Unveiling the structure of the Marrakech Medina: A shape grammar and an interpreter for generating urban form

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Abstract

This paper describes research carried out to develop a parametric urban shape grammar for the Zaouia Lakhdhar quarter of the Medina of Marrakech in Morocco. The goal is to create the basis for a system that could capture some features of the existing urban fabric and apply them in contemporary urban planning and architectural design. The methodology used is described, from the initial historical analysis and fieldwork to the identification of three subgrammars necessary to encode the complexity of the urban preexistences: the urban grammar, the negotiation grammar, and the housing grammar. Top-down and bottom-up approaches to grammar design are analyzed and compared. The bottom-up urban grammar developed is then described, and a hand derivation of the existing urban fabric is proposed. Visual, symbolic, and tagged computer implementations of shape grammars are briefly discussed and a novel design generated by the tagged interpreter is presented.

Keywords: Generative Systems; Islamic Architecture; Shape Grammars; Urban Design

1. INTRODUCTION

This paper describes research carried out to develop a parametric shape grammar able to capture, and replicate in other contexts, some of the urban, architectural, and morphological characteristics of the ancient fabric of the Marrakech Medina, namely its Zaouia Lakhdhar quarter. This research is part of a larger project that aims at incorporating shape grammars (Stiny, 1980) with an existing generative design system based on genetic algorithms (GAs). The project’s final goal is to develop a computational system able to generate novel urban and housing configurations that are more environmentally sustainable and energy efficient, while respecting certain cultural and spatial qualities as captured by the shape grammar. The final computational model should act at two different scales: the urban scale, where the layout of a neighborhood is outlined; and the architectural scale, where the interior topology of individual houses is defined. The development of two other grammars required for describing the whole urban structure—the patio house grammar and the negotiation grammar—will be presented elsewhere. The research described in this paper is focused on the creation of a shape grammar to describe the urban features of the specific quarter of the Marrakech Medina referred to above.

There were three reasons for choosing the Marrakech Medina as the case study for this experiment. First, this particular urban fabric was attractive because of the intricate connections between the urban configurations and the patio houses (Figs. 1–3). Second, previous work (Rocha, 1995) on the Zaouia Lakhdhar quarter, aimed at characterizing morphologically and architecturally the urban and architectural patterns of this area, suggested that a stylistically coherent corpus of designs existed, and that it had enough variety and richness to fit the research objectives. Third, the population increase that occurred in Marrakech during the last decades, as in most north African and Middle East cities, has led to an uncontrolled urban growth that produced urban environments lacking the spatial richness found in historical vernacular areas. Thus, this research intends to provide a computational framework that can assist designers in the design of urban environments that maintain traditional spatial and compositional principles while satisfying the requirements of contemporary life.

This research draws on previous implementation of a generative system using GAs (Caldas, 2001, 2005) and on the application of shape grammars to customized mass housing (Duarte, 2001, 2005), but the work presented here takes the Marrakech Medina as its architectural precedent.
2. HISTORIC AND CULTURAL CONTEXT

In Islam, Muslims pray toward the Kaaba in Mecca, the sacred direction or qibla. The correlation between the qibla and the street pattern is important to understand the relationships among the religious buildings and the surrounding fabric. If the Mosque was built first, as it often is the case in many Islamic cities, then the street pattern would evolve around and from the Mosque. The foundation of Marrakech is related to an important sub-Saharan caravan route, and when it became the capital of the Almoravids in 1107 it already had 100,000 inhabitants (Bonine, 1990; Mortada, 2003). The origin of the Zaouia Lakhdir quarter, one of the oldest in the Medina, is related with the construction of the Ben Youssef Mosque in the 12th century. Cities of Muslim origin share specific culture and social values which are embedded in their everyday system of social organization, and, therefore, in architecture as well. In this section, we identify and put forward a succinct contextualization of these cultural and religious values that have to be taken into consideration in any interpretation of Islamic architecture. Social and cultural characteristics of urban planning and architecture as well as many aspects of Islamic social behavior are related to Islamic law (shari‘ah), and certain principles found in urban environments of Islamic cities are a tribute to shari‘ah. They are clearly founded in the basic source of the shari‘ah, the Qur‘an and the sunnah (life of the Prophet), whereas others come from traditional building codes related to, inheritance, and endowment laws. This set of religious and social values and rules determine many of the social patterns of Islamic society and its urban and architectural spatial configurations. An unstated Islamic condition is that a strong social relationship is underlined by the concept of brotherhood, which has frequently been mentioned in the Qur‘an, and that family is the most fundamental element of Muslim society, where strong family ties are expected to last. This partially explains the organization of domestic architectural spaces that are close to each other and contain a multifunctional space surrounding a courtyard. It also partially explains the unsolved familiar tribal problems found in certain areas, which can lead to spatial arrangements such as the closing of a derb, a dead-end street, the change of its function, the destruction of a house or its division, or decisions about land division among family members and disputes of inheritance pools. Islamic societies have building and urban codes that are organized with criteria that strongly differ from those in the Western world. Islam through its shari‘ah has provided principles that determine the way of life of Muslim communities and individuals, which in turn, shapes the urban environment. Oleg Grabar says in his study on traditional Muslim urban environment, "It is in Islam which gave resilience to the Muslim city and to its bourgeoisie, not because it was necessarily aware of all urban problems but because it had the abstract form in which all of them could be resolved" (Grabar, 1976, p. 103). These laws, which are constantly applied in everyday life, form a dynamic set of rules that actuate in a bottom-up fashion to shape the urban tissue. This tradition deserves to be preserved, but at the same time, encoded in more contemporary ways of living within the Islamic culture. By this we mean to secure better sanitary conditions, including adequate infrastructure and proper access to daylight and natural ventilation, while maintaining the basic formal structure of the urban fabric and the houses.

3. METHODOLOGY

The methodology used to develop the computer model of the Zaouia Lakhdir quarter, particularly the urban grammar described in this paper, encompassed the three preliminary steps described below: analysis of previous work carried out to infer basic shape rules, development of an experimental computer program encoding these rules, and fieldwork to collect additional information to complete the rules.

3.1. Previous work

In previous work it was hypothesized that the Marrakech Medina urban tissue, as other Islamic cities, was organized as a progression from public space to progressively more private realms (Fig. 4), until reaching the privacy of the patio house, the predominant urban type in this part of the Medina (Mocha, 1995). The patio is the place where the outdoor activities of the family take place. The patio is also the means to provide daylight and ventilation to the house, contrary to traditional European configurations in which the main external space is the street, and buildings are lit and ventilated primarily through street-facing facades. External housing facades in the Marrakech Medina are mostly closed, with very little openings. Because lighting and ventilation requirements are not significant in the design of street-facing facades, privacy does not become an issue either, and street width can be considerably reduced. The street thus becomes mainly a device for physically accessing the house entrance, causing it to become very narrow and often covered with constructions from the first floor on, called subsides, thereby generating corridor-like configurations called derbs.

3.2. Experimental program

Following the initial hypothesis mentioned above, several conjectural attempts were carried out to simulate what could
have been the urban growth of Marrakech. The idea was not so much to reach a final and conclusive model but to explore the problem and to identify modeling issues. A simple shape grammar composed of ten parametric rules was developed. Then, it was encoded into a computer program implemented in AutoLISP to observe the behavior of the model simulating urban growth, defined by the successive and iterative application of rules. Finally, the program was run with 50, 100, 200, 500, and 1000 iterations (Fig. 5). Four problems could be observed. First, growth became too slow, preventing the polygon representing the neighborhood to be filled in completely. Second, derbs grew in all directions, whereas in Zaouiat Lakhdar they tended to follow predominant directions. Third, the distance between “parallel” derbs was not controlled, causing a considerable variation of the plots’ depth. Fourth, the limits of adjacent lots did not allow running the program showed that assuming that lots abutted posed a major challenge in the development of the grammar and its implementation. These impacted the subsequent fieldwork, which tried to gather information to solve the second and third problems, and the choice of computer implementation in order to overcome the first and fourth ones.

3.3. Fieldwork

To collect additional information that permitted completion of the grammar, a field trip to Marrakech took place in early 2005. Four sources of information were explored. The first consisted in surveys of the site based on laser measurements, digital photos, and hand drawings. These surveys permitted acquisition of rigorous information regarding the length and width of the derbs, the height of the buildings, and the location and size of doors. The second source was documents and drawings obtained at the Agence Urbaıne de Marrakech and at the Inspection Générale des Montants, such as an aerial photo of the city taken in 1950 and the plan of the Medina in digital format. The third source was interviews with local experts, which permitted gathering speculative information regarding the genesis of the neighborhood and the reasons for certain spatial configurations. Finally, the fourth source was a satellite photo of Marrakech acquired from QuickBird. The analysis of these sources of information led to the elaboration of a more accurate plan (Fig. 6).

4. URBAN GRAMMAR, NEGOTIATION GRAMMAR, AND HOUSE GRAMMAR

The view of the Medina of Marrakech suggested an organic and almost chaotic city growth. However, a close analysis unveiled a well-established order with repeated urban patterns. For example, the way lots are placed on derb corners are similar. Such patterns are not geometrically but topologically similar, meaning that they can differ in the values of parameters like the angles and dimensions of lots and derbs. Consequently, it was possible to capture the variety of patterns into a reduced number of parametric schemata to develop a parametric shape grammar (Knight, 1998).

At the outset, it was considered necessary to deal with both the urban scale and the scale of the house. As such, the development of two independent grammars was foreseen: an urban grammar that would account for the layout of the derbs and the definition of lots, and a housing grammar that would account for the functional organization of the houses. As the study evolved, it was realized that these two grammars could not be fully independent. In fact, the functional organization of the houses seemed to be partly responsible for the geometry of their perimeter. Moreover, the perimeter of different floors in the same house did not always match. Therefore, preestablished quadrilateral lots could not account for the generation of existing houses. This consideration of an interaction between the design of the houses and the urban layout and a third grammar was proposed as a result. This grammar, called “negotiation grammar,” mediates between the other two grammars and regulates the permutation of spaces between adjacent lots according to the necessities of their owners. It is not certain that this “negotiation” between neighbors took place as not enough historical evidence was found. However, considering the close families ties that characterize Islamic society, to consider that it did exist seems reasonable. In fact, only a society with this tight-knit social environment could have produced such complex spatial configurations. Figure 7 illustrates the different stages reached by these grammars, and the urban grammar will be described in this paper.

5. PREVIOUS URBAN GRAMMARS

Other urban grammars have been developed in the past. Catherine Teeling (1996) designed a grammar to encode
the generation of urban form using a specific section of the decklands in Friedrichshafen, Germany, as a case study. She proposed a top-down approach to describe the division of quadrilateral into one or more quadrilaterals by describing the analyzed urban layout. Subsequent tests showed that the grammar also could account for the generation of other existing sections of the city. Beirão and Duarte (2005) also addressed the topic of urban grammars in a design studio held at Lisbon Technical University School of Architecture. The goal was to use urban grammars as a methodology for flexible urban design. The idea was that urban planning could evolve by first defining a set of rules and then by designing solutions based on such rules in response to particular contexts. The authors' claim was that the resource to a grammar-based system would guarantee order while maintaining flexibility. Students in the studio approached the problem both in top-down and bottom-up fashions. In top-down approaches, they drew rules that first created smaller urban units and then aggregated them to form the urban fabric in a nondeterministic way. In the latter case, the final shape of the plan was not determined at the outset, but depended on the particular site and shape of the urban units inserted during the design process. Because implementation was not a concern, the problems of non-determinism raised by bottom-up approaches were not addressed; consequently, the grammars developed by the students, however interesting from a designer's viewpoint, were simplified and incomplete. In the next section, we discuss ways of overcoming these problems.

6. INFERRING AND STRUCTURING THE GRAMMAR

Given the scale of the Medina of Marrakesh, the development of the grammar raised two problems: one related to the inference process, and the other to the structuring of the grammar. In previous studies, shape grammars were developed based on a corpus of different designs within a given style. The type and scale of designs ranged from Chinese windows (Stiny, 1977) to Palladian villas (Stiny & Mitchell, 1978). It is the current study the goal was to develop a grammar that generated urban layouts, a design of a considerably larger scale. The Medina is composed of many neighborhoods, and although these might look similar, they are quite varied in terms of morphology, street layout, urban culture, and way of living. Zaouat Lakhâr, one of the oldest neighborhoods, has a relatively well-preserved urban fabric, and its inhabitants seem to enjoy a healthy balance of safety, community life, and relatively low economic levels. It has a rectilinear base configuration with two dominant orthogonal directions. The unique characteristics of Zaouat Lakhâr made it the most appealing of all the visited neighborhoods, and so it was selected as the model for the development of the urban grammar. As such, the corpus of existing designs was restricted to a single design. To overcome this limitation, the strategy used to infer the grammar was to divide the neighborhood into sectors by considering that the cluster of lots accessed by a particular derb formed a sector. This permitted the creation of a corpus of partial design solutions.

Structuring the grammar required a decision on whether to follow a bottom-up or top-down approach because both seemed possible. The top-down approach provides a centralized form of controlling the design as it progresses from smaller to larger scales. In the specific case discussed here one can imagine that the first step would be to divide the Zaouat Lakhâr into sectors with access from the surrounding streets or from a derb as also mentioned above. The advantage of this approach is that the relation between smaller parts is controlled from the beginning of the computation. With the shift to smaller scales only occurring when problems of larger scale are solved. This meant, for instance, that an eventual clash of derbs would be avoided because each had its previously defined area of influence, and areas that were defined by taking into account the legal dimensions of lots. The bottom-up approach offers a decentralized form of controlling the design, based on the independent behavior of its parts. In this approach, larger scale problems are solved by solving small-scale ones. In the studied case, urban growth would be based on the individual, yet interdependent, growth of derbs coupled with the insertion of lots. Each derb would grow incrementally taking its surroundings into consideration. This approach raises some difficulties, namely, how to solve all large scale problems, such as the clash of derbs, the alignment of lots, and so forth. The generation of a valid design might require an algorithm with considerable embedded intelligence. Its advantage is that it generates designs in an organic way, which might be more just to the organic character of the urban fabric.

Not enough historical evidence was found to determine which of these approaches originated the Zaouat Lakhâr or whether they took place simultaneously, interwoven, or sequentially. According to Wilhaus (2003), the neighborhood's area was first divided into areas belonging to different families, and then each was divided into lots accessed by one derb. This would explain why many derbs are named after families (e.g., derb Souk or derb Arra). Other historians claim that urban growth was spontaneous and organic; new houses would adapt to the existing situation, and derbs were the empty spaces left over for access purposes. Ideally, the general process embedded in the grammar should replicate the actual evolution of the urban fabric. Nevertheless, as there was enough historical evidence to support the choice of one approach, the pros and cons of each from the shape grammar viewpoint were considered and one was selected.

6.1. Top-down approach

The top-down approach requires the decomposition of the neighborhood into smaller units. This can be accomplished in two stages as diagrammed in Figures 8 and 9; first, by recursively dividing the neighborhood into smaller entities until some condition is satisfied (steps 1-13), and second, by merging the limits of such areas to show all that can be accessed from the exterior (steps 14-21). The problem with this approach is how to divide recursively irregular forms whose division can yield forms that are topologically different from the original ones. This can be overcome by inscribing recursive forms into rectangular frames. Then these frames are divided parametrically into two or four smaller frames using one or two orthogonal lines. Then the original frame is deleted and the dividing lines are trimmed so that they do not extend beyond the limits of the neighborhood and become the limits of smaller areas. The computation proceeds until some condition is satisfied. For example, all the streets have predefined areas and dimensions that guarantee they can be accessed through derbs and divided into "legal" lots. Two types of areas will result from the computation: in peripheral lands, lots are directly accessed from the surrounding streets and host commercial functions. In inner areas, lots are accessed from derbs and are reserved for housing.

6.2. Bottom-up approach

The bottom-up approach emphasizes the notion of growth rather than division. It requires shape rules that define both the incremental expansion of derbs and the systematic insertion of lots (Fig. 9). The basic idea is that entrance points are defined in the parameter of the neighborhood (steps 2-5), and then derbs grow independently from each one. Lots that have direct access from the surrounding street are defined at an early stage (step 3). Derbs then grow and fill in the empty space with lots until none is left and the whole neighborhood is packed (steps 9-16). The problem is that growth cannot be fully blind or independent otherwise, local voids of difficult access would be constantly created, and the limits between neighboring lots would hardly ever be sustained. Thus, a certain level of intelligence has to be embedded in this system, both in the choice of rules to promote growth and in the way they are applied, particularly, in the assignment of values to rule parameters. There are two ways of solving this. The first approach involves performing local analysis to determine which rule to apply and the adequate assignment of values. This second approach implies applying a given rule with a given assignment of values and then to perform a test to check whether the inserted derb or lot clashes with existing forms. If not, it remains part of the design and the computation proceeds; otherwise, it is deleted and another attempt is made using a different assignment of values or a
different rule. If a bottom-up grammar is to be implemented and run automatically, it will be necessary to develop one of such higher level systems to determine whether and how growth rules can be applied.

6.3. Mixed approaches

The top-down and the bottom-up approaches can be combined in two different ways to develop mixed approaches. The first (Fig. 10) top uses a top-down approach to divide the given site into different areas as described in Section 6.1, and then a bottom-up approach to pack each of the resulting areas with 

6.4. Selected approach

There is no need to check either derbis to avoid collision during growth. The second mixed approach (Fig. 11) bottom-up comprises a bottom-up stage to insert derbis and their zones of influence, and a top-down stage to divide such zones into accessible lots. In this case, the problem is to avoid the clash of different zones, and so an intelligent algorithm similar to the one mentioned in Section 6.2 needs to be considered in the bottom-up stage.

7. Proposed grammar

The proposed Marrakesh grammar is a parametric shape grammar defined in the Cartesian product of the $U_{2}$,$W_{2}$ algebra. Weights are used to distinguish areas occupied with lots of those that are empty still. The derivation of designs proceeds through six stages: define the limits of the neighborhood, insert entrances to derbis, insert extenders and actuators forming derbis, insert lots along the bordering street and derbis extenders, insert lots at derbis ends, and modify the layout of derbis and lots. These stages are not necessarily sequential as rules from different stages may be applied alternately. Because of space restrictions, it is not possible to describe and show all the rules of the proposed grammar in detail. The remaining rules and further detail are presented in Appendix A. For a quick grasp of the type of actions performed in each of the six stages of the process, see the abbreviated derivation provided in the figure at the end of Section 7.1.4.

7.1. Rules

7.1.1. Stage 1: Define limits of the neighborhood

Stage 1 defines a polygon representing the limits of the neighborhood. This may vary in size, geometry, and number of sides, but the edges should be, at least, twice as long as the minimum depth of a lot (i.e., $2 \times 8$ m), and the internal angle between edges should be bigger than 60°. Two rules apply at this stage: 1.1 and 1.2 (Fig. 11). Rule 1.1 generates a basic triangular polygon that constitutes the initial shape and rule 1.2 introduces a vertex into an edge of the polygon so that more complex polygons can be obtained. By recursively applying rule 1.2 to the edges of an evolving polygon, a perimeter like the one that limits Zanzalin Lakhdar is obtained. Technically, this stage is necessary for the design of the grammar, but it may be defined differently in the future computer implementation as polygons might be known at the outset.

7.1.2. Stage 2: Insert entrances to derbis

Rules 2.1, 2.2, and 2.3 apply at this stage (Fig. 12). Each of these rules introduces an entrance point $E$ in such a way that each edge cannot have more than two entrance points. In rule 2.1, $A'$ is an edge of the polygon and $X'$ and $X''$ are the closest labeled points to $A'$ and $A''$, respectively. They can be neither other vertices of the polygon (An) or entrance points (E). To guarantee that lots with adequate dimensions can be inserted later in the computation, the distance between two consecutive entrance points measured on the perimeter cannot be smaller than twice the length of the minimum lot depth (lim, $D$). Conditions on both the left- and right-hand sides of the rule guarantee that this is the case.
7.1.3 Stage 3. Insert extenders and articulators forming derbs.

The third stage consists of the insertion of derbs, and it encompasses Rules 3.1 through 3.2. Derbs are composed of extenders that extend the derb in a predefined direction and are labeled with an empty triangle. Articulators define new directions for the derb and are labeled with filled triangles. In the generation of a derb, rules that generate extenders and articulators are alternately applied, so that an extender is always followed by an articulator. Although the urban fabric inside the Zaouati Lakdar quarter is not orthogonal, derbs tend to follow two somewhat perpendicular directions. Therefore, the directions defined by the articulators are restricted so that the angle between a subsequent extender and each of the two perpendicular directions is within 20° and the angle between sequential extenders is between 30° and 150°. The combination of these two restrictions defines an interval, specific to each rule application and eventually composed of noncontinuous subintervals, within which new directions for the derb can be chosen.

Rule 3.1 inserts the initial extender of a derb (Fig. 13). In this case, the extender is located outside the perimeter of the neighborhood and is determined by the direction of the derb. Rule 3.2 through 3.9 insert an articulator after a derb. They differ in the type of the inserted articulator. Rule 3.2 inserts an articulator that permits to extend the derb without changing its direction.

Rules 3.3 (Fig. 14) and 3.4 insert elbowlike articulators, and rules 3.5 and 3.6 insert T-like articulators. Rule 3.7 inserts an archedlike articulator, rule 3.8 a Y-like articulator, and rule 3.9 a crosslike articulator. Finally, rule 3.10 connects an extender to an articulator marked with a filled triangular label. The parameters in this rule are the length (l) and the ending width (w) of the extender. The extender may have a varying width as depicted in the figure. In fact, in Zaouati Lakdar, most derbs do not have a constant width.

7.1.4 Stage 4. Insert lots along bordering street and derbs' extenders.

In stage 4 the lots are inserted along the bordering street and the derbs. The lots along the street may have four or five sides and are used mainly for commerce. In most cases, the lots along the derbs are almost rectangular and, in the proposed shape grammar, this quadrilateral shape is captured by a general topological schema with specific constants (Fig. 15). The value of internal angles and the dimensions of their sides vary between specified intervals. Furthermore, the proportion of the lot is confined to the interval between 1.1 and 2.3, meaning that its geometry may vary from a square to a rectangle in which the length cannot exceed 1.5 times the width. Not all lots are quadrilaterals, as some may have more than four sides. However, it is possible to identify a main quadrilateral shape in such lots, which is then used for matching the schema on the left-hand side of the rules. As lots follow the general topological schema just described, the internal shape parameters are not shown in the rules for inserting lots for simplification purposes. The insertion of lots proceeds while the derbs grow incrementally with the addition of extenders and articulators. The rules are described below. Note that added lots have a darker shade of gray to improve legibility.

Rules 4.0a-d are used to insert lots along the bordering street. Rules 4.0a-b and 4.0c-d insert a quadrilateral and a quadrangular lot, respectively, at a street corner, whereas Rules 4.0c-d and 4.0c-d insert them in the middle. Rules 4.1-4.5 define the insertion of lots along extenders. Rules 4.6-4.13 define different forms of inserting lots on the outer side of elbowlike articulators, and rules 4.14-4.16 on the equivalent on the inner side. Finally, rules 4.17-4.21 deal with the situations created by other articulators. Rule 4.1 (Fig. 16, top) is the seed rule at this stage, as it is responsible for the insertion of the first lot of the derb and it takes into account the perimeter of the neighborhood. Rule 4.2 (Fig. 16, bottom) inserts a new lot along an extender that has not been completely filled in yet. An extender is identified as empty or full through label E or F, respectively. Rule 4.2 only applies to situations where the extender has the label E and it keeps its unchanged. Rule 4.3 does the same as Rule 4.2 except that it fills the extender thereby changing the label to F. Rules 4.4 and 4.5 are applied when the extender's available length is smaller than the lot's minimum width. Rule 4.4 changes the label to F without adding a lot. Once an elbowlike articulator has been added to the extender, rule 4.5 introduces a lot that stretches beyond the limit of the articulator.

Rules 4.6-4.13 deal with all the possible situations that can be created by the introduction of elbowlike articulators. In the application of parametric rule 4.6 (Fig. 17), three
parameters \((e, y_1, y_2)\) need to be assigned values: \(e\) is the distance of the limit of the lot to the limit of the articulator. It is measured on an auxiliary axis, whose origin is 0. There are values to the left. Depending on the value of \(e\), angles \(y_1\) and \(y_2\) can change to one of two values to align the limit of the lot with the incoming extender or the outgoing extender. If \(e = 0\), then the angle \(y_1\) is not defined and \(y_2\) can change to one of two values, \(90^\circ\) or \(180^\circ - \beta\) with \(\beta\) defining the angle between the two extenders. If \(e > 0\), then \(y_1\)'s value is either \(90^\circ\) or \(180^\circ - \beta\). If \(y_1 = 90^\circ\), then the limit is perpendicular to the incoming extenders, and \(y_2\)'s value can be either \(90^\circ\) or \(\beta\) (i.e., the lots' limit is either parallel to the incoming extender or perpendicular to the outgoing extender). If \(y_1 = 180^\circ - \beta\) (i.e., the lots' limit is perpendicular to the outgoing extender), then \(y_2\)'s value can be either \(90^\circ\) or \(180^\circ - \beta\) (i.e., the lots' limit is perpendicular to the outgoing extender parallel to the incoming one). The closed polygonal shapes of the lots are not fully represented in the rules. As the rule specifies the location between the lots and the extenders, to which they are connected (in this case, an incoming extender, an ebbulator articulator, and an outgoing extender), how the polygon is closed is not important. The remaining rules follow a similar scheme. Note that in all the rules, angle \(y_2\) is such that the limit of the lot is parallel to the incoming extender or perpendicular to the outgoing extender.

Rules 4.14, 4.15, and 4.16 are used to fill inner concave corners (corners defined by the intersection of one incoming and one outgoing extender) with lots (Fig. 18). These corners need not be exclusively derived from the insertion of elbows, type articulators. Any corner with an angle smaller or equal to \(90^\circ\) can be tackled with these rules, regardless of the specific articulator involved. The problem is addressed in the following way. Rule 4.14 places a label \(P\) on the vertex of the last lot that is more distant from the corner between the incoming and outgoing extenders. If the distance of the lot from point \(P\) and the outgoing extender is larger than the maximum width of a lot, then rule 4.15 is applied to transform the lot into a corner lot. If it is smaller, then rule 4.16 transfers the label \(P\) to the last but one lot, and deletes the last lot. This rule is applied recursively until rule 4.13 can then be applied.

Rules 4.17 and 4.18 (Fig. 19) insert a lot in an outer corner (corners defined by the intersection of two outgoing extenders), which may be yielded by rules 3.5, 3.6, and 3.9. Four variables are involved in the parametric rules: \(x_1\) and \(x_2\) are the distances between the limits of the lot and the extenders and extenders, which can vary from \(70^\circ\) to \(110^\circ\) each. Rules 4.19 defines the insertion of lots in the specific case where the incoming direction coincides with one of the two outgoing ones. In this case, a contiguity of extenders is observed and may be generated by rules 3.5, 3.6, and 3.7. For this rule to be applied, the distance \(e\) between the right most limit of the last lot and the articulator has to be lesser than a given limit. Then, the values of the parameters on the right hand side of the rule must be satisfied: \(x_1\) and \(x_2\) can vary from \(70^\circ\) to \(110^\circ\), \(y_1\) must be positive, and \(y_2\) and \(y_3\) (width and depth) must be greater than \(1\) and \(30^\circ\). Finally, rules 4.20 and 4.21 handle the insertion of lots on the sector defined by the intersection of the outgoing extenders, whereas rule 3.7 (or rule 3.8) have been previously applied.

7.3 Stage 5: Insert lots at dent's ends

Stage 5 deals with the insertion of lots in the ending extender of a dent. There are six possible layout configurations that can be found in the left-hand side of the rules in this stage. These configurations differ in the positions of the two lots relatively to the end of the extender. For each of these configurations, there are several ways in which lots can be placed at the end of the extender and these are encoded into the right-hand side of the rules. Rule 5.1 is shown in Fig. 20. This rule inserts three lots at the end of dent. For the rule to be applied, the positions of the last lots on both sides of the extender must be such that the distances between their limits and the end of the extender \(d_1\) and \(d_2\), respectively, are smaller than the minimum dimension permitted for a lot, \(30^\circ\), which means that no further lots could have been placed using rule 4.2. The constraints on the dimensions and angles of placed lots are those in the general scheme described above. The remaining rules (rules 5.2-5.19) work in a similar fashion.

7.4 Stage 6: Modify the layouts of lots and dent

Finally, stage 6 encompasses rules that modify the existing lots to create smaller or larger lots, to access locked lots, or to reach locked empty spaces to reduce growth. Figure 21 shows some of these rules, and the remaining can be found in Appendix A. The modifications introduced by these rules is the lot respect the general topological scheme described in Section 7.2. As such, the specific constants on the shapes of modified lots are omitted in the rules. Rule 6.1 divides a large lot into two smaller ones. Rules 6.2 and 6.3 expand a lot at the expense of an ending extender (literally a dead-end alley). Rule 6.4 inserts an extender perpendicular to an existing extender at the expense of a locked lot to provide access to a locked lot or to an empty area. Rule 6.5 through 6.7 are similar except that in rule 6.9 the new extender is aligned with the existing one, and in rules 6.6 and 6.7 a change of direction requires the introduction of an articulator. Rule 6.11 is similar except that its purpose is exclusively to provide access to locked lots and no further growth of the dent is foreseen. Rule 6.12 also provides access to a locked lot, but by modifying its topology at the expense on adjacent lot, instead of inserting an extender. Rule 6.10 provides access to a lot that is connected to a dent solely through a vertex. In this case, the topologies of two lots are modified so that an entrance area is generated off the lot that is already accessible through the dent. Finally, rule 6.11 connects two dents by means of a diagonal direction. In general situations in which a dent is locked within the fabric, but not local modifications introduced in lots may generate such situations.

7.2. Partial derivation of the existing Zaouiat Lakhdar

The grammar just described is nondeterministic and unenforced. In general, more than one rule can be applied at a given step in the derivation. Furthermore, a single rule can generate different outcomes depending on the value assigned to parameters. This means that from the same permutated variations of the grammar rules will likely yield different solutions. Consequently, the application of the grammar generates unpredictable results. Figure 22 shows the partial generation of the Zaouiat Lakhdar neighborhood; the first three steps show the design after the application of the rules from stages 1 through 6 is indicated in the image. The following steps show the design after approximately 55 rules applications each. The complete generation of Zaouiat Lakhdar can be found in Appendix B.
shapes. The first group includes visual implementations, for instance those by Krishna (1983) and Tapia (1999). They are called visual because shape rules match directly on the geometry, as "we see it," by closely following Siny's mathematical foundation of shape grammars. Thus, for these implementations only encompass two-dimensional (2-D) line algebras; three-dimensional (3-D) algebras require solving particularly difficult technical problems. The second group includes symbolic implementations, for instance, those by Hesserman (1993) and Siny and Caian (1995). In these implementations, shape rules match on symbolic descriptions of shapes. Because they avoid the hard technical problems posed by visual implementations, symbolic implementations include 3-D algebras of solids in the case of Hesserman; and of lines in the other case. Siny's and Hesserman's implementations do not strictly use Siny's maximal line representation. Instead, they use Requicha's (1980) wireframe representation traditionally used in CAD systems as an extension of his proposed by Hesserman and called split-edge representation, which supports nonmanifold solids (solids composed of different parts-ssing a point or an edge). Nevertheless, they support shape emergence. The third group includes the implementation of set grammars, a subset of shape grammars, in which shapes are treated like indivisible atoms and represented as tagged data. For instance, implementations by Wang and Duarte (2002) for 3-D solid algebras and McGill (2002) for 2-D linear algebras fall into this category.

As a result of the different representations, visual implementations support shape emergence and automatic shape recognition, symbolic implementations do not support shape emergence but support shape recognition, and tagged representations support none. In contrast, symbolic implementations make it easier to deal with parametric shape rules, and tagged implementations go one step further by avoiding difficulties posed by automatic shape recognition. For a more complete overview of shape grammar implementations see Chiu et al. (2004). Because shape emergence is not a feature of the Marrakesh urban grammar, whereas parametric shape rules are, and the converted shapes generated from hard shape recognition problems, the interpreter of the Marrakesh urban grammar (MUG) is a tagged implementation. The interpreter was developed as a proof of concept in AutoLISP, a scripting language of AutoCAD, a widely used CAD program. The use of AutoLISP presented two advantages. First, it made it possible to take full advantage of AutoCAD commands, thereby avoiding developing a shape modeler. For instance, Boolean operations were used to overcome shape recognition problems caused by the overlap of lots, and navigation tools eased the visualization and assessment of solutions. Second, it facilitated the interface with other software necessary to create effective models of the solutions such as rendering programs and rapid prototyping machines. The interpreter manipulates 3-D shapes, because these can easily be obtained from the 2-D shapes considered in the grammar by adding the third dimension. In summary, the choice of environment simplified the implementation greatly but enabled doing so effectively. Figure 25 shows the interpreter being used in the generation of a new urban solution, and Figure 26 shows the physical model of a new solution produced from the generated digital model using a laser cutter. It took the user just a few minutes to generate the shown solution using the interpreter, but he was not trying to meet particular design requirements. Generating a solution in such conditions might take considerably longer.

9. DISCUSSION AND CONCLUSIONS

The research described in this paper constitutes one step toward the development of a computational model of the Zanzini Lataktes neighborhood in Marrakesh. The ultimate
At this stage of the research, it is not clear whether obtaining solutions that meet contemporary living conditions can be accomplished by searching through the universe of solutions defined by the current grammar, or if more fundamental changes to this grammar are expected. We future research to clarify exactly this issue. This means that our research should determine to which extent the cultural and social fabric of modern societies, in their current state of living, and the cultural factors that they require, are as close to a possible to such a fabric, and yet met the requirements.

10. QUESTIONS AND ANSWERS

10.1. Question 1

"Could you comment on the usefulness of design representation languages in terms of reuse, readability, debuggability, etc.? This has been shown in the programming language community. That is, different languages have different affordances--how do we assess the particular affordances of a design representation language?"

10.2. Answer 1

"We assume that the expression 'design representation languages' refers to shape grammars and other technical formalisms used to represent design languages. Shape grammars were created to explain, in a computational and visually understandable way, how designs are generated within a particular design language. Understanding is important to make them easier to users who do not participate in the process of developing the grammar.

The first shape grammar developed by Stiny and Gips for abstract compositions were very successful in this regard. The simplicity of the grammars and the design they generated made it possible to use shape markers to control the generation of designs, while keeping the process visually clear. However, the grammars for nonabstract designs developed afterwards, for instance, the grammar for Palladian plans, required the use of more complex control devices. This led to the creation of algebraic symbols that when combined with algebraic rules generated control over the generation process. It is the implication of open and complex grammars used to deal with even more complex information associated with the process of designing and to gain a better control of the generation process. This control of the semantic aspects of design is important to guide the generation of solutions toward specific performance goals (user adaptation, structural stability, environmental sustainability, etc.). As the technical apparatus of shape grammars grew more complex, they became much more difficult to read and debug. Readability and debuggability are particularly difficult when the grammar is intended to be encoded into a computer interpreter and therefore needs to incorporate a considerable amount of information. The computer implementation of shape grammars is nevertheless crucial to facilitate their use and achieve some of their most important promises, namely, the fast generation of design alternatives that are adapted to particular design contexts. In these cases, one can without an argument that shape grammars are a valuable tool for visual clarity, thereby allowing for interrelationships and design. This solution was used, for instance, in the grammar for Stiny's Malagueira houses, which encoded several parallel grammars, one for each viewpoint (plans, sections, elevations, 3D views, and descriptions). One of these viewpoints was simple enough to make the essential process visible clearly, thereby facilitating the learning and reuse of the grammar by other people. This solution proved to work in a set of experiments in which people were asked to use the grammar to generate Malagueira houses for particular clients (Duarte, 2001).

Another solution that constitutes a more advanced version of the previous one is to develop the computer implementation in such a way that it permits us to visualize viewpoints with different levels of detail. This solution requires a considerable investment in the design of the interface to make it user-friendly. If this is done successfully, it should permit users with different intentions and degrees of knowledge to interact with the interpreter in an appropriate manner. Users whose concern was to develop new designs within an already defined domain would not need to have access to all the technical details of the grammar. The interpreter could even explain the rationale behind the generation of a given design. Users whose goal was to design a new grammar could access the details of the grammar, but they did not need to deal with a programming language. They would develop the grammar by manipulating shapes. In addition, this ideal shape grammar editor would possess debugging capabilities similar to those found in other languages. Only when we succeed in developing such an interpreter would we be able to take advantage of the full potential of shape grammars. To accomplish this, we need to overcome the difficulties mentioned in Section 6 in this paper. In the meantime, we should be happy with the advantages permitted by the current state of the art and widely documented in the literature.

10.3. Question 2

"Would people accept this technique for urban form design? How do you deal with scale in your grammar?"

10.4. Answer 2

"Attempts to achieve any degree of design automation always encounter two types of reaction. On the one hand, we have the people who are against the idea. These people depart from a..."
philosophical viewpoints that it tends to perceive design as an inherently humanized process, somewhat intuitive, and not complete to be carried through a process that necessarily requires simplification and abstraction. On the other hand, we find people who favor the approach. These people value the benefits that it brings about, even if the abstraction that it entails reduces complexity and risks losing some meaningful information. They consider that the model of reality it implies requires abstraction and, like any other model, it is valid as long as it becomes useful. The usefulness of the model has thus depended on using it within the appropriate context. This is also the case in other fields. For instance, Newton’s physics are useful if one’s goal is to explain the movements of the planets or to build a space satellite. They are not useful if one’s aim is to explain the origins of the universe, the model is limited and requires the use of quantum physics. Obviously, we take the second standpoint. The current state of the art only enables the development of rather simplified models, like the one that corresponds to the current state of our project. For instance, it does not take into account topography and other important contextual information. However, such a simplified model is already useful. It makes it possible to gain a better understanding of the formal structure behind traditional Italian urban fabrics. Moreover, once we implement the application linking the grammar to the genetic algorithm that will improve solutions from performance viewpoints, we will be able to understand the trade-off among different design alternatives. The tool proposed, at this stage, is not designed to provide an answer to such a high-level design context. It relates to the particular situation of this Islamic medina, where urban fabric characteristics are deeply connected to the characteristics of the pedestrian spaces. In this context, we consider the model acceptable for urban design, where a precise set of rules for generating houses is also deeply rooted in the original rules for generating urban designs.

Previous meetings in Marrakech with members of the Agence Urbaine and of the Ministère de la Culture (Institution des Monuments Historiques et Sites de Marrakech) showed that the present research was accepted with great interest. Moreover, it gained much current local concern about the uncontrolled urban growth of the Marrakech Medina and the lack of available technology and qualified professionals to undertake the development of new urban and housing projects. The necessity to simultaneously fulfill environmental sustainable requirements and traditional architectural needs in new planning and design is the cornerstone of the project. At this stage, the project addresses two main scales. The first is the urban scale. The second is the scale of the plan and its design. In this context, we consider the model acceptable for urban design and its double role of rules for generating urban designs. We thank Rodrigo Correa, André Valverde, and João Cardoso for their work in developing some of the Marrakech urban models that interpret André’s and João’s work evolved within the course edited Programming and Computation for Architecture (DAC II) taught at the University of Lisbon, School of Architecture, and by Carlos Cafiero and Filipe Machado at the University of Lisbon, School of Architecture. We also thank Ahmed Ouessaid, head of the Département des Études de la Minsterie de l’Intérieur, Agence Urbaine de Marrakech, and Hassali Chennaoui and Abdellatif Massri, chefs of the École des Céramiques et des Arts d’Handicaps, for providing valuable information about the history of Marrakech. This research was carried out within the framework of Project POCI/AR/42/47/2001, coordinated by Luisa Caldas, with the financial support of PCPT. Portugal We thank Luis for her participation in the initial discussions on the development of the grammar described in this paper.

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REFERENCES

APPENDIX A: COMPLETE SET OF GRAMMAR RULES

FIG. A-1: Stage I: Define the limits of the neighborhood.