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Generating Circulation Designs Using Shape Grammars

Chao Li, Lei Jiang, Fanrui Sun, and Kang Zhang*

Abstract: Shape grammars are well-known tools to explore abstract systems of shapes and their relationships. Although there has been much research on the use of shape grammars in the field of architectural styles, there has been little investigation into the concept of circulation using shape grammars. Circulation is a tool used in architecture and interior design and is formed by connecting the points left by the movement of human beings through indoor or outdoor spaces. This study shows that shape grammars are also helpful in this particular field by presenting how a parametric shape grammar is applied to generate circulation designs, and the system automatically generates four basic types of complex circulations. According to the specific conditions and requirements of each commercial space, different forms of circulation can be specified and generated.

Key words: circulation; shape grammar; Palladian grammar; shape grammar interpreter

1 Introduction

In public spaces, circulation design^[1] is often discussed, because a good circulation design is important for exhibition spaces, such as museums and shopping malls. Much knowledge is required to understand how to make people entering a space feel comfortable in moving around, without being obstructed by an obstacle or losing their way. In addition, traffic jams occur in amusement parks or other large parks without a good traffic circulation plan. Circulation design is also important in supermarkets and department stores that may emphasize using indirect routes so consumers can walk long distances and see as many products as possible. Automatically or semi-automatically generating circulation plans according to a given set of requirements are also beneficial.

As well-known architecture and mechanical part specification tools, shape grammars^[2] are powerful tools

that help study abstract systems of shapes and their relationships. In the architecture field, these tools have been used to aid the design of various architectural plans, such as Palladian-style plans^[3]. Palladian villas have frequently been used to introduce new concepts for shape grammars; in turn, a shape grammar has also been used to supplement Palladian-style concepts. However, no work has been undertaken on using a shape grammar to specify and generate circulations. Circulations are the connections of the points that are created due to the movements of humans through indoor or outdoor spaces.

This paper shows that shape grammars, commonly used in the field of architectural design, especially in Palladian-style plans, are powerful enough to automatically generate circulation designs. The paper makes the following specific contributions.

(1) It explains the fundamental commonality of the structure and appearance manifest for buildings requiring circulation.

(2) It provides the interpretative machinery required to generate new circulations.

The rest of the paper is organized as follows. After reviewing the related work in Section 2, Section 3 introduces the concept of circulation used in architecture and interior designs. Section 4 then presents the proposed shape grammar specifications for circulation design, and

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concrete examples of generating designs using our recently enhanced shape grammar interpreter are presented in Section 5. Lastly, Section 6 concludes the paper.

2 Circulation

Circulation is a concept used for architecture and interior design and is formed by connecting the points left by the movement of human beings through indoor or outdoor spaces. For architectural planning and design, circulations play an important role for effective and efficient use of the given space^[1]. In simple terms, a circulation denotes points that form a line, where each footprint leaves a point and the strings of footprints form a line, as shown in Fig. 1.

2.1 Role of circulation

In a public space, circulation design is commonly used. A good circulation design is important for exhibition spaces, such as museums and shopping malls, and much knowledge is required to clearly understand how to help people entering a space feel comfortable in moving around without being obstructed by any obstacle or losing their way. In addition, traffic jams would be experienced in amusement parks or other large parks in the absence of good traffic circulation planning. Circulation design is also important in supermarkets and department stores that may emphasize using indirect routes so consumers can walk long distances and see many products.

Therefore, not all circulations in space are designed for rapid movement. In designing circulation, two key aspects must be considered: (1) fixed structures and furnishings, and (2) the routes traversed by people or moving agents. These two aspects can influence one another due to design changes. The aspects can be defined according to guidelines on the shape of the space and can be shifted relative to each other due to micro-adjustments of the space. For specific designs, the size of the space, including the area and the height; the geospatial relationships within the space; and the activity requirements of people and their habits comprise the basic elements to be considered when designing the circulation.

The circulation design for an exhibition hall can be used as an example and is shown in Fig. 2. First, the



Fig. 1 Schematic diagram of circulation.

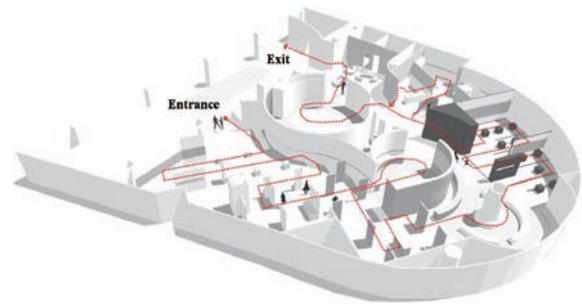


Fig. 2 Schematic diagram of the circulation design in an exhibition hall.

visit route should be arranged based on the contents being exhibited, and the products should be exhibited in order of priority. To determine the correct manner to exhibit these products, many elements must be considered in the circulation design: the visit route, how to ensure that visitors would be able to view as many products as possible, how visitors can be attracted to the main products, and how to maintain smooth traffic flow. Second, limitations of the current architectural space should be considered so that the two requirements are in harmony; thus, the circulation is designed based on the space. Therefore, the reasonable use of space is vital to designing the exhibition circulation. In addition, space operation, field subdivision, and the constitution of macro-space should be considered at the same time. The purpose of circulation design is to provide convenience for visitors. Therefore, the convenience level should be considered in conjunction with these requirements for the exhibition design. In some cases, once a circulation design is finished, the spatial configuration is also complete.

2.2 Circulation design

Setting the route for streams of people in an exhibition space depends on the design theme, the structural and functional divisions, and other factors. The ideal setting for a visit circulation should have a defined order and a short and convenient constitution form. Thus, in the museum example, visitors can walk through the entire exhibition, and their attention can also be attracted to the media and information centers. During the exhibition design process, both mutual convection and repeated walkthroughs by visitors should be avoided. Visitors should be prevented from accidentally omitting or repeatedly visiting something, and the design should avoid making visitors feeling tired.

Generally, a circulation may be in a clockwise direction, moving from left to right, according to the common visual habit. An unordered circulation design

may confuse visitors and cause them to omit some areas while repeatedly visiting others. Also, the division of the exhibition design in the circulation area should be simple and clear and with necessary turns and curves so that visitors can focus on the exhibition and naturally walk through the space. Depending on the size and nature of the exhibition determines whether the order of the visiting points is essential. For example, most large international exhibitions or comprehensive supermarkets do not have a fixed circulation and only stipulate the exit and entrance; thus, there is no interference if the movements of customers do not obey the rules.

2.3 Types of circulation

This paper discusses the basic rules of circulation design, using an exhibition in reality as an example while considering the differences between visual and movement forms. The basic units of circulation design can be divided into three types: series organization, radiation organization, and radiative series organization^[2], as shown in Table 1. Table 1 illustrates that the basic form of circulation depends on the design of points, lines, and

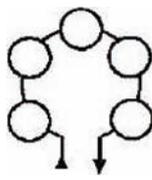
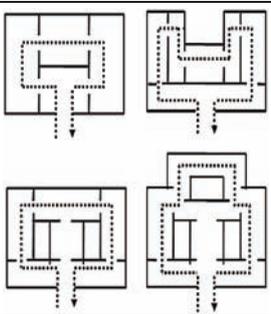
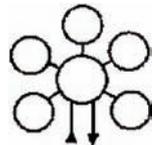
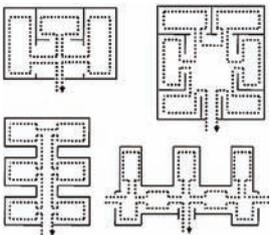
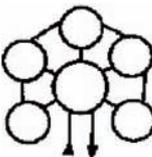
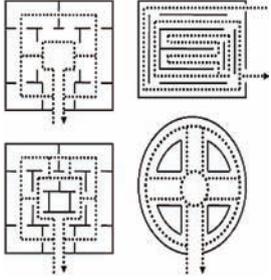
squares.

A circulation composed of points should flexibly display end points and nodes. Here, end points are the exit and the entrance, and nodes are the junctions on a route chosen by visitors. A circulation composed of lines usually employs a flow direction of straight lines, curved lines, and broken lines. A circulation comprised of squares is designed according to a combination of the above two types of circulations. A grid circulation generally uses a combination system of standard components in a pillar-free hall. The shapes of the grids are usually geometrical and include squares, rectangles, rhombi, and other polygons.

3 Specification of Circulation Designs

This section describes how parametric shape grammars can be applied to the specification of design rules and the generation of circulation designs. This characterization ideally has three main purposes: (1) inherit and develop Palladian grammar, (2) explain the underlying commonality of the structure and appearance manifest

Table 1 Schematic diagram of the circulation design in an exhibition hall.

Type	Description	Example of the type	Example of the circulation
Series organization	<p>(1) Each exhibition hall shall be connected. Visitors experience a smooth visit route in a single direction. Flexibility is poor, and traffic jams are likely to occur.</p> <p>(2) Suitable for small or medium-sized exhibition halls with high continuity.</p>		
Radiation organization	<p>(1) Exhibition halls are arranged around a radiation center. After visiting one or a set of exhibition rooms, visitors can go to other rooms through the radiation center. The route is flexible.</p> <p>(2) Suitable for large or medium-sized exhibition halls.</p>		
Radiative series organization	<p>(1) Each exhibition hall is connected within a transportation hub, in series, or in parallel. The visit route is clear and flexible, and the traffic area is large.</p> <p>(2) Suitable for continuous parts or sectional parts of large or medium-sized exhibition halls.</p>		

for buildings requiring circulation, and (3) provide the interpretative machinery required for the generation of new circulations, as specified by shape grammar.

These designs may be generated in three stages that roughly correspond to a natural and intuitive design process. A corridor is formed by moving the square, and this process is defined in Section 3.1. A moving route represents a formation of the circulation, and, lastly, a complete circulation design can be formed by eliminating the gap between two squares. The plan is applied in the following stages:

- (1) Squares and exterior-wall definition;
- (2) Corridor realignment; and
- (3) Principal entrances.

3.1 Squares and exterior-wall definitions

Circulation designs are constructed in terms of labeled tartan squares, each representing a part of a hall. Adjacent squares are separated by a fixed wall thickness, and the position of a square is determined based on different types of circulation. Designs are generated with respect to the north-south axis of the two-dimensional Cartesian coordinate system on a canvas (Fig. 3), so the shape can be parametrically defined. Every square in the production consists of 5×5 cells on the canvas. The canvas partitioned into a large number of cells facilitates the parameterization of rules and all the cells are of the same size.

Once a square has been generated, it contains all subsequent applications of the production to force the associated variables to assume the correct values. In the same way as the manner used for the Palladian grammar^[4] used in villa plans, the axes are indicated in the initial shape, which is used to generate all designs by sequential and recursive application of the rules specified below to obtain the labeled shape as follows: $(0, 0) A$.

The parametric shape grammar for the hall and the exterior-wall is displayed in Fig. 4, and it consists of a set of graph rewriting rules (productions). For example, in Fig. 4, Production 1 is a box labeled 1 with graphs. In addition, each production has two graphs: the left graph

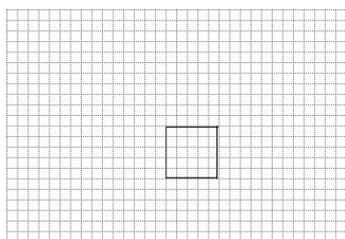


Fig. 3 A square of 5×5 cells on the canvas.

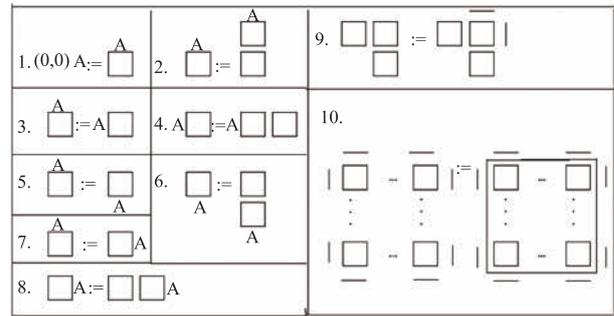


Fig. 4 Productions for generating basic circulations and exterior-walls.

(\mathcal{L}) and the right graph (\mathcal{R}). Each production is in the generation ($\mathcal{L} := \mathcal{R}$) direction. For the productions of a parametric shape grammar, each square is labeled. For simplicity, A is used to label the direction of movement of each square, and the relative positions of A and the square represent the next movement position of the square. In Production 2, the left graph is a square with A at the top; thus, a right graph can be generated with the square moved up, or the original square can be maintained, and the label A can be moved to a new square in the previous position.

Having applied a series of grammars in Fig. 4, the initial formation of the H-type case is obtained, as shown on the left in Fig. 5a. The red arrow represents the movement locus of the square, and thus that of circulation. The exterior-wall to the right (Fig. 5b) is formed by Production 10.

3.2 Cellular Automata (CA) in the formulation of basic type

The above productions and intuition (visual abstraction) can be used to derive the basic type of circulation in Fig. 5. It is, however, clumsy to simulate complex system dynamics, since it cannot produce all the basic types of circulation. Thus, the shape grammar for managing the input like those productions in Fig. 6 can be combined with CA for managing the output. This combines the human intuitive method with a computational system that can generate non-deterministic basic types in a traceable

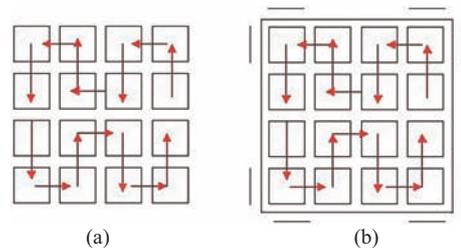


Fig. 5 Using Productions 1–10 to form the initial H-type.

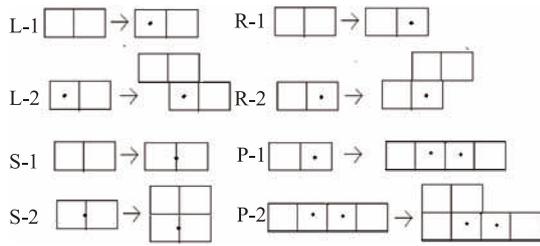


Fig. 6 Shape rules for generating L-type.

manner. A combined approach is employed to produce multiple of primary building modules and to combine them into more complicated modules.

Three stages are now demonstrated for deriving and applying CA rules to develop solutions for the basic L-type. The first stage is applied by the shape grammar in Fig. 6. Similar to the productions in Fig. 4, several productions are defined for the basic L-type, as shown in Fig. 7, where the L-type column module is created by concatenating the P-1 and P-2 rule sets and then applying a selected combination of the L, R, and S rule sets, such as L-1, L-2, R-1, R-2, S-1, and S-2, to produce a complete column. Given the shape grammar definition of the neighborhood of shapes and their relationships (Fig. 6), the shape rules are then directly transcribed into CA rules (Fig. 8).

In Fig. 8, the empty space in the shape grammar production is replaced by a “0” in the corresponding cell within the CA lattice. The “1” represents a cell, and “2”

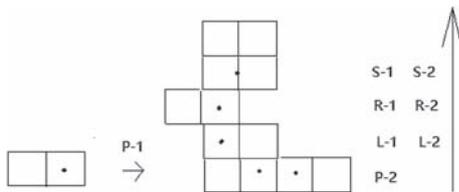


Fig. 7 Process of generating L-type.

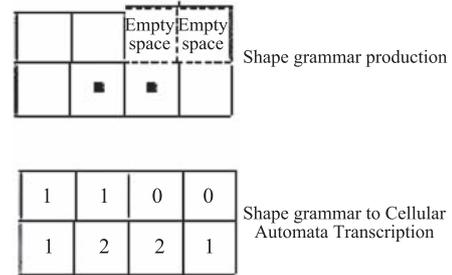


Fig. 8 Transcribing the shape grammar to CA.

represents a black spot. The squares in the circulation are transcribed to numbers, and they are then expressed as neighborhood list mappings. The first stage is to define the cell characteristics and produce the L-type, and second stage can then be transcribed easily as a CA for managing the combined task of generating a large design space. The actual CA for the P-1 and P-2 circulations are shown in Fig. 9 in a one-dimensional CA neighborhood of size 3. In this example, the CA has six triplets which determine the next system state to represent neighborhood rule mappings. The L, R, and S shape grammars are captured by CA rules for generating the additional support rows for the circulations, as shown in Fig. 10.

In stage three, all possible L-type column modules are completely generated by concatenating the CA rules in Fig. 10, resulting in 27 designs, as enumerated in Fig. 11. These CA results are used as the basis of circulation in all further combinations.

3.3 Corridor adjustment

The corridor spaces in the circulation design may be rectangular, T-shaped, L-shaped, U-shaped, or N-shaped. The squares in Stage 1 are combined according to the circulation, and the corridors with these shapes are formed by recursively concatenating the squares in the wall pattern

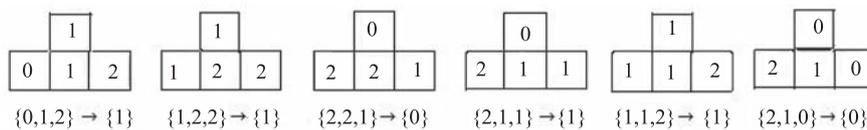


Fig. 9 CA representation of the shape grammar for P-1 and P-2.

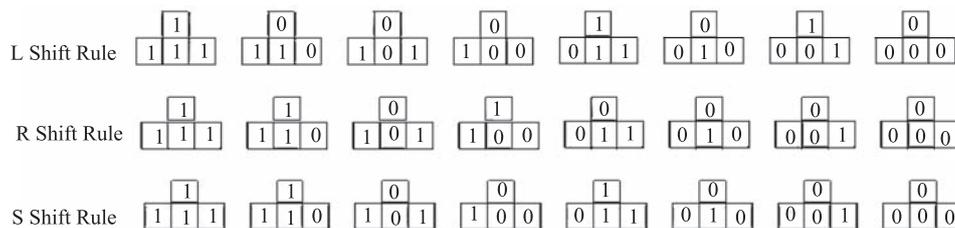


Fig. 10 CA representation of the shape grammar for L, R, and S.

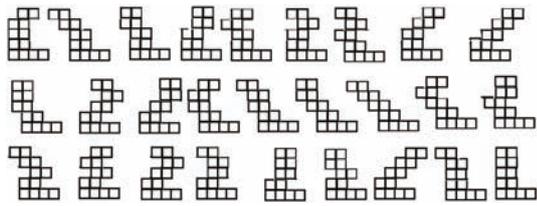


Fig. 11 27 L-types by CA rules.

for the circulation based on the productions specified in Fig. 12.

The generation of the circulation of H-type is shown in Fig. 13, where the first drawing is converted into the second by applying Productions 12 and 14 to the wall pattern, and the second drawing is converted to the third by applying Productions 13 and 16.

3.4 Principal entrances

The productions in Fig. 14 specify the handling of the principal entrances for several circulation designs. The basic type in Fig. 6 is occlusive and the entrances can be designed for the basic types in Fig. 14. In addition, the final circulation can be generated after applying the entrance productions in Fig. 14.

The following example shows several instances of the formation of H-type, M-type, N-type, and S-type configurations (shown in Figs. 15–18, respectively).

H-type, M-type, N-type, and S-type configurations are

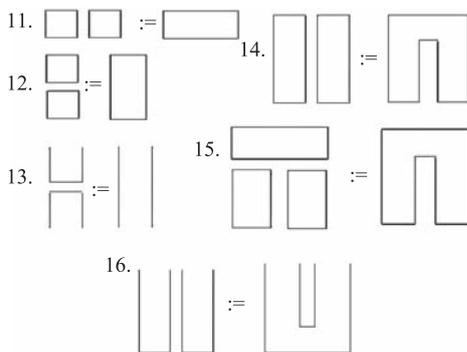


Fig. 12 Productions for corridor adjustment.

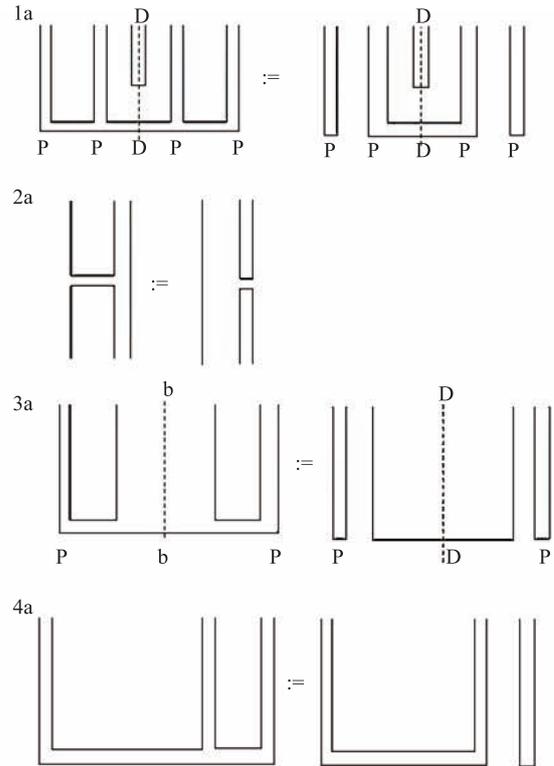


Fig. 14 The principal entrances of several circulation designs.

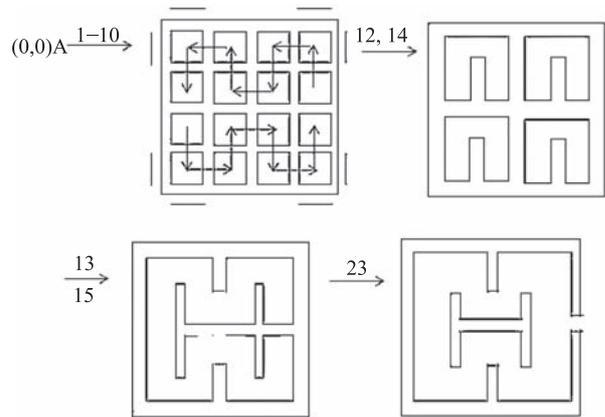


Fig. 15 Formation of the H-type.

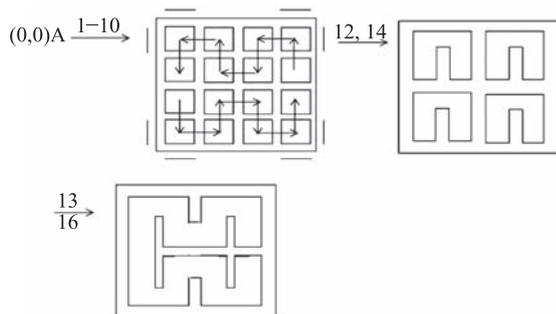


Fig. 13 Formation of the basic H-type.

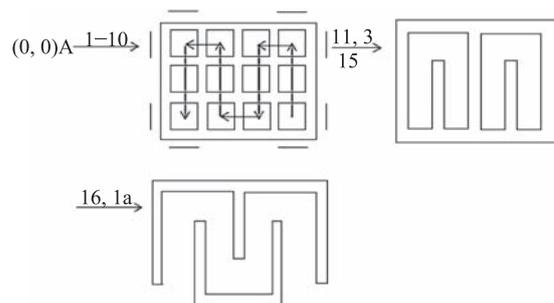


Fig. 16 Formation of the M-type.

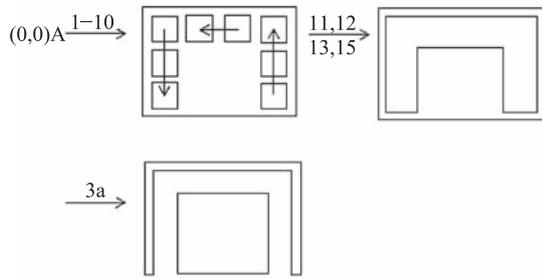


Fig. 17 Formation of the N-type.

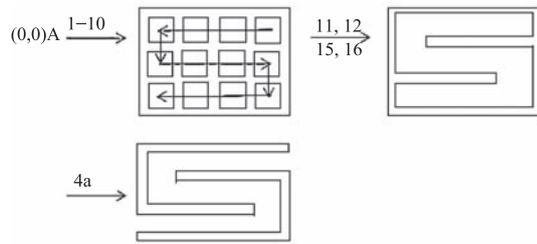


Fig. 18 Formation of the S-type.

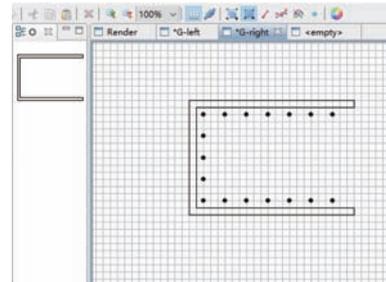


Fig. 20 Basic shape-2.

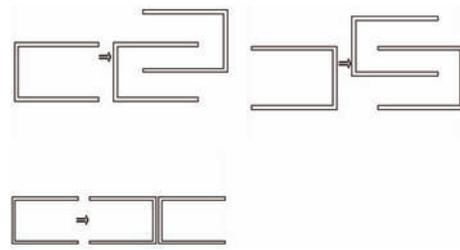


Fig. 21 Three production rules with basic shapes.

the most common basic types of complex circulations. Depending on the specific conditions and requirements of each commercial space, different circulation forms can be designed. Straight lines should usually be avoided and there should be as many turns as possible to avoid visitors.

4 Generation of Circulation Designs in SGI

Shape Grammar Interpreter (SGI)^[5,6] is an open source tool developed for specifying shape grammars and generating new designs based on the specified grammars. Users can use SGI to specify shapes and rules with complete control over the grammar specification and shape generation process. A comprehensive enhancement has been recently made to the original SGI, with new features, such as shape import, image import, and coloring^[7]. The enhanced SGI has been used to formulate circulation designs. In addition, only two shapes (Figs. 19 and 20) with the dotted line labeled in black have been used as the needed circulation, and three simple production rules have been used (Fig. 21), which the basic shapes in Figs. 19 and 20 are included in these production rules. After compilation, the circulation shown in Fig. 22 is generated.

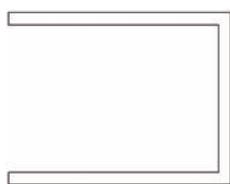


Fig. 19 Basic shape-1.

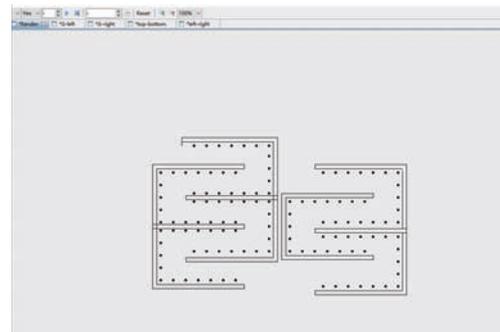


Fig. 22 A simple circulation generated by productions in Fig. 14.

5 Related Work

5.1 Palladian grammar

Palladio’s villas revolutionized Western architecture in the 17th and 18th centuries, produced the school of Southern architecture in the 19th century, and changed the way homes appear in our contemporary world. Palladian villas have consistently been used to introduce new ideas for shape grammars. The work by Stiny and Mitchell^[8] in 1978 created a parametric shape grammar that can generate the ground plans of Palladio’s villas and was applied to generate the plan for the villa Malcontenta. Palladian grammar has been used as a definition of Palladian style, and the grammar clarifies the underlying commonality of structure for buildings in the corpus and provides a mechanism for determining whether a building belongs to a certain architecture.

There has been a hypothesis that different grammars can be used to generate the same corpus of buildings and that a set of shape grammars can be used to generate different kinds of architecture styles. The former has been proven by Benrós et al.^[9], and it provides an alternative grammar that can be used to create Palladian villas. This grammar includes subdivision rules that enable a more economical formulation. Thus, a new corpus of solutions has been explored, and the derivation is compared with the original Palladian grammar.

The latter hypothesis can also be proven by Benrós et al.^[10] The possibility of the latter hypothesis has been demonstrated by proposing a shape grammar that can produce three different design styles using a process that is distinctively different from other tested examples but still produces the same corpus of designs.

The analytical use of shape grammar in the field of architecture has also been discussed. Both shape grammar and parametric model implementations have been proven to be effective tools for generating design solutions of the same style.

These findings have potential uses in both architectural practice and design theory. Our work offers a more comprehensive framework using cellular automata that can generate various circulation designs. The framework consists of a set of tools within a user-friendly environment for designers to freely explore innovative designs using their imagination.

5.2 Palladian plan and graph grammar

Several articles have covered the issue of implementing shape grammar. For instance, GRAPPA, an implementation of Palladian grammar, has been used to systematically describe bodies of design^[11, 12]. A method that reduces the complexity of floor plan graphs to facilitate computational comparison of space allocation programs has also been introduced to coarsen the graph in several steps based on the category information^[13].

5.3 Cellular automata

A cellular automata is a discrete model studied in dynamical systems, and it is also applied repeatedly to a system state as a step rule. To simplify the model, cellular automata is shortened to CA. A rule that can consist of a logical computation and/or pattern match is applied to each cell as based on the values of cells in its defined neighborhood to determine its value at the next step^[14]. The origin of CA is usually attributable to Neumann and

Burks^[15, 16], and its resurgence to Wolfram^[17] who has emphasized that simple rules can create complex systems. Once the CA is visualized, crystal growth can be modeled. Our work is drastically different in that the shape grammar is transcribed into an abstract CA, mapping physical relationships among shapes into local neighborhood of cells to obtain the associated CA rules. To our knowledge, no prior research has been performed on circulation design using CA.

5.4 Circulation

Previous literature has popularized the basic circulation knowledge so developers and designers can obtain a systematic and extensive understanding of circulation designs^[2]. The work by Qin and Li^[2] discusses different visiting streamlines that can initiate the study of different exhibition space forms. This method was used to examine the spatial movement and spatial characteristics of museum buildings, leading to a deeper consideration of architectural form. Our work can be used to guide relevant designers to generate new architectural understandings.

A generic rule system that can be used as a basis to create an individualized grammar has been provided^[12] and can be used to compare the rule systems and rule structures of four different grammars.

Although there has been much research on the use of shape grammar in the field of architecture style, there has been no attempt in specifying the design of circulations, which is the focus of our work.

6 Conclusion

Circulation is a linkage that connects each functional unit within a space. In addition to coordinating all functional units, it provides horizontal and vertical links for the entire commercial space, making it a complete and orderly design.

This study has demonstrated that shape grammars, combined with cellular automata, can be used to generate variety of circulation designs. The plane shape of the architecture was first defined. Then, the directions of corridors and the main entrances were then determined. Lastly, our generative system automatically generated four basic types of circulation designs for the given example. The paper also discussed the rule of dynamic evolution for circulation and space and showed how to use the enhanced SGI to design the circulation grammar and automatically generate circulation designs.

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