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A Computer-Aided Rule-Based Mamluk Madrasa Plan Generator

Abstract. A computer-aided rule-based framework that restructures the unstructured information embedded in precedent designs is introduced. Based on a deductive analysis of a corpus of sixteen case studies from Mamluk architecture, the framework is represented as a generative system that establishes systematic links between the form of a case study, its visual properties, its composition syntax and the processes underlying its design. The system thus formulated contributes to the areas of design research and practice with a theoretical construct about design logic, an interactive computerized plan generator and a combination of a top-down approach for case study analysis and a bottom-up methodology for the derivation of artifacts.

Keywords: Computer-aided design, logic of design, visual reasoning, precedent-based design, design process, mamluk architecture, shape grammar

1 Introduction

Design involves multiple activities and tasks that are based on reusing past design solutions. Design knowledge gained from studying precedents plays a significant role in the pre-design and precept reasoning stages. This is due to the fact that previous experiences help in understanding new situations and in casting older solutions into new problems, at least in the early stages of the problem-solving process. Precedent-based design experience is used when performing different tasks, whether they involve routine activities or require creative contributions. A process of interpolation and matching is conducted for the routine activities of comparison and exclusion in the processing of the creative ones. This is also the case in architectural design, where many problem-solving tasks are based on modifying past solutions. In fact, a major part of the pre-design investigation in architecture is concerned with studying case studies (precedents) that are related to the problem at hand. Multiple layers of information can be inferred from case studies to form a point of departure for new designs.

Starting with a precedent-based design model can enhance the solution of a new design problem by taking as a point of departure a case as a whole or a combination of selected parts or features of different cases. In order to be of practical use, information inferred from precedents has to be represented in a meaningful way so as to enable designers to restructure and reassemble the extracted data for the generation of a new design. Precedent-based models can be represented in many forms. The one that will be emphasized in this paper is the Rule-Based Design (RBD) model, which Tzonis and White [1994, 20] called the Principle-Based Reasoning model. RBD provides dynamic and flexible solutions since many alternatives can be derived by applying a combination of rules (selected from a finite set) on a small set of basic shapes. In RBDs, data extracted from a group of precedents is

formulated as concise productive rules and defined vocabulary elements by using a top-down approach. In this approach, a design problem is studied as a whole unit to derive the basic constituent elements and relationships underlying its structure. In this regard, RDB models can be associated with Problem-Based Learning techniques [Dochy et al. 2005] to strengthen their pedagogical power. In Problem-Based Learning settings, a whole problem is introduced, investigated and analyzed to allow learners to derive all the relevant basic data and details. For scope limitations, issues of Problem-Based Learning associations and impacts will be discussed in a separate paper.

The main hypothesis of this study is that the logic of form making and style definition can be represented as a finite set of generative design rules and shape compositional principles. Thus, information embedded in precedents can be represented by a finite set of planning procedural rules and parameters for aesthetic articulation.

The main scope of this research is to develop a computer-aided precedent-based system that can describe, analyze and generate two-dimensional representations of architectural design by applying productive rules of composition. The system is implemented on the floor plans of educational buildings (*madrasas*) in Mamluk architecture as case studies.

The main goal of the study is to formulate a structured and systematic framework for analyzing the form of historical artifacts and for generating emergent designs based on the morphological analysis of precedents. The main objective is to restructure the originally unstructured or weakly-structured information embedded in precedents in the form of clearly formulated rules to make the information more usable and recyclable.

The rule-based design framework developed in this paper is expected to contribute to the theory, practice and teaching of design. Based on a structuralist view¹ of the morphology of precedents [Caws 1988], the framework proposes a theoretical construct that encompasses a system of compositional and procedural rules for form generation. It enhances the body of knowledge in design areas by means of an externalized and explicit method of form-making and an incremental process for architectural composition, and by an applicable system for restructuring the weakly-structured information that is embedded in precedent designs. Furthermore, the paper emphasizes the aesthetic values of Mamluk architecture by systematically analyzing its morphology. For design practice, within the scope of this research, the use of the framework can help designers to visualize and evaluate several solutions of a given design problem, particularly in two-dimensional representations, and then to select one or a combination of these designs to develop. In addition, designers can automatically and systematically generate designs based on a knowledge base developed from the study of selected precedents. Regarding the pedagogical significance, applications in analysis and synthesis of basic components of compositions have important implications for design instructors who want to communicate the principles of visual composition and guidelines for the design process. In addition, the proposed framework represents an efficient way of learning about styles or languages of designs, especially about their compositional aspects. A language paradigm for form generation can also reveal general design strategies that students can learn from and use in solving their own design problems. By applying a bottom-up approach of rule search and matching to initial shapes, a student may better understand the form-making process and its associations with style definition.

The research introduces a framework for a set of case studies, the morphology of which did not receive enough attention in the areas of the systematic analysis and synthesis, and

the explicit articulation of the processes of their form-making. The precedents are selected from Mamluk architecture and are widely considered beautiful representative exemplars of Islamic architecture. The formulated framework proposes an integrated system that consists of a multi-layer structure and multi-phase sequence for deriving floor plans of Mamluk architecture.

2 Background

Most previous efforts in the area where precedent-based and rule-based design studies intersect are represented in the form of shape grammars. Shape grammar [Gips 1975; Stiny 1980, 1994; Flemming 1987] is a method of the description, analysis, representation, classification, and generation of the form of an artifact and its incremental design process. In most cases, shape grammars are associated with the analysis of precedents. The common factor in the precedents studied is usually their designer, their style or the similar temporal or geographical context in which they were designed. Design precedents are typically investigated in order to understand the geometrical composition of their appearance and the process of their production. Then, a group of possible rules and initial shapes is derived.

There are two principle kinds of shape grammar: *standard grammar* and *parametric grammar*. While in standard grammars most attributes of shapes are constant, in parametric grammars they tend to be more flexible and variable. Because of its flexibility, parametric grammar is more practical and popular than the standard one. If the number of parameters in parametric grammars is small, designers can recognize and predict several options of designs, but if the number is large and the spatial relations are more complex, shape grammars become too complex to be applied manually. Computer implementations of shape grammars facilitates the search through complex grammars or large numbers of rules and parameters. The relationship between shape grammars and computer implementations can be described in the statement:

Shape grammars naturally lend themselves to computer implementations: the computer handles the bookkeeping tasks (the representation and computer computation of shapes, rules, and grammars, and the presentation of correct design alternatives) and the designer specifies, explores, develops design languages, and selects alternatives [Tapia 1999, 1].

The concept of being able to derive new instances of a given style is certainly interesting as a way of extending the scope of a style by adding imaginary members that have the same compositional attributes. Such a derivation is based on the understanding of the formal patterns and compositional principles underlying the appearance of designed objects that belongs to that style. Consequently, it is fundamental to formulate the rules of a grammar in a flexible way so that the unexpected elements of design are allowed to emerge.

In order to automate and implement shape grammars in an exploratory way, it is essential to formulate rules in an algorithmic, parametric and interactive format so when they are fed into the computer, they generate multiple alternatives of a design. The derived designs present possibilities that may inspire the designer. The rules should be based on the conceptual as well as the formal components of a design, and on the relational, morphological, and topological associations among all components. Computer implementations of shape grammars can function as educational tools for demonstrating the range and power of the grammars, and for illustrating the morphology and process of

designs. They enable students and designers to generate, analyze, evaluate, and select more rapidly and easily from among the various design alternatives that grammars generate without having to deal with the technicalities of grammar development.

In spite of their theoretical appeal, shape grammars did not receive enough attention in the area of their automation. This is most probably the result of the relative complexity of their underlying algorithms and the difficulty of developing an integrated system for shape analysis and synthesis [Tapia 1999].

According to Gips [2000], it is possible to identify four major types of the computer implementation of shape grammars. These are:

1. **A shape interpreter.** In this type, a user defines a shape grammar in the computer, and the program generates shapes in the given language, either automatically or guided interactively by the user.
2. **A parsing program.** A program of this type is given a shape grammar and a shape. The program determines if the shape belongs to the language generated by the grammar and, if so, gives the sequence of rules that produces the shape. This type focuses on the analysis and search aspects rather than the design generation issues.
3. **An inference program.** In this type, the program is fed a coherent set of shapes of a given style, for which the computer automatically generates a shape grammar for the same style.
4. **A computer-aided shape grammar design program.** A program of this type assists users in designing a shape grammar by providing sophisticated tools for rule construction and development.

Some examples of the implementations that have been conducted on shape grammars are listed in Table 1. Gips's interpreter [1975] enables the user to input a simple two-rule shape grammar; the program then generates two-dimensional shapes. Only polygonal vocabulary elements are allowed in this grammar. The program ignores the issue of detecting sub-shapes. Krishnamurti [1980, 1981-a, 1981-b] did pioneering work on developing data structures and algorithms for solving the sub-shape transformation and rule application problems for two-dimensional grammars. Using the Prolog programming language, Flemming [1987] developed a grammar for three-dimensional representations of the Queen Anne house, and Chase [1989] developed a general two-dimensional shape grammar system. Tapia's GEdit [1999] is a general two-dimensional shape grammar interpreter that supports sub-shape detection and shape emergence. Agarwal and Cagan's coffee maker grammar [1998] has been implemented using a JAVA program. A shape grammar interpreter was designed by Piazzalunga and Fitzhorn [1998] for three-dimensional oblong manipulations using the LISP language. Also using a version of LISP, Eilouti's FormPro1 [2001] develops a universal grammar for three-dimensional architectural compositions with possible style variations for each resultant design. Duarte's program [2005] implements a shape grammar for Malaguera house designs.

In most previous efforts, computational problems related to encoding rules and their executions were focused on producing abstract shapes rather than architectural representations. They considered the layer of form processing that mostly concentrates on the construction grid and overall shapes of actual designs. Classification of components according to their functional and architectural articulations was in most cases ignored.

Furthermore, in most efforts, issues of designing the interactive and user-friendly interface of a program did not receive enough attention. Thus, most of these systems were not easy to use for nonprogrammers, novice users of shape grammars, or design practitioners.

No.	Name	Reference	Language
1	Simple interpreter	Gips, 1975	SAIL [Standard Artificial Intelligence Language]
2	Shape grammar interpreter	Krishnamurti, 1981-a and 1981-b	
3	Shape generation system	Krishnamurti and Giraud, 1986	PROLOG
4	Queen Anne houses	Flemming, 1987	PROLOG
5	Shape grammar system	Chase, 1989	PROLOG / Mac
6	GEdit	Tapia, 1999	LISP / Mac [Macintosh Common LISP (MCL)]
7	Shape grammar interpreter	Piazzalunga and Fitzhorn, 1998	ACIS/LISP
8	Coffee maker grammar	Agarwal and Cagan, 1998	JAVA
9	FormPro1	Eilouti, 2001	AutoLISP
10	Malaguera Program	Duarte, 2005	

Table 1. A List of shape grammar computer implementations

The computer-aided generative system presented in this paper is a multi-layer, multi-phase shape interpreter that transforms a layout construction grid derived by rule applications in one phase into a full architectural plan with walls and openings in another phase. It is designed with a quickly-learned and easily-used interface. Furthermore, the stylistic prototypes of the program outcomes are developed from a valuable set of precedents that have not received enough attention of researchers, especially in the systematic and applied research areas. This set consists of Mamluk educational precedents.

3 The theoretical framework for the rule-based generative system

Grammatical inference can be defined as the task of logically inferring a finite set of rules from the systematic investigation of a coherent set of designed objects. In its architectural application, a building design or group of designs is defined. The designs are analyzed by decomposing them into a vocabulary, which represents the lexical level, and rules, which represent the syntactic level of their structure. Spatial relations, or arrangements of vocabulary elements in space, are identified in terms of the decompositions of the original designs. As a result of the re-synthesis of the decomposed elements, the shape grammar generates the original designs and possible new designs that did not exist before. New designs are generated by restructuring new combinations of the vocabulary elements in accordance with the inferred spatial relations, or by re-assembling the same elements using different rules or sequences.

In order to develop a generative design system which applies rule-based assembly models, a foundation of a flexible parametric representation of rules and basic shapes must be formulated. The rules and initial shapes are inferred from a set of precedents, drawn in the present paper from Mamluk architecture. The study focuses on a set of educational building (*madrasas*) that belong to this style. Mamluk madrasas represent some of the most beautiful examples of the Islamic architecture. Despite their historical and aesthetic value, they have not received enough attention from researchers, especially in the areas of systematic analysis of their morphological structures or designs.

This research examines a group of sixteen Mamluk madrasas from the different regions ruled during the Mamluk period. The case studies include thirteen precedents from Egypt (located in Cairo), one precedent from Syria (located in Aleppo), and two precedents from Palestine (located in Jerusalem). The study cases from Cairo are: al-Ashraf Barsbay, al-Kadi Zein al-Dien Yehya, al-Amir Kerkamas, al-Sultan Inal, al-Ghour, Umm al-Sultan Sha'ban, Kani Bay Kara al-Remah, al-Sultan Kaytebay, and Abu-Baker Mezher Madrasas from the covered court type; and al-Thaher Barquq, al-Sultan Hasan, Serghtemetsh, and al-Sultan Qalawun Madrasas of the open court type. The study cases from Jerusalem are: the Tashtamar Madrasa from the covered court type and al-Baladiyya Madrasa of the open court type. The case from Aleppo is al-Saffaheyya Madrasa which is of the open court type. The morphological study of the case studies, as well as the spatial organization of the components is discussed in a separate paper [Eilouti and Al-Jokhadar 2007].

As a result of the structuralist analysis (see note 1) to find the commonalities that underlie the cases, and the comparisons of the sixteen precedents, it is concluded that in order to reconstruct a floor plan of a Mamluk madrasa, five sets of rules need to be defined. The first set is the rules for schematic layout. Applied in a top-down, out-in approach where form evolves from the exterior-most abstracted shapes into the interior and detailed articulations, rules in this set are used to derive the shape of the exterior layout and its major organizational axes. The second set consists of the rules for the architectural components, which articulates the interior space and room shapes based on their functions and the logic of how the components are related within the floor plan diagram. Rules in the first two sets are schematic and are applied to establish the construction lines and major axes of orientation and symmetry. The third set includes rules for determining wall thicknesses. These assign a thickness for the construction lines generated through the layout and architectural component rules. Thus, rules in the third set transform the schematic diagram generated by the first two sets into an architectural representation of the floor plan at hand. The fourth set consists of rules for openings. These add shapes for door and window openings to the floor plan layout generated by the previous three sets of rules. The fifth set includes the rules for termination. These conclude the process of floor plan generation.

The five sets of rules and the information they represent are illustrated in Table 2. Each set represents a phase in the derivation sequence. The generation process starts with phase one, cycles between the second, third and fourth phases as needed, and finally concludes with the fifth phase, which terminates steps of the process. Rules in each phase are listed with their count and information as follows:

The formulated grammar consists of 93 rules distributed as:

Rule type	Number of Rules
Rules for generating schematic external layout shapes	12
Rules for generating architectural components	59
Rules for determining wall thickness	9
Rules for generating openings	9
Termination rules	4

The rules in each category are listed in Table 2.

Rule Phase	Rule Type	Number of Rules	Information Represented
First Phase: Exterior Shape	Rules for generating schematic external layout shapes	12	Exterior shape geometry, proportions, orientation
Second Phase: Architectural Components	Rules for generating interior spaces	2	Shape, location, proportion, topological relations
	Rules for determining the orientation of spaces	1	Angles and location of shape lines
	Rules for generating Iwans & courtyards	3	Location and division into subshapes
	Rules for scaling Iwans & courtyards	3	Axes, divisions and proportion
	Rules for generating spaces between Iwans	2	Location of transitional spaces, proportion and dimensions
	Rules for generating lateral spaces	4	Shape, dimensions and set operations
	Rules for generating Mihrab in the Qibla-Iwan	3	Axis of symmetry, location of semi-circle, transformation, set operation
	Rules for articulating interior spaces	4	Court type, roof type, location and geometry of fountain, sadla & minbar, iwan divisions
	Rules for generating Tomb or Mausoleum	13	Location, proportion, orientation, scale, shape and topological relations
	Rules for generating Ablution spaces	2	Location, orientation, shape and topological relations
	Rules for generating cells & rooms around the courtyard	4	Shape, transformations and topological relations
	Rules for generating the main entrance and Derka	18	Shape, location, proportion, size and topological relations
Third Phase: Wall Thickness	Rules for determining wall thickness	9	Wall thickness
Fourth Phase: Openings	Rules for generating openings	9	Placement, size and set operations
Fifth Phase: Process Termination	Termination rules	4	Removal of construction lines and labels

Table 2: The rule system for the derivation of Mamluk madrasa precedents

The Mamluk madrasa grammatical rule numbering system, and the initial and the exterior layout shapes are illustrated a separate paper [Eilouti and Al-Jokhadar 2007].

As an example of how the formulated rules restructure the information embedded in the case studies, rules (AC-5-D) and (AC-6-M) specify that there are transitional spaces between the courtyard and two Iwans. In addition, Rule (AC-7-S) specifies the dimensions of the courtyard (V_B) and (H_B). The proportion between (V_B) and (H_B) is 1:1, while the proportion between the courtyard and the total interior space is around 1:2.54, 1:2.30, or 1:2.22.

Rules (AC-8-S) and (AC-9-S) determine the dimensions of the two Iwans ($H_C : V_C$) and ($H_D : V_D$). All of these spaces are symmetrical about the main axis $Y_2 - Y_2$. Fig. 1 illustrates three of these rules and their associated symbols. These rules, namely (AC-7-S), (AC-8-S) and (AC-9-S), are used for scaling two of the major components of madrasa plan morphology, the courtyard and the Iwan components.

As an example of the information extracted from the floor plans of the sixteen precedents, the mathematical relations and ratios that govern the courtyard geometry of the case studies are illustrated in Table 3. The H and V values in the table denotes the horizontal and vertical dimensions of the court B. B represents the area of the court, and A represents the area of the court and the spine of the Iwans. B:All represents the area of the court compared to the total area of the madrasa at hand. X,Y signifies the origin point which is usually the centre of courtyard. These proportional and locational values of shape are translated into parametric assignment for the rules in the generative system structure.

A numerical analysis similar to that illustrated in Table 3 is conducted on all architectural components of the case studies.

The five-fold framework outlined above is developed into a computer implementation, which is designed to be viable for practical design problems. The computerized framework is designed to enable designers to understand existing designs and to generate new forms that have the same style of the studied precedents.

The computerized version of the generative system reflects the multi-layered multi-phased characteristics of the rule structure in order to permit a rapid generation of Mamluk madrasa prototypes through an incremental and lucid step-by-step sequence of selecting shapes, operators, transformations, parameter assignment, and rule application.

The method used to develop the generative system for the Mamluk madrasa design can be applied to any set of precedents and can be extended to allow experimentation and exchange between designs and styles.

Fig. 1. Rules for proportional scaling of courtyard and iwans

No.	Case Study	B					
		Courtyard (<i>al-Sahn or dorqa'a</i>)					
		H _B	V _B	H _B : V _B	B : A	B : All	(x, y)
1	al-Ashraf Barsbay Madrasah	14.35	16.00	1 : 1.11	1 : 2.30	1 : 6.7	(0, 0)
2	al-Kadi Zein al-Din Yehya Madrasah	7.70	7.50	1 : 1.02	1 : 2.30	1 : 11	(0, 0)
3	al-Amir Karkamas Madrasah	8.60	8.60	1 : 1	1 : 2.57	1 : 4.45	(0, 0)
4	al-Sultan Inal Madrasah	10.50	10.50	1 : 1	1 : 2.54	1 : 5	(0, 0)
5	al-Ghuri Madrasah	9.50	9.90	1 : 1.02	1 : 2.66	1 : 9.4	(0, 0)
6	Umm al-Sultan Sha'aban Madrasah	11.20	13.90	1 : 1.22	1 : 2.30	1 : 6	(0, 0)
7	Kane Bay Kara al-Remah Madrasah	7.40	7.60	1 : 1.02	1 : 2.54	1 : 8.5	(0, 0)
8	al-Sultan Katebay Madrasah	8.65	8.65	1 : 1	1 : 2.52	1 : 12	(0, 0)
9	Abu Baker Mezher Madrasah	9.55	7.90	1 : 1.22	1 : 2.41	1 : 5.3	(0, 0)
14	al-Tashtamur Madrasah	30.25	29.20	1 : 1.02	1 : 2.37	1 : 6.5	(0, 0)
10	al-Thaher Barquq Madrasah	17.90	22.00	1 : 1.22	1 : 2.22	1 : 7	(0, 0)
11	al-Sultan Hasan Madrasah	31.40	35.00	1 : 1.11	1 : 2.15	1 : 6.55	(0, 0)
12	al-Amir Derghemsh Madrasah	21.18	17.12	1 : 1.22	1 : 2.15	1 : 5	(0, 0)
13	al-Sultan Qalawun Madrasah	15.85	19.75	1 : 1.22	1 : 2.44	1 : 3.95	(0, 0)
15	al-Saffaheya Madrasah	8.60	7.12	1 : 1.22	1 : 2.22	1 : 6	(0, 0)
16	al-Baladiyya Madrasa	13.20	12.95	1 : 1.02	1 : 2.30	1 : 5.5	(0, 0)

Table 3. The parameters that control the shapes of the courtyards of Mamluk madrasas

4 The program interface

In general, it is widely assumed that people who use shape grammars tend to be visual thinkers, and those who program and implement computer codes are symbolic thinkers. People who think well both visually and symbolically seem to be quite rare [Gips 2000]. This may explain the insufficiency of computer implementations of shape grammar systems and the problem of the interface design in the existing implementations.

The issue of successful user design interface is significant in the design of computer implementations for shape grammars. Interface issues were addressed in a comprehensive way in Tapia [1996; 1999]. Tapia emphasizes the importance of improved computational machinery for a general two-dimensional shape grammar interpreter, along with a simple, intuitive, visual interface. The user of a computer-aided rule-based interpreter program needs to learn both about rule structure and how to use the program. To facilitate this, the program design should be transparent. Certainly it should make it easier to use the program than to try out rule application by hand [Gips 2000].

To generate or reconstruct a floor plan for Mamluk madrasas, the program starts by parsing and classifying the main vocabulary elements, their relationships and possible transformations. The overall flowchart of the rule development system is shown in fig. 2. Because of the large number of rules, the program commands are designed in phases and are decomposed into sequences of rules. The codes of the generative system are written in the AutoLISP language for the AutoCAD operating environment. This saves time in rewriting some existing programming routines and is very suitable for graphic applications.

The interface of the program described here consists of five main menus in addition to the typical file management, editing, viewing and support window-compatible menus. The five menus represent the five phases of the derivation process described above. Each phase reveals the multi-layered structure of the madrasa composition at that stage. The menus are designed in a simple and clear format. The menus are:

1. “Schematic Layout” rules. This menu specifies seven functions: the first six illustrate the six different types of layout for generating the exterior layout shapes of madrasa floor plans. Each layout has two rules. The first determines the proportions of the sides of the shape, and the second determines the angles between each two sides. The seventh and last function in this menu defines the centre of the exterior layout with reference to the interior court.
2. “Architectural Components” rules. This menu has nine submenus:
 - (1) Interior spaces. This submenu includes three rules for inner space organization.
 - (2) Courtyard and Iwans. This submenu includes twelve rules for the open and semi-open space articulation within the exterior layout shape.
 - (3) *Mihrab*. This submenu includes three rules for locating the niche in the southern Iwan wall.
 - (4) Articulating interior spaces. This has three rules for shaping the minor inner spaces.
 - (5) *Sadla*. This submenu includes one rule for forming the geometry of the secondary Iwan.
 - (6) Tomb. This submenu branches into four submenus: tomb #1 (with four rules); tomb #2 (with four rules); tomb #3 (with four rules); and tomb #4 (with one rule).
 - (7) Ablution space. This submenu includes two rules for the articulation of the ablution room.
 - (8) Cells around the courtyard. This submenu includes four rules for the articulation of the supportive cell geometry.
 - (9) Main entrance and *derka*. This submenu branches into six submenus: entrance #1 (with three rules); entrance #2 (with three rules); entrance #3 (with three rules); entrance #4 (with three rules); entrance #5 (with three rules); and entrance #6 (with three rules).

Fig. 2. A flow chart illustrating the process of developing the rule-based model

3. “Walls Thicknesses” rules. The main function for this menu is determining the thicknesses of exterior and interior walls of madrasas. For applying thickness to designated walls, the menu offers nine rules.
4. “Openings” rules. The main function for this menu is assigning the doors and windows for the plan of the madrasa. This is done through specifying whether the tomb is located on the right or left side of the Qibla-Iwan. There are nine rules under this menu.
5. “Termination” rules. These will erase the labels assigned to shapes through different stages for developing the shape grammars. This menu has four rules.

All of the five main menus and the additional submenus are illustrated in the hierarchical organization diagram shown in fig. 3. The information described by the rules is listed in Table 2.

The structure of the aforementioned five menus is shown in images captured from the screen, as illustrated in figs. 4 to 8.

Fig. 4. A screen image of the schematic layout menu

Fig. 5. A screen image of the architectural component menu

Fig. 6. A screen image of the wall thickness menu

Fig. 7. A screen image of the openings menu

Fig. 8. A screen image of the termination menu

5 Program testing and discussion

The Case of al-Ashraf Barsbay Madrasa in Cairo is used to demonstrate the applicability of the program presented in the previous sections. This case represents one of the sixteen precedents analyzed. It exhibits most of the features and components of the generative system. The generation process starts with the basic layout shape shown in fig. 9. The shape of the exterior layout is selected from the set of initial shapes offered by the schematic layout menu.

The plan generation process continues by applying rules from the architectural component menu to add the overall layout shape of the interior spaces and to assign numerical values for the parameters required by the rule prompts. The result of the interior space rule application process is illustrated in fig. 10.

Other architectural components, such as the courtyards, *iwans*, *mihrab*, *minbar*, *sadla*, tomb, ablution space, cells around the courtyard, the main entrance, *derka* and the Sheikh's house, are also added by using the architectural components menu. This set of architectural component configuration and articulation steps of the derivation process is illustrated in figs 11-17.

Fig. 9. The exterior layout of al-Ashraf Barsbay Madrasa after applying rules from the schematic layout menu

Fig. 10. The overall layout of the interior spaces of al-Ashraf Barsbay Madrasa

Fig. 11. The addition of the courtyards and *iwans* for al-Ashraf Barsbay Madrasa

Fig. 12. Generating the *mihrab* for al-Ashraf Barsbay Madrasa

Fig. 13. Generating *minbar* and *sadla* for al-Ashraf Barsbay Madrasa

Fig. 14. Generating the tomb for al-Ashraf Barsbay Madrasa

Fig. 15. Generating the abluton space for al-Ashraf Barsbay Madrasa

Fig. 16. Generating cells around the courtyard for al-Ashraf Barsbay Madrasa

Fig. 17. Generating the main entrance, *derka*, and the Sheikh's house for al-Ashraf Barsbay Madrasa

After the definition of the main architectural components of the madrasa, the door and window openings are added by using the opening menu. The plan with the openings is shown in Fig. 18.

Fig. 18. Generating openings (doors and windows) for al-Ashraf Barsbay Madrasa

Fig. 19. The overall layout of al-Ashraf Barsbay Madrasa after applying rules for the assignment of wall thicknesses

Fig. 20. A new alternative for the final layout of al-Ashraf Barsbay Madrasa after changing the exterior layout, location of the entrance, *derka*, and the tomb (in front of *qibla iwan*)

The penultimate step of the derivation process is the assignment of wall thicknesses to the lines derived so far. The assignment is conducted by applying the wall thickness menu commands. The result of this process, which transforms the construction line grid into the representation of the architectural plan, is shown in fig. 19.

To explore the emergent component of the program, variations in the order of rule selection and application were experimented with. By transforming, combining, and replacing layout shapes and rules, the generated designs can be made more interesting. As an example, various alternative designs that rely on the same principles of Mamluk madrasa design could be generated for al-Ashraf Barsbay Madrasa. One of these is shown in fig. 20, which shows the plan of the madrasa after changing the location of the main entrance, the *derka* and the tomb, and after varying the exterior layout shape.

Applying the automated grammar program highlights and explains through repetition the numerical, relational, and morphological aspects of plan organization of Mamluk architecture, which are usually neglected in descriptions of the style. Mamluk madrasas built in Egypt, Syria and Palestine have many morphological similarities. As shown by the derived example, the location of some components, such as the courtyard and the main Iwans, represents a major factor in shaping the grammar of all architectural compositions of Mamluk madrasa architecture. In addition, visual principles such as proportion, symmetry, axis location, and rotation angles are shared by the case studies and are emphasized during the generation process.

Knowledge of the geometric characteristics of the rudimentary vocabulary elements can be gained and enhanced by manipulating the exterior layout and interior space shapes that are offered by the menus for schematic layout and the architectural components.

Knowledge of the scale, proportion, orientation, symmetry, rhythm, and other visual principles can be enhanced by the numerical assignment of the parameters that are required during the rule application process. The shape grammar of Mamluk madrasas is influenced by many visual principles. These include symmetry, unit-to-whole ratio, repetition, addition and subtraction, geometry and grid structure, hierarchy, complexity, and orientation of parts. The major principles are briefly described as follows:

Asymmetric balance: As shown by the example derived, the typical symmetry that is associated with the sacred precedents is substituted by a concept of order that provides balance between parts which form a coherent whole. This concept was achieved through the use of multiple axes of various directions to control all topological relationships of the vocabulary of Mamluk madrasa components. Balance is achieved by geometry when a dominant form, such as the dome on the mausoleum, balances a massive cuboid that is dominant by its size. Although asymmetry is the general characteristic, Mamluk architecture exhibit some levels of symmetry on the organization of the internal layout. The precedents studied reveal central symmetry in which major axes meet in a focal point that is typically located at the centre of the courtyard and controls the layout of the Iwans. However, symmetry in Mamluk madrasas was not perfect. It was applied to control the organization of some internal components of the floor plan rather than the overall exterior shape.

Rhythm: Repetition, expressed as a rhythm of component distribution, can be found in many instances of Mamluk madrasa floor plans. It is expressed in the form of addition or division of a whole, or simply represented as a series of ratios. Elements of the plan were repeated by using the ratios of 1:1; or less frequently 1:2.57, 1:1.6 (approximately the golden section), or 1:3.14 (1: π).

Orientation of elements: A major factor of coherence in Mamluk madrasa architecture depends on grouping elements which have the same function on the same orientation axis. The major axis of orientation is dictated by the angle of Qibla direction. Again, this is due to the connection between education and religion in Mamluk madrasa architecture.

Hierarchy: Hierarchy was achieved in Mamluk madrasas by ordering primary components (such as the main courtyard) in the most central position and the secondary elements (such as cells around courtyard) in the less dominant locations.

Simplicity vs. Complexity: Although all interior spaces are simply shaped, the overall layout has a complex form. This complexity refers to two features of the layout which prevent the fragmentation of the secondary components:

1. The change of angle was used as a planning technique to create a new axis of orientation to organize the minor vocabulary elements. While the primary components were directed to the Qibla direction, the secondary ones were made more dynamic by changing their directions to distinguish them visually.
2. The large central space acts as a reference point or datum line for all other plan components.

Understanding the morphology and the design process of individual Mamluk buildings may enhance the explanation of town and city growth in Islamic cultures. By projecting component structure and relations in a Mamluk building on various buildings and their

interrelationships in town planning, new layers of interpretation can be added. For example, the previous characteristics such as space hierarchy and angle manipulation can be observed as planning techniques in some Islamic cities.

The example derived in this section illustrates the time-saving advantage of the program. For example, the manual generation of the floor plan required eight hours as opposed to one hour required for the computer-aided derivation of the same plan. The computer implementation presented in this paper represents a tool for designing an accurate and multi-layered madrasa floor plan.

Using the program conveys a message to the user that the process is as important as, if not more important than, the final product. It facilitates the exploration of the design process and product morphology analysis to better understand the beauty underlying its design. The developed grammar with its systemized components (vocabularies, mathematical and topological relations, rules, and initial shapes) enhances knowledge of *design science* through an algorithm-based framework that performs instantiation, transformation, and combination, as well as set operations of shapes and through connecting style attributes with principles of visual composition.

Although the generative system has good predictive, derivative, and descriptive powers, it has limitations when it comes to explaining the historical, social, and other symbolic and semantic considerations in the architectural composition. A future extension of the program may link the historical and social issues to the syntactic grammar developed in this paper in the form of attributed rules that augment semantic interpretations of the grammatical formalisms. Such augmentation can take the form of conditional or context-sensitive rule application. As such, restrictions can be added to guide the users about which rules to select at each step and in what context to apply them.

6 Conclusion

It has been shown in this paper that a Rule-Based Design (RBD) system can be constructed from the information inferred from case studies to guide the design process. Most of the design information embedded in precedent designs is not in a format that is viable for direct reuse. This paper has suggested a five-phase system of rules to enable restructuring and representing of the unstructured information embedded in precedents in the form of reproductive and recursive rules. Such a representation helps in the regeneration of existing precedents and in the generation of new designs that belong to the same stylistic prototypes. The system makes it possible to experiment with various combinations of rule application to explore new and unexpected alternatives.

After the theoretical formulation of the precedent-based generative system, it is translated into a computer-aided program. The program facilitates the automatic exploration of the aesthetic values of existing Mamluk precedents, as well as the generation of emergent examples of the same style.

This paper claims that a large portion of the rules used to define a style are based on the logic of form-making. The system developed supports this claim by articulating two types of form-making rules. These include the planning-based rules and the aesthetic-related parameters and constraints. The first type is concerned with the procedural aspects and the compositional principles and is expressed as a set of organizational axes and focal points of

form-making and is translated into direct rules. The second focuses on the numerical assignment of the dynamic parameters.

The research has shown that an integrated system that is based on a combination of a top-down approach of extracting information from precedents and a bottom-up approach of representing the extracted data as a set of rules can become a powerful tool for form analysis and derivation. The indeterministic nature of the system, coupled with its parametric structure, makes it flexible and dynamic enough to come up with unexpected emergent designs. The theoretical framework as well as the computerized program can be added to the design toolbox to communicate form structure, design process, principles of aesthetic composition and stylistic alphabet, and syntax of architectural design. Limitations of the system include the lack of representation of the social, historical, symbolic, and semantic issues in the form-making process.

A future extension of this research may focus on studying sets of precedents of different styles and developing a multi-style automated generative system and style editor that compares, evaluates, analyzes, and produces architectural designs of various styles. Another extension might take into consideration the morphology of façades or the three-dimensional spatial organizations of the Mamluk precedents as well as their impacts on plan composition. A comparative study could also be conducted to find commonalities or correspondences between the grammar of Mamluk madrasas and that of other madrasas (such as Western madrasas). Furthermore, connections between this research and Problem-Based Learning or E-Learning settings could be emphasized in future research.

Notes

1. According to structuralism [Caws 1988], objects exist in groups that collectively exhibit commonalities in their attributes. Such objects can be grouped into systems which can be defined recursively. Consequently, to understand systems it is necessary to investigate the internal as well as the external relationships of the system components and the structures that underlie their grouping.

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