# Generation of Energy-Efficient Patio Houses With GENE_ARCH

## *Combining an evolutionary generative design system with a shape grammar*

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**Abstract.** *GENE_ARCH is a Generative Design System that combines Pareto Genetic Algorithms with an advanced building energy simulation engine. This work explores its integration with a Shape Grammar, acting as GENE_ARCH's shape generation module. The urban patio house typology is readdressed in a contemporary context, both by improving its energy-efficiency standards, and by rethinking its role in the genesis of high-density urban areas, while respecting its specific spatial organization and cultural grounding. Field work was carried out in Marrakesh, surveying a number of patio houses which became the Corpus of Design, from where a Shape Grammar was extracted. The computational implementation of the patio house grammar was done within GENE_ARCH. The resulting program was able to generate new, alternative patio houses designs that were more energy efficient, while respecting the traditional rules captured from the analysis of existing houses. After the computational system was fully implemented, it was possible to complete different sets of experiments. The first experiments kept more restrained rules, thus generating new designs that closer resembled the existing ones. The progressive relaxation of rules and constraints allowed for a larger number of variations to emerge. Analysis of energy results provide insight into the main patterns resulting from the evolutionary search processes, namely in terms of form factors of generated solutions, and urban densities achieved.*
**Keywords.** *Generative Design Systems; Genetic Algorithms; Shape Grammars; Patio Houses; Energy Efficiency.*

## INTRODUCTION

This paper describes the integration of GENE_ARCH, a Generative Design System based on genetic algorithms and a detailed energy simulation program (Caldas, 2001; Caldas 2008), with Shape Grammars (Stiny, 1972). The goal of this research is the development a computational system for generating novel urban and housing designs, able to optimize the environmental behaviour of design solutions, both in terms of thermal and lighting conditions, while respecting the formal structure of a coherent Corpus of Design.

The Marrakesh Medina patio houses have been chosen for this experiment for several reasons. First, the complexity and diversity verified in the architectural corpus was attractive because most housing configurations emerge from a systematic application of the rules and constraints that define the core of this typology. Second, the Medina and its patio houses represent an intrinsically interrelated structure linking the urban and building scales, which can not be dissociable from each other. Third, the intricate relation between urban fabric, patio houses, and the progression from the public realm to private space that emerges from it, imprints in the urban space some fundamental ideas that may be applicable to contemporary design contexts.

In order to capture the urban and architectural complexity present in the site, it was necessary to develop two shape grammars: an urban grammar, and a patio house grammar. While the urban grammar has been described in detail elsewhere (Duarte et al., 2006a), this paper focuses mainly on the housing scale, addressing the traditional patio house of the Marrakesh Medina. The objective is to create a new generative system able to optimize the environmental behaviour of this typology, in terms of human comfort, while preserving its essential cultural and formal features.

In previous work, GENE_ARCH has proven to be capable of incorporating constraints that allow the translation of architectural intentions into a computer-based system (Caldas, 2008). In this paper, the object of GENE_ARCH will expand from the architecture of a single building to the complexity of an architectural typology. The objective is to demonstrate, through the formulation of a parameterized methodology, how to implement the formal structure and syntax of a given architectural typology into a software like GENE_ARCH.

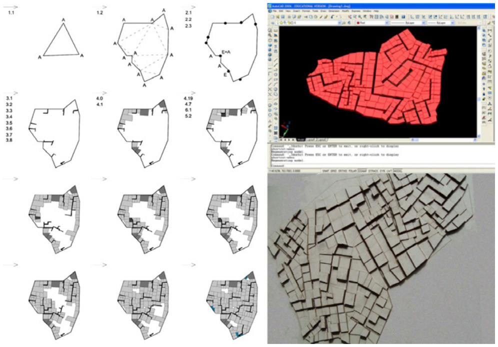
The proposed methodology consists of five stages. The first stage is the architectural analysis of the Corpus of Design, to characterize the typology under study. The second stage establishes a prototype model that synthesises all the essential features of the architectural corpus, from which any particular spatial configuration can be derived. The third stage establishes the rules and constraints applicable to the transformation of the prototype model into a particular housing configuration. In the fourth step, all variable parameters, rules and constraints, as established in the previous step, are coded into the system. Finally, in the fifth stage, the objective functions that will guide the evolutionary-based optimization processes are established.

## URBAN AND HOUSING CONTEXT

Zaouiat Lakdar is one the oldest zones of the Marrakesh Medina. Its urban and architectural patterns suggest a well-defined and coherent architectural corpus, making it an adequate subject for this research. The urban fabric is composed mostly of patio

*Figure 1*
*Left - Zaouiat Lakhdar, plan of the area under study. Center – example of a patio house. Right - example of a derb.*

Figure 2
Urban Shape Grammar. Left: Partial derivation of the existing urban fabric of Zaouiat Lakhdar. Up right: the shape grammar interpreter. Down Right: Physical model for a new urban solution for the Zaouiat Lakhadar perimeter. Source: Duarte et al., 2006a.



houses, where the patio serves as the main source of daylight and natural ventilation to the interior spaces. Contrarily to western urban configurations, where buildings gain access to natural light and ventilation by means of windows that open into streets, in this case streets can be reduced to a minimum width, and act mostly as physical access to houses. The exceptions are the main public streets, which connect housing quarters with major public spaces or buildings. From those streets, there is a ramification of the street network into semi-public, partially-covered corridors (derbs), that will eventually lead to the private space of the houses. This gradient between public and private space is a main characteristic of this particular urban structure. The reduced area dedicated to streets and public spaces makes its construction density surprisingly high for the typical building height of the houses, of only two floors.

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### *Urban shape grammar*

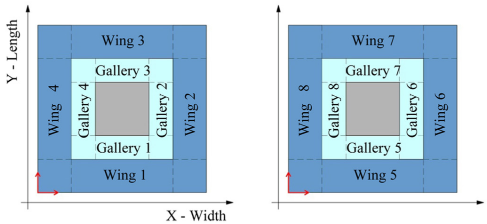
A bottom-up approach was used for developing the urban grammar, emphasizing the notion of growth inside a known boundary (Duarte et al., 2006a). The rules establish the incremental expansion of derbs, starting at specific entry points, and guiding the systematic insertion of lots. Lots that have a direct access to the streets are placed at an early phase of the grammar. After this step is completed, more derbs grow between the first lots, which in turn will allow the placement of new lots. This loop process is repeated until the whole urban area is filled [Figure 2].

The urban grammar is open-ended and non-deterministic, meaning that alternative rules and parameters can be applied in different steps of the derivation process, being able to produce different solutions for the same urban area. In previous work (Duarte et al., 2006a), a partial derivation of the existing urban pattern was developed. A computational tool (Shape Grammar Interpreter) that implemented the urban shape grammar of Zaouiat Lakhdar was also developed, with some results presented in Figure 2.

## PATIO HOUSE SHAPE GRAMMAR

While an initial house grammar development has been presented elsewhere (Duarte, 2006b), in this paper the data collected was subject to a renewed and more complex analysis, due to specific issues related to the creation and implementation of the generative processes required by GENE_ARCH. From

Figure 3
House Grammar Basic Pattern. Decomposition of the patio houses basic formal structure into patio (gray), galleries(light blue) and rooms or 'bayts' (blue). Right, ground floor; Left, upper floor.



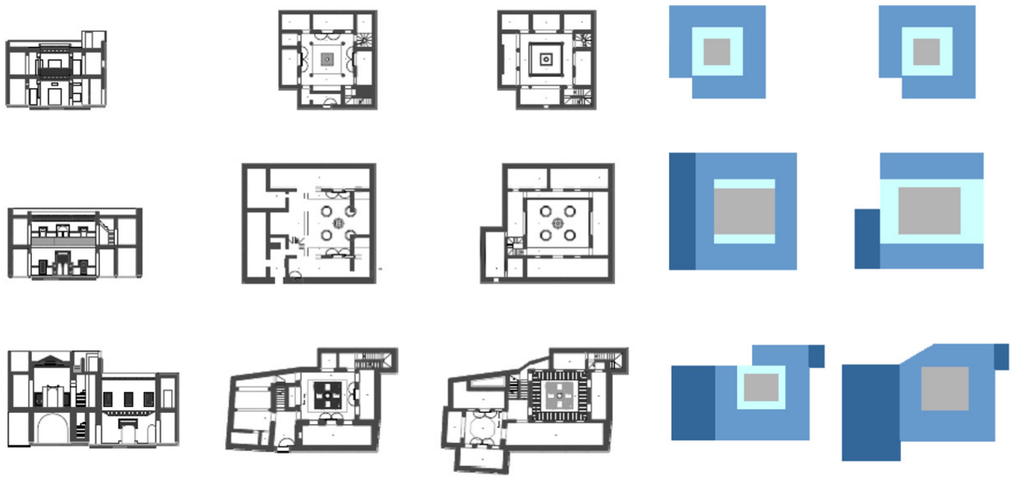


*Figure 4*
*Tree houses of the corpus (left) and their House Grammar formulation (right). The areas in dark blue belong to the third ring, not included in this study.*

this second analysis, new relations, constraints, patterns and rules emerged.

For the elaboration of the shape grammar of the Marrakesh Medina patio house, a site survey was performed for the eight houses that compose the Corpus of Design (Dar 27, Dar 33, Dar 73, Dar Dounia, Dar Frances, Dar Charifa, Dar Hannah and Dar Foundouk). Through the corpus analysis, it was possible to establish a basic pattern formed by three rectangular rings around the inner patio, in two floors [Figure 3].

The inner courtyard, quadrangular or slightly rectangular, is the agglutinating space of the patio house, where all social activities take place. A direct relation can be found between the social and economic welfare of a family, and the size and architectural ornamentation of the patio. All rooms open to the inner patio, and it is from the patio, through the galleries, that one can access them. The patio is normally surrounded by galleries, an important element in the architecture of Moroccan patio houses. Galleries act not only as a buffer space to the more private bayts, but they also provide horizontal circulation to the second floor, and valuable shading for façade openings in the lower floor.

Around the patio, the first ring corresponds to the galleries, the second one to the rooms (bayts), and the third one to additional rooms. The third ring was excluded from this study, since it is used mostly for adaptation of the rigid patio house scheme to site specificities, and is only considered within the Negotiation Grammar. The two inner rings may have one, two, three or four sides.

For the development of the grammar, a dimensional analysis was undertaken in order to extract architectural proportions - like the ratio between length width of  patios - and the dimensional intervals for some important variables and parameters, in order to insure that the grammar results are within the architectural morphology of this typology.

One of the goals of this project was to be able incorporate the several features, complexities, and possibilities that characterize the Marrakesh Medina patio houses typology. Because Genetic Algorithms support the evolutionary search mechanism of GENE_ARCH, this system requires the implementation of a generative process with specific characteristics. Caldas (2008) established the key features and methods to the elaboration of a generative process within GENE_ARCH: first, a basic shape (prototype model) has to be established, accounting for the occurrence of all possible architectural components in it (i.e. walls, skylights. etc.), and for all the possible transformations they can suffer; second, constraints and variable parameters of the basic model are established, to limit and guide the possible transformations that can occur. Constraints applied to the variable parameters are the means to implement the architectural features that can stylistically characterize the different solutions generated.

## SHAPE GRAMMAR LINK WITH GENE_ ARCH

The proposed methodology to integrate GENE_ ARCH with the housing shape grammar is:

1. Prototype Model - Departing from the basic pattern formulated for the House Grammar, a hypothesis for a basic model that synthesises the patio houses basic architectural structure was established. This model followed in many aspects the House Grammar, but had to include other aspects to allow for the emergence of new solutions. The initial model also has to be flexible and elastic, in terms of its geometric behaviour, to ensure a wide variety of solutions.
2. Variables - Several features of the prototype model formal structure are chosen to be variable. Their behaviour is constrained by previously defined rules. The variables allow the derivation of different solutions from an initial model.
3. Rules and Constraints - Rules impose constraints to the variation of the prototype model assigned variables. From the corpus analysis, one can turn explicit the implicit rules underlying in the corpus common architecture. It is through the rules and constraints that are imposed to the basic model that one can ensure that instances that emerge from the generative and optimization process can be characterized as patio houses from the Marrakesh Medina.
4. Objective Function - Finally, an objective function is determined to guide the generative and optimization process. The proposed fitness criteria and search mechanism of the GA selects several solutions from each generation. Selected solutions characteristics will be propagated to the next generations, and the evolutionary process continues towards the optimization of the objective function, until final solutions are reached.

## CORPUS ANALYSIS

The analysis done for GENE_ARCH integration was threefold: volumetric, spatial layout and elevation composition.

*Table 1*
*Patio dimensions and ratios found in the corpus.*

| **Patio dimensions and rations** | | | |
|---|---|---|---|
| **Patio houses** | **Wpatio (m)** | **Lpatio (m)** | **Rpatio (Lpatio/Wpatio)** |
| DAR 27 | 5,50 | 7,00 | 1,27 |
| DAR 33 | 5,50 | 9,40 | 1,70 |
| DAR 73 | 3,60 | 4,10 | 1,14 |
| DAR CHARIFA | 9,03 | 9,03 | 1,00 |
| DAR DOUNIA | 10,71 | 8,04 | 0,75 |
| DAR FRANCES | 7,80 | 8,00 | 1,03 |
| DAR HANNAH | 6,87 | 6,01 | 0,88 |
| FOUNDOUK | 6,60 | 6,60 | 1,00 |

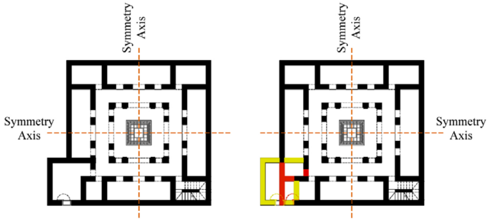



*Figure 5 (left)*
*Implicit double symmetry in Dar Charifa. Left: original ground floor. Right: Minor changes that have to be applied to restore full double symmetry.*

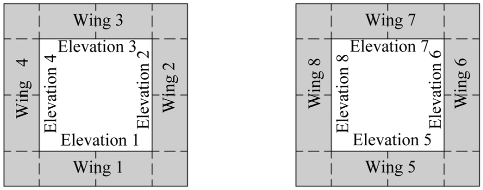



*Figure 6 (right)*
*Second ring patio elevations. Right: ground floor; Left: upper floor.*

## *Volumetric analysis*

Table 1 shows patio dimensions and ratios in the Corpus. The patio dimensions include the first ring (galleries). Thus the insertion of the first ring will subtract from the width and the length of the patio. The patio has a vital relevance in the structure of the house, and determines the dimensions of all the other spaces. It is possible to find a proportion relation between the width (Wpatio) and the lenght (Lpatio) of the patio. This ratio (Rpatio) is crucial for assessing the right proportions in the houses that will be generated by GENE_ARCH. The depth of the first ring (galleries) typically varied between 1m and 1.9m, depending on the patio dimensions.

## *Spatial layout analysis*

Three key types of rooms are considered: the bayts; the entrance hall and the staircase. The entrance hall, in most cases, is located at a corner. The staircase is always in the same wing of the entrance hall, or in its perpendicular wing. The space between corner rooms is generally occupied by one or two rooms.

In terms of plan layout, a tendency for a double symmetry between corner rooms can be observed. Figure 5 shows that even in cases where this double symmetry is not explicit, it is possible, with minor changes, to establish the double symmetry pattern. Double symmetry also exists in the partitioning of the second ring. Finally, room partitioning in both floors tends to be similar, due to structural constraints imposed by traditional construction types.

## *Patio elevation analysis*

The name of each patio elevation, in the context of this analysis, is given in Figure 6, showing the nomenclature used.

Patio elevations are fundamental in the partitioning of the second ring, because it is from them that the access to rooms takes place. The elevations have in most cases only three openings. There is a clear tendency for symmetry in the formal composition of each elevation. The axis of symmetry is located in the middle of each patio elevation and the elevations are composed by a central opening and two lateral ones. The lateral openings can assume two distinct positions. The first position is at the corner. The second position can be located in the first quarter of the patio length. It is the interior room layout that governs openings positioning. If a corner rooms

*Figure 7 (left)*
*Positioning of the patio elevations lateral openings and its relation with the internal layout of the second ring. Left: First position - Dar Frances, Elevation 8. Right: Second position - Dar Frances, Elevation 1.*

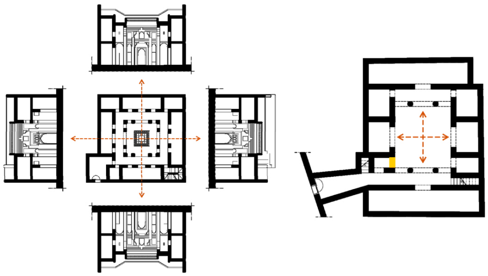


*Figure 8 (right)*
*Double symmetry between patio elevations. Left: complete double symmetry in Dar Charifa. Right: incomplete double symmetry in Dar 33 (it lacks the yellow marked window to become perfectly bi-symmetric).*

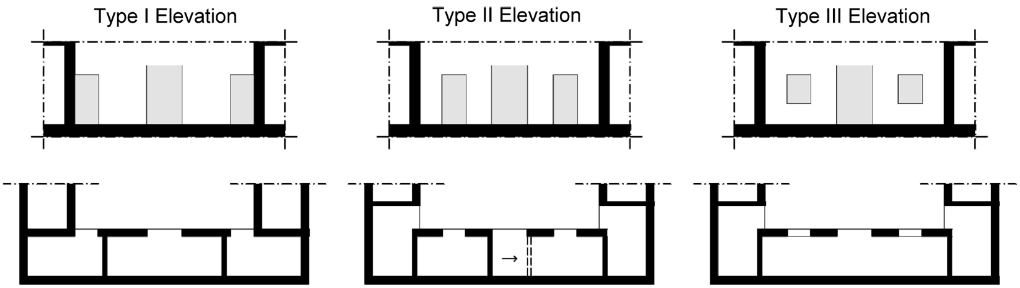



*Figure 9*
*The three elevations types derived from the Corpus, with corresponding plan partitioning.*

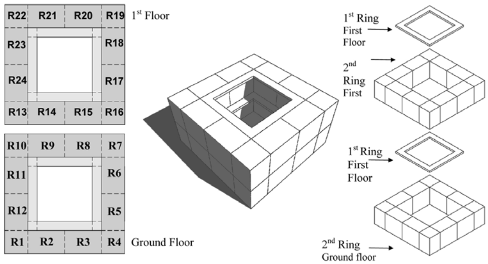



*Figure 10*
*The Prototype Model. Left: Floor plans with room nomenclature. Center: Perspective of the model. Right: Exploded Axonometric.*

belongs to the wing, the correspondent patio elevation will have lateral openings positioned in the first position, and becomes a door into that room. If not, the lateral openings will assume the second position [Figure 7].

The patio elevations also have a tendency for double symmetry between them, with facing elevations being identical, as illustrated in Figure 8.

From this analysis, it was possible to establish three different patio elevation patterns. Figure 9 shows the relation between each elevation type and the correspondent wing partitioning. Considering that rooms always have access from the elevation openings, Elevation Type I occurs when the corner rooms are in the same wing. Type II happens when the wing has no corner rooms and is divided in two rooms. Finally, the Type III elevation is a derivation of Type II but with only one room in the corresponding wing.

## PROTOTYPE MODEL

The prototype model is like a 'rubber building' that can be further sculpted by the GA-based search process. Figure 10 shows the Prototype Model that results from a simplification from the more complex house shape grammar. This model is a two-storey house where the height of each floor is the same

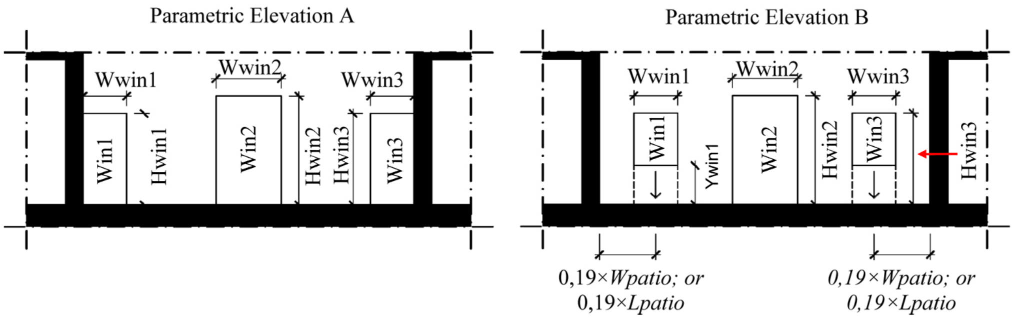



*Figure 11*
*Parametric Patio Elevations. Left: Parametric Elevation A - to be applied when the wing has corner rooms. Right: Parametric Elevation B - to be applied when the wing does not have corner rooms.*

(3,70 m). Each floor contains four galleries, which compose the first ring, and four wings, that will structure the second ring. Each wing can contain a maximum of two rooms between the corner rooms, adding to a maximum of 24 rooms contemplated in this basic model. However, this number does not match the room the maximum number of rooms that can be generated , which will always be smaller, due to the number of openings available in each patio elevation.

Two types of parametric elevations can be assigned to each wing, depending on the corner rooms layout. Each one has three openings, which are also parametric. Figure 11 shows the parametric patio elevations. Parametric Elevation A is applied when the wing has two corner rooms and generates Type I Elevations. If the wing does not have corner rooms then Parametric Elevation B will be applied. It is from this elevation that Type II and Type III Elevations can be derived.

## EXPERIMENTS

Initial experiments were performed using the shape grammar with all the constraints, as derived from the Corpus analysis. The goal was to determine if it was possible to improve the energy performance of the buildings, within the same constraints, or if

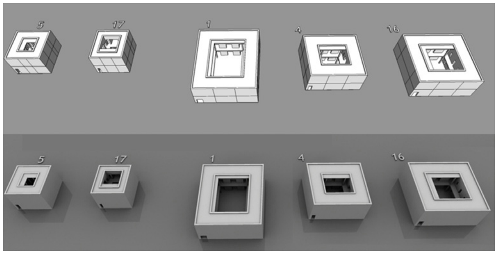


*Figure 12*
*From left to right: Random solutions Rand 1(#5), Rand 2 (#17); Generated solutions Gen1 (#1), Gen2 (#4), Gen 3 (#16).*

the constraints were so limiting that no significant improvement could be achieved while applying them. Variables were: patio dimensions and proportions, house dimensions, space layout and type of elevation (interrelated), dimensions of windows and doors, existence or not of galleries (ground and first floors), and gallery depth. Patio proportions were within the grammar limits, and so were minimum and maximum dimensions for each element, from general house dimensions to windows and doors. In terms of galleries, in the ground floor all four galleries had to exist, to serve as access to first floor rooms, but the first floor galleries were allowed to exist or not. In case they existed, their dimensions followed the grammar rules.

A second set of experiments involved relaxing some the constraints imposed by the traditional so-

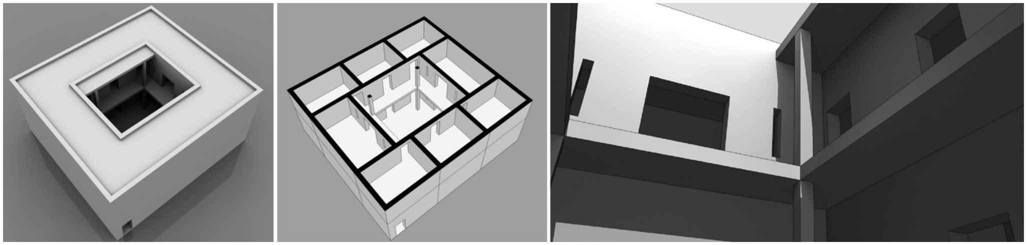


*Figure 13*
*Solution Gen2. Top: Exterior view, showing the south overhang, and plan. Bottom: Larger glazing areas face south (shaded by overhang) and north. Three-room wings thus also become south and north. West elevation has only slits as the lateral openings.*

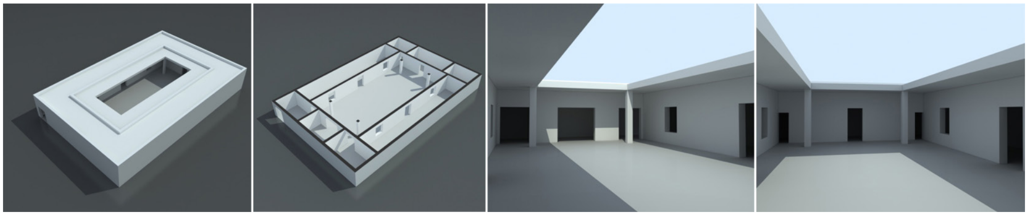


*Figure 14*
*Solution Const 1, with constraints relaxed. 1): Exterior view, showing overhang in all directions. 2) plan. 3) North facade at the end of the patio. 4) South facade at the opposite end of the patio, with fewer openings.*

Table 2
*Energy needs for random and best solutions (Gen and Const1), following the same shape grammar rules.*

| | Lighting (kWh) | Heating (kWh) | Cooling (kWh) | Total Energy (kWh) | Area (m2) | EUI (kWh/m2) |
|---|---|---|---|---|---|---|
| Rand 1 | 4396 | 2872 | 21775 | 34272 | 159 | 215 |
| Rand 2 | 3839 | 2432 | 23709 | 35174 | 132 | 266 |
| Gen 1 | 16940 | 11195 | 37044 | 77341 | 533 | 145 |
| Gen 2 | 11781 | 8909 | 28780 | 58846 | 389 | 151 |
| Gen 3 | 14009 | 9759 | 33264 | 67905 | 467 | 145 |
| Const 1 | 6741 | 11781 | 24120 | 50350 | 328 | 154 |

lutions and allowing more freedom to the system. New constraints permitted larger patio ratios (ratio between length and width), up to 2:1, allowing for longer and slimmer patios. The need for double symmetry in opposing elevations was suppressed, what is significant in environmental terms (for example, south and north facades can have significantly different requirements). However, the requirement for space layout double symmetry was kept. The maximum window/door width was increased to be as large as the wall where it stood, minus two gallery depths, instead of having a limit fixed by the grammar. Finally, the houses were additionally allowed to have only one storey. This last case is the one displayed in this paper.

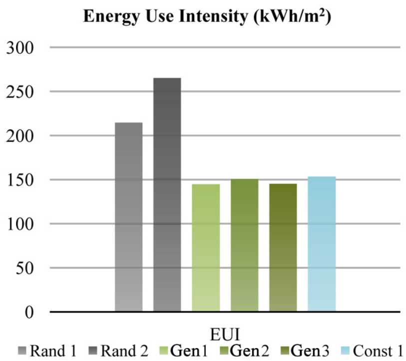
Three groups of GENE_ARCH generated patio-house solutions are presented in Figure 12, with the north direction facing upward. The first group, to the left of the image, are random solutions (Rand), randomly selected from the initial solutions generated by the GA. The second group (Gen), to the right of the image, consists of solutions, keeping all the constraints from the existing medina patio houses. The solutions shown are the best designs from three separate runs of GENE_ARCH. The third group (Const) are solutions resulting from relaxing the constraints imposed by the traditional solutions and allowing more freedom to the system, and will be shown in Figure 13.

## ANALYSIS OF RESULTS

Solutions were analyzed in three different ways: 1) Visual inspection, with renders and movies; 2) Energy analysis; 3) Analysis of shape characteristics.

### *Visual Inspection*

Figure 13 displays solution Gen 2 in greater detail. The patio has a ration of 1.29, as the depth of the



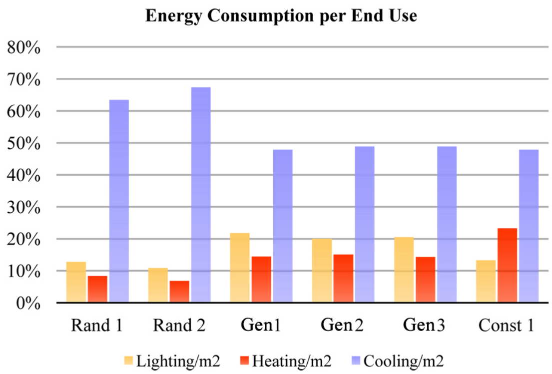
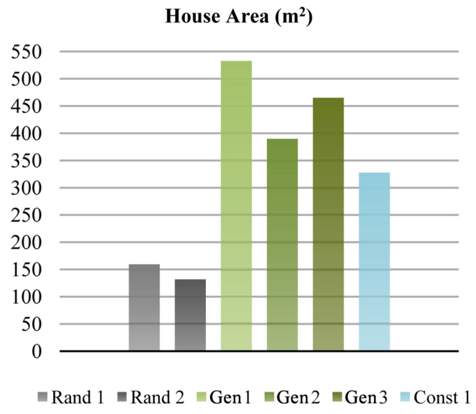




Figure 15
*Left - Energy Use Intensity (energy per unit area) for the random and best solutions (Gen and Const1). A 61% average reduction was achieved, while respecting the shape grammar. Right: Cooling is the most significant end use, in all cases.*



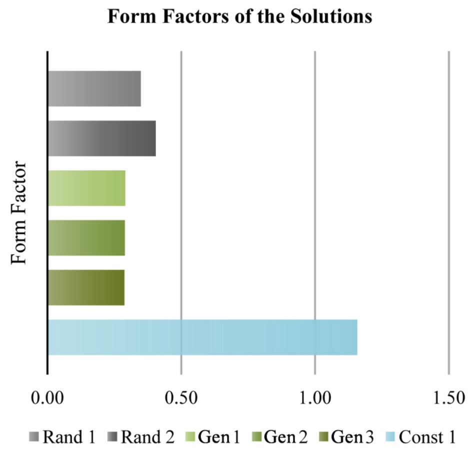




*Figure 16*
*Left: Area of random and generated and constrained solutions. Right: Despite having different areas, all generated solutions (Gen1, Gen2,Gen3) were found to have the same Form Factor of 0.29.*

rooms is 4.1m. There is only one overhang in the top floor, which is facing south. The south and north facades are similar, as imposed by double symmetry rules. GENE_ARCH makes the elevations with the most percentage of glazing those facing south (shaded and north), thus orienting the building so that the wings with three rooms are south and north too. Due to the rules that relate the design of the elevations with the spatial layout, the wing with three rooms must also be the one that has three doors, and thus a larger percentage of openings. In the wings that have only one room (east and west, where shading is more difficult and the risk of overheating is higher), the central opening is larger, and the two lateral ones are just slits in the wall.

In solution Const 1 [Figure 14], the system takes advantage of the relaxation of constraints. It generates a 2:1 patio ratio, higher than previously allowed. Because the 1-storey volume with the wider patio provides less self-shading, it created galleries to all directions. Since double symmetry is no longer imposed for the elevations (even though it is for the space), it creates larger openings to the north, which only get direct sun at fewer hours of the year, and shade appropriately the south facade, also providing it with smaller openings.

Initial visual inspection also showed that generally, the main feature that immediately emerges is that the solutions have a much larger size, in relation to the initial ones (which are closer in this aspect to the existing houses, as seen in Figure 1), even though the overall proportions remain similar.

| | **Length** | **Width** | **Area** | **Plot size** |
|---|---|---|---|---|
| Rand 1 | 10.1 | 9.8 | 159 | 100 |
| Rand 2 | 10.4 | 9.6 | 132 | 99 |
| Gen 1 | 22.0 | 18.9 | 533 | 415 |
| Gen 2 | 15.4 | 16.7 | 390 | 257 |
| Gen 3 | 18.0 | 18.8 | 466 | 338 |
| Const 1 | 29.6 | 18.9 | 328 | 558 |

*Table 3*
*Patio-house dimensions and plot size.*

*Table 4*
*Construction index, patio ratio and form factor of the several solutions.*

| | Construction Index | Patio Ratio | Form Factor |
|---|---|---|---|
| Rand 1 | 1.6 | 1.1 | 0.35 |
| Rand 2 | 1.3 | 1.1 | 0.40 |
| Gen 1 | 1.3 | 1.3 | 0.29 |
| Gen 2 | 1.5 | 1.3 | 0.29 |
| Gen 3 | 1.4 | 1.1 | 0.29 |
| Const 1 | 0.6 | 2.0 | 1.16 |

### *Energy analysis*

Energy analysis was based on the following assumptions: in the context of the Marrakech Medina, poor environmental design would not result in energy consumption, but in human discomfort, as there would be no systems to consume energy. However, it is rather complex to compare solutions in terms of discomfort conditions. It was then assumed that the offset between comfort conditions and actual conditions in the building could also be expressed in terms of how much energy would be required into the building to make it comfortable, both in terms of heating, cooling and lighting.

Results are shown in Table 2. Final results are expressed in Energy Use Intensity (EUI, in kWh/m2), which means energy consumption per unit area, so that solutions can be comparable despite their differences in area (since area was not a constraint in these experiments). On average, the found solutions reduced energy needs by an average of 62%, while complying to the same shape grammar rules [Figure 15]. The best solutions generated by GENE_ARCH have very similar EUI levels.

The reduction in energy use intensity was mostly achieved by reducing the cooling loads in the houses. As can be seen in Figure 16, a reduction in the percentage of cooling loads was very significant, improving from representing about 80% of the total loads for achieving comfort conditions (cooling, heating, lighting), to only 60%. That means the best designs are more robust in terms of resisting to overheating, even if that stress is still the highest, due to climate characteristics. On the other hand, lighting loads increased from 15% in the random solutions to 25% in the generated solutions (Gen), showing that the houses also became a little darker, in the process of protection from overheating. That does not happen with solution Const 1, where the high form factor (relation surface/volume) promotes better daylight use. Heating loads also increased form 9% in the random solutions, to 17% in the Gen solutions, and 28% in the Const 1 solutions (here the increased form factor working to its disadvantage), given the low night temperatures felt in desert-like climates.

### *Shape analysis*

In order to understand the solutions that GENE_ARCH was proposing, another level of analysis was introduced, regarding the geometrical and formal characteristics of the proposed designs. The first observation was the general increase in size [Figure 16]. However, that area increase corresponded to a similar Construction Index (relation between plot area and built area), and to similar construction density levels. Thus, a significant conclusion is that it is possible, in this type of urban fabric, and respecting the strict rules of the grammar, to decrease energy consumption levels by 60%, without decreasing construction density. It implies that high densities can be achieved with reasonable energy performance, by resorting to a patio-house based urban solution. Nevertheless, the significant increase in overall building dimensions was a concern.

In terms of the generated solutions (Gen), the patio proportion ratios remain very close to the random solutions, and showed no impact in the energy consumption of the solution. The factor that most closely correlated with the decrease in energy consumption of the Gen solutions was Form Factor. In fact, all Gen solutions had a Form Factor of 0.29, even though they have rather different appearances [Table 4 and Figure 17].

## CONCLUSIONS

Results prove that it is possible for GENE_ARCH to incorporate the main features of an architectural typology, and re-incorporate them in the solutions it generates. In the first set of experiments (Gen), the different configurations obtained were diverse but stylistic coherent with the shape grammar developed, and showed a 61% average decrease in energy consumption, in relation to random patio houses generated within the same shape grammar.

The second set of experiments was conducted to assess the impact of the relaxation of some constraints on both energy performance and formal configurations. The constraint relaxation applied has significant impact in the appearance of solutions, although it does not significantly deteriorate the coherence of the architectural solutions. This relaxation had some minor penalty in relation to energy consumption levels.

From the analysis of the solutions generated by GENE_ARCH, it was possible to extract some patterns that permit to understand the main factors underlying the success of typical configurations that emerge during the search process. In particular, it was found that the Form Factor of the patio houses showed a strong correlation with energy consumption levels, with all the best solutions showing the same Form Factor of 0.29, despite their rather different appearances.

A significant finding was that it is possible to decrease energy consumption levels by 60% without decreasing construction density, for this type of urban fabric and within the strict rules of the grammar. This implies that high densities can be achieved with reasonable energy performance levels, by resorting to patio-house based urban solution.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## REFERENCES


Bouchlaghen, N 2000, 'Optimizing the design of building envelopes for thermal performance', *Automation in Construction*, vol. 10, no. 3, pp. 101– 112.

Caldas, LG 2002, 'Evolving three-dimensional architecture form: an application to low-energy design', in J. Gero (eds), *Artificial Intelligence in Design*, Kluwer Publishers, Dordrecht, pp. 351–370.

Caldas, LG 2008, 'Generation of Energy-Efficient Architecture Solutions Applying GENE_ARCH: A Evolution-Based Generative Design System', *Advanced Engineering Informatics*, vol. 22, no. 1, pp. 59-70.

Couchoulas, O 2003, *Shape evolution: an algorithmic method for conceptual architectural design combining shape grammars and genetic algorithms*, Ph.D. Dissertation, University of Bath, UK.

Duarte, JP, Rocha, J, Ducla-Soares, G and Caldas, LG 2006a, 'An urban grammar for the Medina of Marrakech', *Proceedings of the 2nd International Conference on Design Computing and Cognition*, Eindhoven, The Netherlands, pp. 483–502.

Duarte, JP, Rocha, J and Ducla-Soares, G 2006b, 'A Grammar for the Patio Houses of the Medina of Marrakech - Towards a Tool for Housing Design in Islamic Contexts', *Proceedings of eCAADe'06*, Volos, Greece, pp. 860-866.

Elbeltagi, E, Hegazy, T and Grierson, D 2005, 'Comparison among five evolutionary-based optimization algorithms', *Advanced Engineering Informatics*, vol. 19, no. 1, pp. 43–53.

Stiny, G and Gips J 1972, 'Shape Grammars and the Generative Specification of Painting and Sculpture', *Information Processing 71*, Amsterdam, The Netherlands, pp. 1460-1465.