DESIGN GENERATION OF THE CENTRAL ASIAN CARAVANSERAI

Use of a parametric shape grammar for the analysis of historic Islamic architecture

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Abstract. Challenges for the study of Islamic architecture include its abundance and diversity in expression and its classification based on distinct functional or stylistic types. We address these issues by presenting shape grammars as a methodology for the analysis and design generation of Islamic architecture, with a specific example in the form of a parametric shape grammar for central Asian caravanserais. The grammar is developed by identifying distinct design types. Shape rules are created based on a study of the spatial elements and their organisation in the designs. We illustrate the utility of the grammar by deriving an extant design and as well as, previously unknown designs. We conclude by discussing possible extensions to the current grammar and future work involving the development of a grammar based framework for the comparative analysis of medieval Islamic courtyard buildings.

1. Introduction

The contribution of the Islamic civilisation in the field of architecture is both vast and diverse. Spread across three continents from Southeast Asia to North Africa and Southern Europe from 750 AD till the present time, Islamic architecture adapted itself to local climate and materials, and thus portrayed a unique face in each region.

The abundance and diversity in expression of Islamic architecture presents historians with several problems in classifying and analyzing Islamic architecture based on distinct functional, geographical or stylistic types, as very often these types overlap or have hazy borders (Hillenbrand, 1994), thus pointing towards a need for the development of an alternative method for the analysis of Islamic architecture (Menon, 1999). Another issue facing Islamic architecture is the generation of a contemporary idiom — one that projects the community's identity and specificity by relating itself to historic architecture, whilst being modern and true to its time (Lewcock, 1988).

This paper addresses the aforementioned issues by presenting shape grammars (Stiny and Gips, 1972) as a methodology for the analysis and design generation of Islamic architecture. One of the most important characteristics of Islamic architecture, which makes it a subject amenable to the methods of rule based analyses, was its basis on advanced concepts of geometry and mathematics and the use of modular design systems (Hillenbrand 1994; Holod 1988). Being a rule based methodology shape grammar are well suited to the design generation techniques of Islamic architecture.

The study relies on a brief examination of Islamic principles of design, which aid in the creation of a meaningful conjecture of the design process of historic Islamic buildings. This deduction of principles from the precedent of historic buildings is deemed as a vital factor, beneficial for the computation of meaningful designs of future buildings.

In this paper we describe a parametric shape grammar for the generation of the ground plans of Central Asian caravanserais and demonstrate its use for representing extant designs as well as generating new ones in the style of the caravanserai.

2. The Concept of the Central Asian Caravanserai

Caravanserais were rest houses for caravans, built on trade routes between central Asian cities in the middle ages. Several types of caravanserais developed in Asia from the 10th century onwards, varying according to time and place.

The central Asian caravanserai was designed as a fortified development with a central courtyard, and a cellular growth of rooms all around it. It was square, round or octagonal in plan, concentric in nature, with bastions marking the fortification wall and towers at the angles. The access was often through a single portal placed at a location on the orthogonal axis. Often, the courtyard of the caravanserai was surrounded by arcades, with emphasis at the central bays, following the traditional four *iwan* plan (Pope, 1971). Figure 1 illustrates a variety of caravanserais and related buildings.

The courtyard was used as a place to tether the animals, whereas cells provided living space for the travelers. Toilets were placed in the towers at the corners of the building. In later caravanserais, an extra zone between the living quarters and the peripheral wall was developed to house stables for the animals. Since caravanserais were often isolated outposts in the countryside, they also fulfilled the role of defense bases.

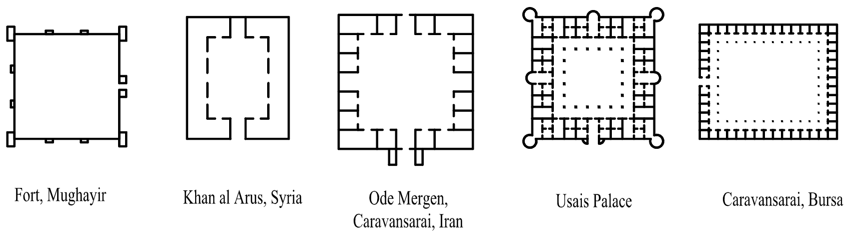

Figure 1. Examples of caravanserais, desert palaces and forts.

The complexity in design of the caravanserai grew with the increase in its functions and scale over the centuries.

Often a 'four *iwan*' plan was adopted for the caravanserai. In this type of a building, there was added emphasis on the central bays on the orthogonal axes, which were developed into large, arched rooms, open to the court. This was deemed as a 'generic' plan, at once applicable to various kinds of Islamic buildings such as palaces, private dwellings, caravanserais, mosques and madrasas (Michell, 1978).

The design of the caravanserai has been said to be influenced by Roman forts as well as domestic courtyard architecture. Some writers also point to Buddhist monasteries and Chinese military posts as possible sources of the caravanserais; although it is conceded that at an early stage, caravanserais most closely resemble forts, or *ribats*. The primary components of such forts were heavy construction walls, massive towers, bastions/buttressing and huge portals set at strategic points in the fortification. The local building tradition was followed in construction of fortifications, with round, square or elongated towers at the angles of the fortification (Michell, 1978).

3. Islamic Principles of Design Associated with the Central Asian Caravanserai

A universal characteristic of buildings all over the Islamic empires was their fundamental reliance on mathematics and geometry for planning and construction (Michell, 1978). The use of geometry has been ascribed an esoteric dimension, as it is seen as a vehicle to manifest the Islamic doctrine of unity (Critchlow, 1970; Ardalan and Bakhtiar, 1973). Geometric organisational principles such as symmetry, hierarchy and axiality were used (Hillenbrand, 1994) to create ‘perfect forms’ (Michell, 1978).

Symmetry is often seen as the basic principle of design in Islamic architecture. It involved the balancing of similar, not necessarily identical, parts of a design on the opposite sides of a fulcrum or axis (Golombek, 1988). Hierarchy was used as a primary means to subdivide a building and to highlight some spatial elements over the other. Hierarchical principles were used in conjunction with those of scale to create emphasis in design (Hillenbrand, 1994).

A proportional framework was used not only for the development of details, but also for layout and form development, with the intention of bringing all parts of building into a harmonious relationship with each other (Volwahsen, 1970). Building designs were developed on grids based on modules, which corresponded to the prevailing brick size. The dimensions of various parts of the building were based on simple ratios of these modules (Michell, 1978; Holod, 1988).

Thus, Islamic buildings can be seen as a configuration of spatial elements bearing formal relationships with one another. In the shape grammar formalism, such spatial elements can easily be translated into ‘shapes’ that constitute spatial relations. The ordering principles can be translated into ‘shape rules’ that are responsible for the organisation of spatial relations.

4. Shape Grammars as a Tool for Design Analysis and Generation

Shape grammars (Stiny and Gips, 1972) have been in use for over three decades. Their utility in design generation and analysis has been well documented (Knight, 2000). Grammars are both prescriptive and descriptive: the rules of a grammar generate designs but can also be considered descriptions of the forms of the designs. Stiny (1980) has made a number of observations on the benefits of using rules to produce languages of designs, among them:

- They are less complicated than the designs they generate;
- They create new directions for design within a given vocabulary;
- Rules shift the emphasis from individual designs to sets (languages) of designs;

- Use of a language of designs allows a designer to examine a design and its variation without loss of understanding, simply by applying the rules to construct them;
- Rules can be modified systematically to define new languages of design.

A shape grammar consists of a set of rewriting rules that can be used to generate a set of designs (the language). A computation starts with an initial shape. A rule can be applied when an instance (geometric transformation) of its left hand side shape can be found in the current state (shape) of the computation. This transformation is then replaced with the equivalent transformation of the right hand side of the rule. Figure 2 shows a simple grammar with one rule that can generate church plans based on the spatial relations of a Greek cross. The language of designs generated by a grammar can be considered analogous to a design style.

More complex grammars can be created by employing additional computational devices. Parametric grammars use variables to allow a wider variety of designs from a single grammar, e.g. to vary dimensions. The use of labels in the form or markers or points can constrain rules to be applied in specific contexts, e.g. as a means of establishing a specific sequence of operations that could represent stages of design.

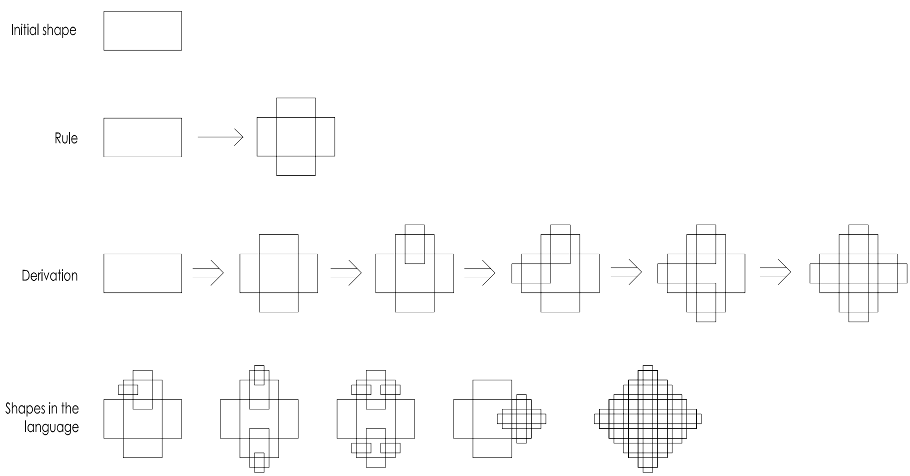

Figure 2. Simple shape grammar for Greek cross church plans (from Knight, 1994)

5. The Caravanserai Grammar

The caravanserai grammar generates the ground plan of a fortified courtyard with a configuration of corner towers, entrances and bastions marking the external wall. A maximum of two built-up zones (cells & colonnade) are generated by this grammar. The following sections elucidate the development of the grammar.

5.1 GENERAL CONSIDERATIONS

A special feature of Islamic architecture that has been acknowledged is that of its multi-functionality of building design. Islamic architecture developed ‘perfect building forms’ that could be adapted for various purposes (Michell, 1978). The same building plan could be utilised for fortresses or for caravanserais (Michell, 1978), and often one building would be indistinguishable from another judging by the ground plan alone (Hillenbrand, 1994). Hence the grammar created in this project generates ground plans not only of the caravanserai building type, but also of forts and desert palaces with similar designs.

The vast abundance and diversity in the historic buildings of Islamic architecture presents a problem in any generalisation of design. To make the task easier, only the buildings that shared a commonality in structure have been considered. Variations in design due to site constraints or other reasons have been ignored. The shape grammar so developed does not generate all varieties of designs that have existed in history, but would be able to generate a wide range of buildings.

Errors and slight inconsistencies in axes, proportions, and angles have been ignored in order to facilitate a more wholesome discussion of the generation of design. Wall widths have been ignored for the purpose of this project.

Parameterisation of space dimensions has not been detailed in this project. It is believed that if attempted, this would not pose any difficulty since building designs in Islamic architecture were based on modular systems. However, the size of the module as well as spaces based on it would vary according to time and place (Michell, 1978).

5.2 APPROACH

The following processes were followed for the development of the caravanserai shape grammar:

5.2.1. Identification of Design Types

Three related design types were identified. The generic design is that of a fortification which is constituted by an open space enclosed by a wall. The second level of design is that of a courtyard enclosed by a single built up zone, consisting of unitary or multiple cells. Finally, the third level design creates a courtyard surrounded by two built up zones i.e. a colonnaded space and a cell zone.

5.2.2. Identification of Spatial Elements & Their Organisation

Spatial elements such as the courtyard, the fortification wall, corner tower, primary and secondary bastions, primary and secondary entrances etc. were identified and delineated. The center of the courtyard, represented by an intersecting orthogonal axis, was identified as the generator of the design. Spaces and spatial elements have bilateral symmetry about these axes, with often a strong emphasis at the central bays.

5.2.3. Creation of Shape Rules and their Sequencing

The spatial elements were converted into parametric shapes bearing relationships with one another in shape rules. The primary parameter was established to be the size of a cell module, *m*. The sequential ordering of the rules was mostly intuitive and highly dependant on the shape recognition techniques of the shape grammars formalism.

5.2.4. Setting up Constraint and Control Mechanisms

Constraints were set up in the rules to control the applicability of a rule. This was considered necessary, in order to limit the generation of irrational designs, whilst allowing the possibility of a wide range of new and varied designs.

5.3. RULE CONTROL MECHANISMS

5.3.1. State Labels

State labels have played a significant role in the application of rules. One of their most important uses has been to make certain rules ‘obligatory’, where the requirement of a state change makes the application of a rule necessary for the progress of the design generation (Knight, 1994). For instance, rules 11a and 16a are obligatory for a design to reach a final state. Other rules may be termed as ‘optional’ for the development of a design. These contribute to the generation of a wide array of designs in the grammar.

State labels have also been used to control the number of times a rule could be applied to a design. For example, a constraint placed on the state label in rule 1a allows it to be applied only twice (note that states are indicated in the rules by Roman numerals).

5.3.2. Spatial Labels

The primary spatial labels used in this design are the orthogonal axes running through the center point, and the 'cross' signifying the courtyard. These spatial labels control the choice of the Euclidean transformations under which a rule may be applied. Other spatial labels that have been used are line markers, such as those used in rules 3b and 6a, which control *where*, or to what parts of a design a rule can be applied.

5.3.3. Other Labels

Dimension lines have been used to delineate the size of elements. Text labels have been used for the denotation of shapes.

5.4 SHAPE RULES

The shape grammar is developed in five stages. Stage A contains rules for the development of a generic design for the built zone of the building. Stage B allows the definition of this built zone. In Stage C, a generic design for the fortification wall is created, while stage D contains rules for the stylisation of the fortification wall. Stage E hosts termination rules.

The organisation of rules in such a manner gives a grammar the potential to be transformed easily by ascribing new forms to stylisation/definition rules. This would result in designs which are essentially based on an Islamic construct, but have a new expression.

5.4.1. Initial Shape

The initial shape (Fig. 3) is a labelled polygon *P(0)*, with its vertices marked. Orthogonal axes marks the centre point, whereas a dotted cross indicates the open space of the courtyard. The dimensions of the shape are based on multiples, n' and n'' of a modular length, m.

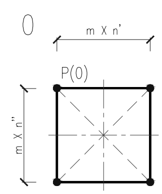

Figure 3. Initial shape in the caravanserai grammar

5.4.2. Stage A: Building Zone Development

Figure 4 illustrates the initial rules for defining building zones, the major organizing elements of the plan.

Rule 1a is an optional rule that creates a polygon inside the given polygon, thereby reducing the size of the courtyard by a multiple of the modular length m. The rule can be applied recursively to generate a single built zone (cell zone only) or two (cell & colonnade) built zone designs. A design with no built zone, i.e. a fortification, can be generated by skipping the rules in stages A, B and C.

Rule sets 2 to 4 govern the development of designs with one or two building zones.

Rule 2a is an obligatory rule for single zone designs. It creates entrances to the courtyard in the wall *P(1)* at all locations on the orthogonal axes. The dimension of the opening is parameterised to be dependant on the length of the module and number of bays in the entire length of the wall.

Similarly, rules 3a, 3b and 3c are obligatory rules for designs with two built zones. Rule 3a creates entrances on all orthogonal axes in shapes *P(1)* and *P(2)*. The size of the entrance is a multiple of a modular length, *m*. Rule 3b changes the labeled shape *P(2)* into a colonnade, by setting up a counter to create *n* bays of module *m*. The rule applies recursively till line markers overlap, making possible the application of rule 3c.

Rule 4 is an optional rule that can be applied recursively to create 1,2,3 or 4 'iwans' or halls at central locations in both 1 or 2 zone designs.

5.4.3. Stage B: Cell Rules

Rule sets 5 to 8 (Fig. 5) govern the generation and design development of cells in single and double built zone designs. Rule set 5 concerns unitary cell configurations, whereas rules 6, 7, 8 apply to multiple cell configurations.

Rule 5a creates a break in the center of the wall *P(1)*, thereby creating an entrance to a large, unitary cell. Rule 5b is an optional rule for unitary cell configurations. It creates stables of modular length on the inner periphery of the wall *P(0)*. With the application of rules 5a and 5b, the design moves directly into stage D.

Rule set 6 deals with the creation of multiple cells of modular length *m*. Rule 6a is applied recursively till the desired number of cells are created. The application of the rules in rule set 6 makes obligatory the application of a rule from the corner cell rule set, which governs the correction of a closed corner cell.

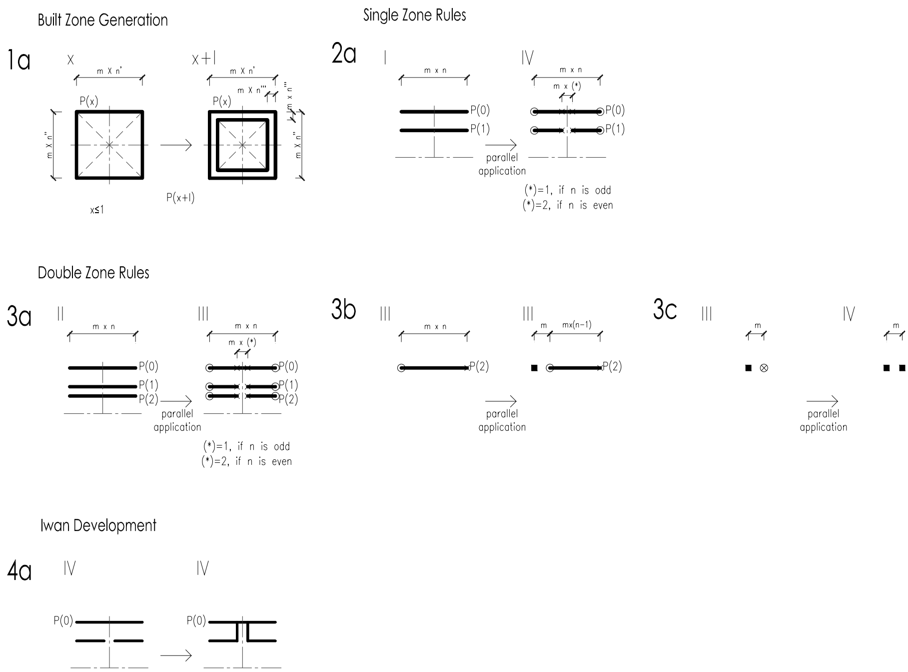

Figure 4. Stage A rules for building zone development.

Rule 7a deletes a wall, and merges the corner cell with one of the adjacent cells. Rule 7b creates a break in one of the walls of the corner cell so that it can be accessed from an adjoining cell. Rule 7c merges adjacent cells with the corner cell and bevels the corner. Other such rules may be defined.

Rule 8a is an optional rule that may be applied to designs that underwent multiple cell generation. It divides all the cells in the design into half. This rule is associated with a state change, so can be applied only once. Rule 9a is a state change rule that allows designs from earlier stages to jump over to the next stage.

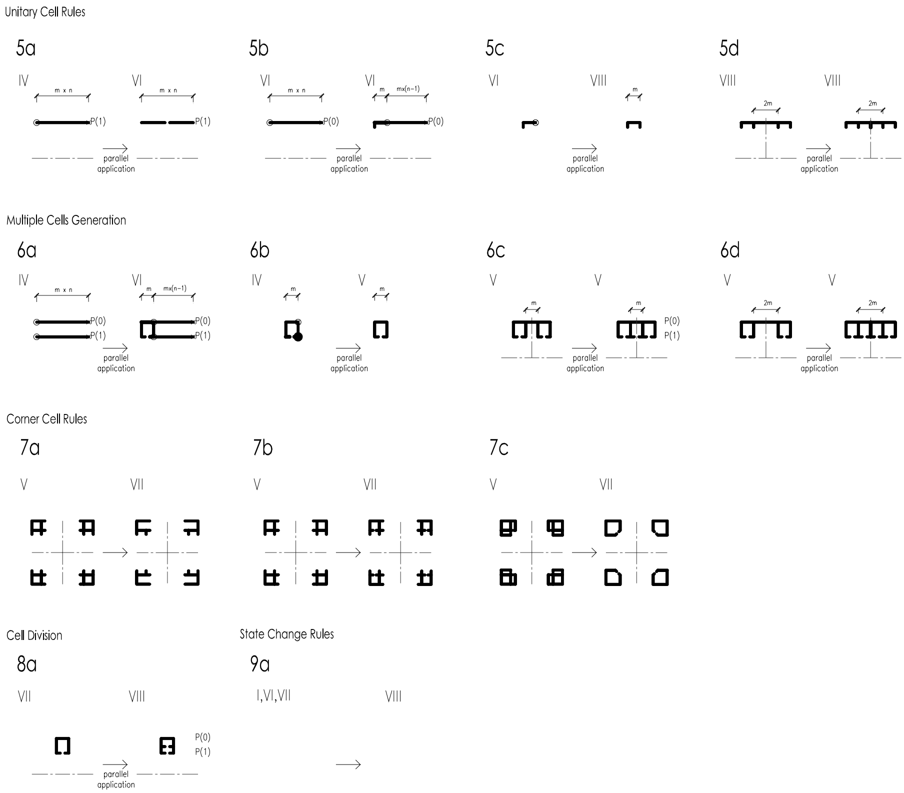

Figure 5. Stage B rules for cell development.

5.4.4. Stage C: Fortification Wall and Entrance Development

This stage (Fig. 6) marks the development of the fortification wall *P(0)*. Rules 10a and 10b are optional rules that place configurations of secondary bastion markers, *B(s)* on the fortification wall.

Rule 11a is an obligatory rule for all designs. It creates a primary entrance in the fortification by breaking the wall *P(0)* at a central location. Two secondary bastion markers *B(s)* are placed adjacent to the entrance. A circular marker signifying a stylised entrance is placed at the interior of the entrance.

Rules 11b is an optional rule that can create 2, 3 or 4 secondary entrances. Rule 11c places primary bastions at central positions on the wall.

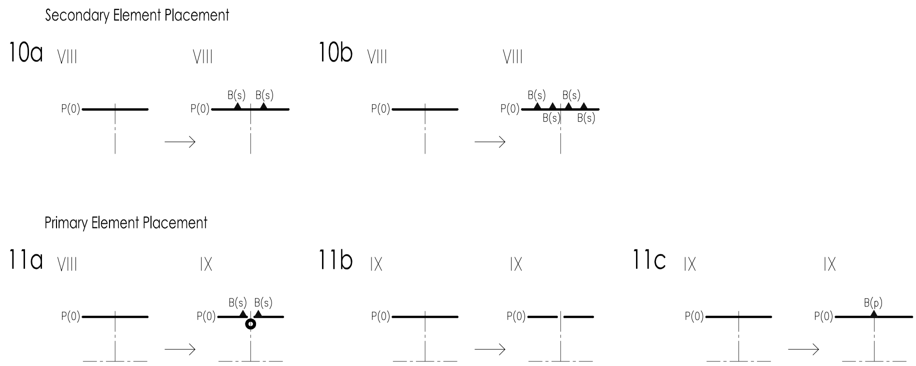

Figure 6. Stage C rules for entrance and wall fortification.

5.4.5. Stage D: Definition of Spatial Elements

Figure 7 illustrates the rules for defining spatial elements.

Rule set 12 lists the design definitions for a stylised entrance. Rule 12a merges the primary entrance bay with adjacent cells. Rule 12b creates openings in the walls adjoining the primary entrance bay.

Rule sets 13 & 14 define the various styles that corner tower and bastions may adopt in a design. Constraints have been placed such that although all corner towers will have the same designs, the bastions may adopt differing styles, thus in keeping with the Islamic design principle of conceptual symmetry. (Golombek, 1988).

Rule set 15 defines bastions at primary entrances.

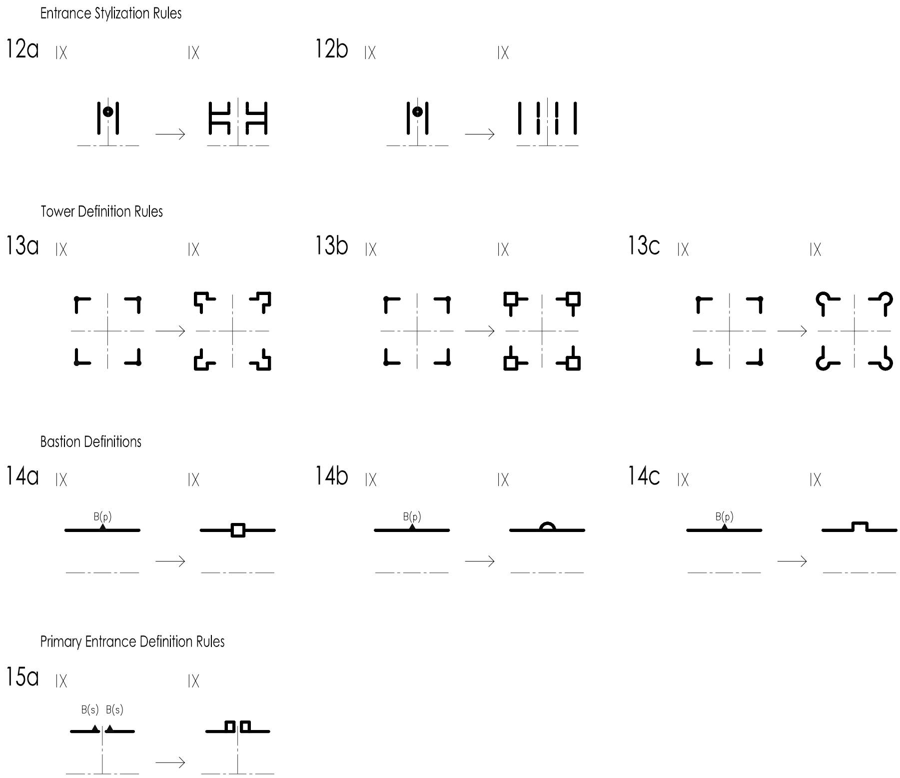

Figure 7. Stage D rules for the definition of spatial elements.

5.4.6. Stage E: Termination

Figure 8 illustrates rule set 16, which terminates rule application by erasing all the labels and markers remaining in the design and steps the design to the final state.

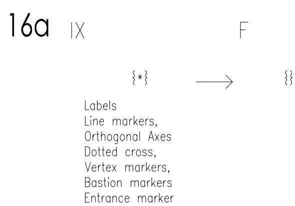

Figure 8. Stage E termination rules (in abbreviated form).

5.5. DERIVATIONS

In Figure 9 we present an example derivation of a caravanserai as depicted by Hillenbrand (1994, p. 557 #6.85). As buildings of this type tend to have minor idiosyncrasies, the grammar generates a design approximating that of the example without being an exact representation. The application of a rule used several times in sequence (typically to generate all instances of a duplicate feature such as a bastion) is shown only once. Figure 10 shows additional designs in the language generated by the grammar.

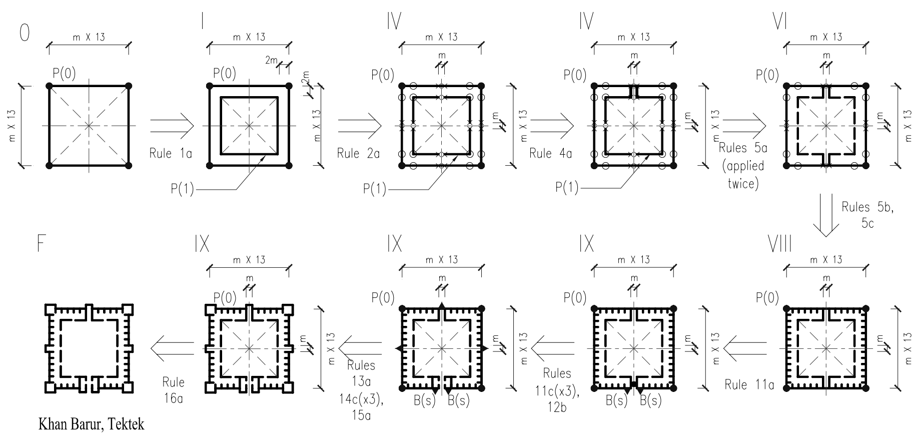

Figure 9. Derivation of a caravanserai.

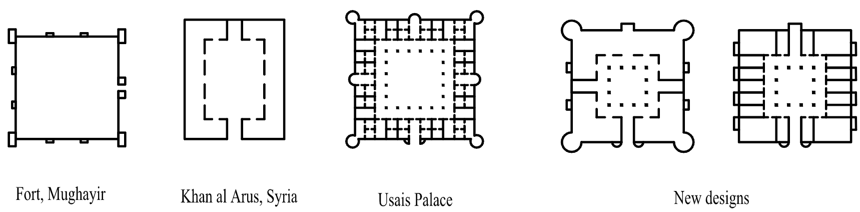

Figure 10. Additional designs in the language generated by the grammar. The three on the left are based on actual buildings, while the two on the right are new designs.

6. Discussion and Further Work

6.1. DISCUSSION OF THE CARAVANSERAI GRAMMAR

The shape grammars created in this project are limited to the generation of square or rectangular ground plans. This limitation can be overcome by parameterising the initial shape to generate polygons of six or eight sides. This would explain a number of designs with hexagonal and octagonal plans of medieval Iran, which closely resemble four sided plans in terms of their spatial organisation.

One of the biggest challenges in the creation of the grammar was to allow the possibility of generating a variety of designs, while limiting the rules. Moreover, strong constraints and control mechanisms had to be used to limit the generation of irrational designs.

As building types of Islamic architecture are fairly variegated (Hillenbrand, 1994), it is not claimed that the grammar written in this project would create all kinds of caravanserais existing in history. Rather it is felt that the caravanserai grammar embodies an approach to design based on Islamic principles. Its real scope lies in evolving the grammar to give contemporary meaning to elements generated in generic configurations, so that valid present day designs are generated.

6.2. COMPUTATIONAL FRAMEWORK FOR THE STUDY AND COMPARISON OF ISLAMIC BUILDINGS

Our ongoing work involves the investigation of the transformation of the caravanserai grammar to grammars that generate related building types of Islamic architecture. Among those we are investigating are more complex caravanserais, madrasas and mosques. We are adapting the techniques developed by Knight (1994) to investigate the relationships between similar design types.

This study points to the development of a set of related grammars that could be merged to create 'composite' grammars. This method of design development is consistent with the design methods of Islamic designers of the past, as a unique characteristic of Islamic architecture was that it developed by borrowing from various sources and was 'notable primarily for the originality of the manner of combining diverse elements' (Musgrove 1987; Hillenbrand, 1994). The shape grammar methodology also tackles the issue of the analysis of the great multiplicity in design in Islamic architecture of the past, and could lead to the creation of a great number of contemporary Islamic designs.

6.3. SUMMARY

By developing a parametric shape grammar for caravanserais, it was demonstrated how such a rule based methodology can be adapted to the geometric design generation techniques of Islamic architecture.

The use of the shape grammar methodology described here offers a new and alternative approach for the study and analysis of historic Islamic architecture, with a focus not on chronology, building style or type, but on design complexity. Such a study offers an analytical understanding to the structural changes that may have appeared in the designs of historic buildings. With reference to Islamic architecture in particular, the methodology can be used to understand the transformation of design in architecture, which drew inspiration from several sources.

The utilisation of shape grammars developed from the analysis of traditional historical styles has the potential to offer a unique computational method for the design of contemporary Islamic architecture.

References

Ardalan, N. and Bakhtiar, L.: 1973, *The sense of unity: the Sufi tradition in Persian architecture*, University of Chicago Press, Chicago.

Critchlow, K.: 1999, *Islamic patterns: an analytical and cosmological approach,* Inner Traditions, Rochester, Vt.

Golombek, L.: 1988, The function of decoration in Islamic architecture, *in* M.B. Ševčenko (ed), *Theories and Principles of Design in the Architecture of Islamic Societies*, The Aga Khan Program for Islamic Architecture, Cambridge, Mass. pp. 35-45.

Hillenbrand, R.: 1994, *Islamic architecture: form, function, and meaning*, Columbia University Press, New York.

Holod, R.: 1988. Text, plan and building: On the transmission of architectural knowledge, *in* M.B. Ševčenko (ed), *Theories and Principles of Design in the Architecture of Islamic Societies*, The Aga Khan Program for Islamic Architecture, Cambridge, Mass. pp. 1-12.

Knight, T.: 2000, Shape grammars in education and practice: History and prospects, *International Journal of Design Computing* **2**, http://www.arch.usyd.edu.au/kcdc/journal/vol2/articles/knight/index.html, last access 11 Aug 2004.

Knight, T.W.: 1994, *Transformations in Design: A Formal Approach to Stylistic Change and Innovation in the Visual Arts*, Cambridge University Press, Cambridge.

Lewcock, R.: 1988, Foreword, *in* M.B. Ševčenko (ed), *Theories and Principles of Design in the Architecture of Islamic Societies*, The Aga Khan Program for Islamic Architecture, Cambridge, Mass. pp. v-vi.

Menon, A.G.K.: 1999, Historical Conundrums, review of *The New Cambridge History of India, Architecture and Art of the Deccan Sultanates* by George Michell and Mark Zebrowski in *The Book Review*, The Book Review Literary Trust, New Delhi, September 1999, pp. 1-7.

Michell, G. (ed): 1978, *Architecture of the Islamic world: Its History and Social Meaning,* Thames and Hudson, New York.

Musgrove, J. (ed): 1987, *Sir Banister Fletcher's A History of Architecture*, Butterworth-Heinemann, London.

Pope, A.U.: 1971, *Introducing Persian Architecture*, Oxford University Press, London.

Stiny, G.: 1980, Kindergarten grammars: Designing with Froebel's building gifts, *Environment and Planning B* **7** 409-462.

Stiny, G. and Gips, J.: 1972, Shape grammars and the generative specification of painting and sculpture in C.V. Freiman (ed), *Information Processing 71*, North-Holland, Amsterdam, pp. 1460-1465.