectural production, much because of their ability in free form modelling and manipulation. In the simulation of building performance issue it's been proved that simulation programs are more reliable, faster and accurate than any other methods.

[1] CAD - Computer Aided Design; CAAD – Computer Architectural Aided Design.

[2] Building Information Model – parametric applications which associates the geometric description of the three-dimensional model to a data base where other properties are defined

Despite the great contribution that this two types of digital design applications, both are limited, because they don't support creativeness and decision, relying only on a user´s description in order to obtain or an abstract model, that represents the architectural subject, or a simulation of a particular aspect of the building. They are unable to provide a wider spectrum of solutions in early design stages and they can't help the human user in the interpretation of the performance results in order to develop more accurate strategies for the design improvement.

However, in the development of digital design tools two new paradigms emerged providing a more advanced integration of the computer use in the conception of architectural design: generative design and performative design. The generative design is based on algorithmic methods from which several formal potential solutions can be conceived. In contemporary architecture the form plays a major role, though recently a wide range of generative processes were develop, many of them from other disciplines, such as biology and mathematics: Cellular Automata, L-systems, Fractals, Voronoi Diagrams and Shape Grammars.

On the other hand, the performative design applies sophisticated simulators that assess the form and materiality proposed by the architectural solution, against established performance criteria, in order to sustain the necessary changes to improve the performance of the whole. Performance factors have an increasingly role in the conception of the form, giving it a real sense and purpose. The performative approach goes beyond aesthetic issues, focusing the generative systems on building behaviour under various aspects, as the main theme in the development of the design. Optimization techniques include the most varied fields going from structures, economical aspects, acoustics on to aspects related with bioclimatic and sustainable design. To optimize any problem we must establish what we want to optimize, how we will optimize it and even when we may optimize. The key factors for the optimization formulation are: design variables, design constraints, objective function and design criteria.

Despite various optimization techniques the most applied in digital design are: the Simulated Annealing and Genetic Algorithms (GA).

The Simulated Annealing is a combination optimization algorithm. This algorithm performs optimization producing a series of transitions between possible configurations within the design solution space, applying the combination of three processes: generation mechanism, objective function and selection function.

The GA´s are adaptive heuristic search methods that use a set of procedures to generate and select the best performance solutions possible, taking into account the objectives established to the objective function, based on Darwin concepts, as the survival of the fittest and natural selection. For the GA's a solution to the problem under consideration is an individual. A group of individuals is a population. Each time a population is created, a generation occurs. To generate new individuals differentiated the GA uses three genetic operators: reproduction, crossover and mutation. The optimization process, performed by the GA, begins to generate a number of possible solutions to the problem. Then the GA evaluates all individuals, taking into account the value of the objective function of each one, runs a selection then the GA apply the genetic operators to the genetic population in accordance with the degree of suitability of each individual, i.e. in accordance with the performance of each individual. From this process emerges a new population with an average performance better than the one of the previous population. This cycle is repeated until the number of generations established ends.

However a new paradigm emerged: Generative Design Systems (GDS). These systems provide a more complete approach to the potential of computational tool's by integrating the two previous paradigms. Thus, the GDS enables the computer to perform creative exploratory tasks, using generative processes, as an effective decision-support partner, and apply optimization techniques that will guide the generation of solutions towards the desired performance criteria. The GDS introduce a new concept in the methodological approach to design: goal oriented design. With this concept the design search is driven*,* form the start*,* to pre-established objectives, unlike traditional methodology where the building performance is evaluated and later attempted to be improved by introducing, in an empirical fashion, changes. It is concluded that the GDS constitute a real turning point in the methodological approach to the project, perhaps as much importance as the first CA(A)D applications. It is then essential to expand, develop and consolidate the new theoretical and practical concepts that emerge from the implementation of this new type of digital design software. For this, three GDS examples, which deal on architectural matter and spatiality, were analyzed: AudiOptimization; EifForm and Gene_Arch.

3. Critical Analyses of Three GDS

3.1 AudiOptimization

The AudiOptimization applies the concept of goal oriented design to the acoustic design. Thus, the user first establishes goals for the sound field of a particular for space to after create, interactively with the computer, a solution that approaches the previous outlined objectives (Monks et al., 2000: 77). Monks algorithm is composed of a simulation engine combined with an optimization process with formal and material manipulation techniques, based on the discrete parameterization of several variables.

The simulation model is the Monks Hybrid Simulation Algorithm which uses the Beraneks evaluation approach, the Objective Rating Method – ORM. The ORM uses the analysis of six acoustic measurements (Monks et al., 2000: 78): Interaural Cross-Correlation Coefficient (IIACC), Early Decay Time (EDT), Bass Ratio (BR), Strength Factor (S), Initial Time Delay Gap (Ti) and Surface Diffusivity Index (SDI). The ORM also allows evaluating the acoustics of a multifunctional space which requires various acoustic performances, adding a description of the different objective use functions, assigning each of them a weighting factor that determines its importance in the general acoustic performance of room (Monks et al., 2000: 80).

It is intent to minimize the ORM during the generative process. To do this the objectives for each of the six ORM's acoustic measurements are established and the material and geometric properties are variable, in order to the generative process conceive alternative solutions. The GDS will search within the solution space the closest solutions to the established goals using two optimization techniques: Simulated Annealing and Steepest Descent. The Simulated Annealing does a general optimization. The Steepest Descent does the optimization of the sample found by the Simulated Annealing. This dual optimization ensures a bigger reliability of the results provided by AudiOptimization, because it finds the best solution within the neighbourhood of the global minima.

The AudiOptimization was applied to the Kresge Auditorium, a MIT multifunctional auditorium for conferences and concerts. The Objective Function included the two primary uses of the auditorium: symphonic music and lectures. The optimization combined geometric and materials aspects. The GDS assigned more absorbent materials to the bench seats and stage floor, reflective materials to walls and other areas near the stage. The GDS also raised the panels set more distant from the front stage and lowered the closest ones. The wall behind the stage moved forward, closer to the sound source. The Optimization took 17 minutes to converge from a sample of 80 possible configurations, improving the general acoustics, i.e. considering the two usages of the auditorium: lectures and symphonic music, in 47.8% (Monks et al.: 88).

3.2 EifForm

The EifForm was developed by Shea (2005b) and generates and optimize a wide range of two and three-dimensional structures, as diverse as domes, lattices, vertical transmission structures to towers, among others. The EifForm doesn't mean the replacement of the human designer. In EifForm the initial configuration, the optimization model, geometric and functional constraints are defined by the human designer. The intervention degree of this GDS depends only, on the guidelines elaborated by the human user in the problem definition.

The EifForm applies a combination optimization generative process: Structural Topology and Shape Annealing (STSA). The STSA integrates shape grammars, a model of structural performance evaluation, the Finite Element Method, and finally optimization techniques using the Simulated Annealing algorithm.

Due to the difficulty in the conception of the problem and the original model for the STSA method this GDS was integrated, with XML models, with an associative and parametric modelling program: Generative Components (GC) (Shea et al., 2005b). Taking advantage of the GC modelling and visualization abilities, models are developed in GC and transferred to EifForm as a starting point for the generative process. The total parameterization of models created in GC enables the improvement of the exploration of innovative structures due to the dynamic and reactive feedback that exists between the two tools. Modifications to the model in GC mean a new optimization routine in EifForm and the GC initial model updates itself through the incorporation of EifForm amendments, obtained on its optimization process.

To evaluate the capabilities of this GDS, it was applied in the design for a support structure for the swimming aquatic area roof of the University Centre of Carnegie Mellon University (Pittsburgh, USA) (Shea et al., 1999). The problem consists in designing eight triangular shape like planar lattices simply supported in two structural walls. The objective was to meet the functional design criteria and minimize structural mass (Shea et al., 1999: 15). The solutions found by EifForm have a very similar quality. The biggest mass difference observed between structures was only 3.6%. Certain assumptions about the structural behaviour was put into question, for example, the idea that symmetric structures has always a better performance than asymmetrical. In the optimization and generative routine, when the height is constrained, the lighter solution found by EifForm is asymmetric. It was also observed the more higher the number of geometrical restrictions applied to the generative process, simpler are the resulting shapes, but on the contrary, more restrictions means more geometry complexity. By comparing the solutions proposed by human designers and EifForm's it is noticed that the GDS, besides proposing similar solutions, displays other which had not been considered by human designers. It's concluded that the EifForm is able to generate a wide range of solutions with similar structural performances, but also contributes effectively to deepening the structural performance knowledge, mainly because some of the experiments indicated solutions that wouldn't be considered by human designers and others that challenged some pre-established theoretical assumptions.

3.3 Gene_Arch

This GDS developed by Caldas (2006), is a computational tool that pretends give solution to the difficult problems of thermal and lighting at the design stage, focusing its generative process in the optimization of the designs from the point of view of energy consumption. The Gene_Arch applies the concept of design driven by and to objectives – goal oriented design. The solutions optimization is obtained through changing the initial model in order to maximize the usage of natural light, reducing in this way the artificial light consumption, and minimize energy consumption needs for heating and cooling spaces. The Gene_Arch performs these objectives resizing windows and other façade openings, modifying the materials and changing the three-dimensional shape of the design, simultaneously or isolated, in its generative process. This GDS integrates simultaneously Genetic Algorithms (GA) and an environmental analysis simulator, DOE2 .1E. The GA supports the mechanisms for formal generation and the evolutionary optimization of the solutions. The DOE2 .1E is the thermal and lighting analysis module (Caldas, 2006) enabling the shaping of the various solutions. The Generative method of the Gene_Arch manipulate the initial model of the DOE 2.1through its parameterization with variables encoded by GA. Variables can be of two types: (1) independent variables – the ones whose discretization is determined by the user but the value is automatically generated by the GA; (2) dependent variables - the ones that results of the behaviour and relations between independent variables. The different values generated for each variable, by the GA, will necessarily generate different architectural solutions. It is concluded that to define the generative process its essential to conceive a file that describes a basic initial model, i.e. a three-dimensional pattern from which you can derive all alternatives. The Objective Function always focuses on energy consumption but its calculation method may vary depending on the application case. When faced with a very restricted in its geometric aspect, usually, the Annual Energy Consumption (KWh year) is applied, while when the problem is characterized by a large formal freedom, the Intensity of Energetic Use (KWh/sqfoot) is applied.

Different types of genetic algorithms as been tested and applied to find better and more appropriate optimization methods for this GDS. Initially the MicroGA and the Standard Genetic Algorithm (AGS) was applied. In a second phase the Pareto Genetic Algorithms (PGA) were used to solve multi- criteria problems where the objective function is characterized by a complex interaction between different factors. The solutions submitted by PGA normalizes the optimization of the performance of all criteria by considering their different trade-offs in order to get the best overall performance.

This SGP was tested in various practical applications as the optimization of the skylights, sun shading canopies and façade openings, of FAUP H Tower. The objective function used was the Annual Energy Consumption. To embed architectural intentions into the generative process some rules were set out from the examination of each elevation, such as: compositional axes of the various elevations, fenestration proportions, the allocation of specific types of openings to certain compartments, etc. The rules set out restrictions to the variable parameters defining a range for each variable (Caldas et al., 2001: 2). The Gene_Arch generated similar solutions to the original building and also emerged different solutions. The strategies differ as more or less manipulation freedom that was given to the GDS, but it can be said that the proposed solutions by the GDS have more efficient performance, especially in the space heating chapter, due to changes in the south façade, and also the skylight that is more indicated to illuminate the upper floor differs in much of the original (Caldas et al., 2001). It is concluded that the application of this GDS is useful not only for the design of increasingly sustainable spaces but also to increase energy implications perception of thermal and lighting problem.

4. Case Study

The case study presented demonstrates how an architect can handle a GDS by conceiving rules and restrictions that encode architectural intentions of complex nature, proposing a generative model for the Gene_Arch GDS based on parameterization. The Gene_Arch was selected because, in addition to address directly to architecture concerns, allows the manipulation of shape manipulation, the test of different construction compositions and elevation schemes, and particularly, applies the concept of goal oriented design in its optimization and generative process, taking into account the sustainability of the solutions, an essential aspect and concern in contemporary architecture.

The subject is the Patio House of the Medina of Marrakech. The study of a vernacular typology is very interesting because, on the one hand, the architectural model is rich in its formal composition and topological organization, on the other, contains itself bioclimatic strategies tested and consolidated for centuries. Combining computational techniques with Low-Tech constructions traditions produces a feedback that contributes for the enrichment architectural culture by increase our insight to design new housing models supported in tradition but adapted to the new functional and aesthetic requirements.

The Patio House of the Medina of Marrakech is, generally, a two storey building with, usually, blind exterior façades. The House consists of narrow and long rooms (*Bayt*) with a high functional flexibility, arranged along the enclosed patio, in most cases, in its four sides. The patio, a squared plan shape, is the common and unifying space, where all the family social activities take place. Their openings ensure ventilation, lighting and, in most cases, access to different rooms.

We must emphasise that the Parametric Shape Grammar of the Patio House (Duarte and Rocha, 2006), developed in the project research on which this dissertation relies on, was a reference to structure the problem and the formulation of rules and restrictions that will govern the proposed analytical parameterization for the Gene_Arch. However, before starting any methodological procedure, an exhaustive and rigorous analysis of the architectural *corpus* of the Marrakech Patio House was carried out. Thus, the eight homes that compose the *corpus* were analysed from different points of view: Volumetric Composition of Plans., Elevation Composition and Inner Division Configuration. From this analysis enabled it was possible to establish the rules of a very diversified *corpus*, diversified due to its vernacular nature.

From the analysis was possible to build an Initial Basic Model from which all solutions can be derived. This template has been transposed into the DOE 2.1. The resulting code represents the essential structure of the Marrakech Patio House, and its parameterization will allow the design and energy performance evaluation of the various architectural solutions conceived by the Gene_Arch. The Basic Initial Model is a Patio House with two storeys, four wings, four galleries and twelve rooms per floor. The Patio Elevations have three openings, symmetrical displayed, which can take two settings, for dimensions parameterization: Parametric Elevation A – where the side windows are located along the elevation corners and where all openings function like open doors (French balconies); Parametric Elevation B – where the side Windows may not be French balconies and are in the first quarter elevation sector. The determination of the internal elevation to each wing depends on the setting of corner rooms.

After the formulation of the Initial Basic Model, rules that limit the variation of the shape behaviour where created so that the Gene_Arch generates solutions that are within the same stylistic signature.

The rules have been inferred from the tripartite analysis of the *corpus*, and for that so the rules may be from on of three types: <u>Volumetric Rules</u> – this rules regulate the behaviour of general aspects of the house as its general dimensions, the wings and the galleries of both storeys; <u>Patio Elevations Rules</u> – the patio elevations have, by far, the most rigid and remarkable architectural composition of the Marrakech Patio House and because of it these rules are essential for the preservation of the architectural features on the GDS solutions; <u>Plan Configuration Rules</u> – this rules allow to particularize and detail the Patio House, producing feedback in the volumetric behaviour and elevations composition. By this rules the key rooms are placed and essential composition principles are applied, such as, the tendency to bi-symmetry of the corner rooms and its alignment. Because of extension and complexity of the body of rules, in certain cases it’s impossible to observe all the rules, so it was necessary to establish exceptional cases and determine the behaviour of the variable parameters in those cases.

Having the Initial Basic Model, the rules and the exceptions to the generative process perfectly explained, it is possible to begin the parameterization. This consists in two essential steps: (1)

identification of the parameters that may be parameterize, regarding the restrictions imposed by the rules; 2) characterization and encoding of the multiple variables behaviour that parameterize the Initial Basic Model, taking into account the restrictions that rules impose and the various possibilities for each one.

Notice that many of the encoded variables are not necessarily commands, but quantities, measurements and essential values essential for the determination of certain value that responds to a specific command of the DOE 2.1E. Thus, two parameters types were coded:

General variables – this group of variables allows the establishment of a set of dimensions and formal variations in the Patio House. These variables are separated into General Volumetric Variables (determines the existence of each wing and each gallery) and General Dimensional Variables (establishes the general dimensions of the basic pattern such as, rooms ring's width, length and width of the patio, the parametric elevations dimensions, etc.).

Particular variables – these variables encode each room of the Patio House. Its depend on the application of the rules and the behaviour of the General Variables. It's specifically through these variables that the file of the Initial Basic Model is parameterized. These variables are grouped by type of room: corner room or intermediate room.

5. Conclusion

Analysis of three examples of GDS concluded that effectively these tools integrate the computer in the design development. The computer that was a merely an interpreter and a performer of the several commands given by the user, i.e. an electronically drawing board with more potential, goes beyond its passive character by incorporating and developing creative processes essential to support decision-making. The concept of *goal oriented design* proposed by GDS reverses the traditional method of developing projects where one thing is described, and then is assessed against design criteria and/or performance systems to be changed in an attempt to improve certain aspects. On goal oriented design method, the goals, rules, constraints and design criteria are the first aspects to be defined. The development of the project has always in sight an evolution, by transition, to achieve the proposed objectives. In this way it is given an objective to the generative processes, which are responsible for designing and search forms, through the application of optimisation techniques that approximate successively solutions of the pre-established goals.

It was noted that these systems not only increase the capabilities of the use of the computational tool but also human abilities are extended. The solution space research carried out by humans is limited and tends to decrease in proportion with the success of first hypotheses. The results of GDS practical applications showed solution samples that in most of the cases won't be considered by applying traditional or more conventional methods. More, many of the solutions found by the different studied GDS undertook emergent results were unexpected solutions emerges to solve the problem at issue. Thus, these systems not only, speeds up the design search process, justifies and consolidates the solutions and strategies taken, but also, increases our understanding, insight and knowledge of the complex nature and multi-criteria problems that define architecture today.

However, was noted that a substantial of knowledge of computing it's required to dominate and apply these programs. It is necessary to develop techniques that optimize and improve interfaces in order for more intuitive an easier handling of these computational applications.

The paradigm of goal oriented design also resets the architect's attitude when facing the design statement. With the implementation of GDS, the architect ceases to be a draftsperson to play a bigger role on which he formulates the problem (essential issues), the generative process (such as, how the response should be express), and the optimization vectors (what the solutions should achieve). By analogy, the architect assumes the role of "nature" dictating rules, constraints to setting an environment to evolutionary architecture. Assessment and selection tasks as also the generative and optimization problem redefinition, taking into account previous results, will become increasingly central with the implementation of this type of tools.

It is in this context that the case study discusses the formulation of an analytic parameterization methodology for Gene_Arch. To develop and consolidate a generative process, that expands previous methodologies (Caldas, 2006) from singular buildings to architectural typologies, the role that the architect will have by applying this type of systems was inevitably addressed.

The proposed methodology of the analytical parameterization for the Gene_Arch is based on the following steps:

1) Volumetric Analysis of Elevations Composition and Interior Spatial Division – intended to frame and define the study subject by identifying the implicit and explicit;

2) Basic Initial Model – after the analysis is possible to establish a standard type which can be derived for the formulation of any solution, fitted within the characteristics that define the typology or architectural *corpus*. This model is described in code that will run in DOE 2.1E. a thermal, lighting and energetic performance simulator, embedded in Gene_Arch, that will be parameterized later.

3) Rules and Constraints – derived directly from analysis, taking into account the possibilities of processing a basic pattern, intend to impose restrictions on the transformation possibilities to the initial basic pattern, ensuring the stylistics coherence of the solutions that can be generated;

4) Identification and Encoding of the Variable Parameters – from the initial basic model and taking into account the limitations imposed by the rules, the variable parameters of the file that describes the basic template were established, and its behaviour defined through programming techniques;

5) Goal Performance – in this case will be the Energy Intensity Use minimization. The Energy Intensity Use was chosen because it allows the comparison of different scale solutions.

In the chapter of future developments to the parameterization proposed in this thesis first the work of code depuration must be finished in order to obtain results that will allow a rigorous analysis to understand the different and valid strategies used by the GDS to solve the design problem. Nevertheless its possible to number the following improvements and developments: 1) introduction of the 3rd ring – the urban negotiation ring; 2) Shaping shadow plans in the courtyard in order to simulate the arcade; 3) Shaping exterior shadow plans that contextualizes the house in its urban surroundings.

It must be emphasized that in the development of this thesis it was carried out work (not finished yet) to the conception of contemporary architectural models from the relaxation of the constraints and rules undertaken in this parameterization proposal. This future work will allow the comparison of contemporary solutions with traditional ones and also the creation of hybrid architectures that resumes traditional and modern features.

At last new and more advanced visualization methods must be developed. This may be undertaken by the development of LISP routines that will provide a more rigorous e detailed visualization of the GDS results in CAD packages, making easier the transposition of an abstract simulation model to a more detailed and attractive visual model. The use of a CAD interpreter also enables an easier connection to CAM (Computer Aided Manufacturing) technology like Rapid Prototyping (RP). The physical models are indispensable to a rigorous comparative analysis because, as Caldas (2001:5) argues, the physical models are at the moment the best method to evaluate different aspects and architectural components of the different solutions.

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