The Framework of Generative Design System using Shape Grammar for Jewelry Design

[1] Somlak Wannarumon, [2] Prapasson Pradujphongphet, [3] Erik L.J. Bohez
*1, Corresponding Author, 2 *Faculty of Engineering, Naresuan University, Phitsanulok, Thailand, somlakw@nu.ac.th*
[3] *School of Engineering and Technologies, Asian Institute of Technology, Pathumthanee, Thailand, bohez@ait.ac.th*

Abstract

The paper proposes a framework of generative design system for an automatic shape generation tool, which is to be used to support designers in exploring design concepts, and as a source of inspiration. Shape transformations in the sketching process of jewelry design were studied to identify how designers transform shape from one state to another. The transformations of curved outlines in a logical manner are explained through shape grammar and shape rules. The results of this study were used to develop a mechanism that systematically generates alternative shapes based on a finite set of shape rules defined within a shape grammar. Examples of design families generated by the proposed mechanism are included in the paper.

Keywords: *Conceptual Design, Generative Design, Shape Transformation, Jewelry Design, Parametric Design*

1. Introduction

In conceptual design stage, sketching is employed to serve in various purposes, for example, communicating designer's ideas, understanding and analyzing problems and exploring design solutions. Schütze *et al.* [1] have proved that the sketching process has a constructive effect on the quality of design solutions in the early stage of design process.

Sketching is considered as a creative design process [2] that involves exploration of design alternatives [3], reinterpretations and transformations of an overall shape outline, and its sub-shapes [4]. Sketching is a quick and flexible process, which assists designers in generating ideas and transforming shapes. In conceptual design, free-hand sketches are naturally used to rapidly explore design ideas and to effectively record design alternatives. In the early stage of design process, designers exploit two iterative-interactive processes, seeing and moving, for exploring sketches [5]. 'Seeing' is a reinterpretation process of design elements in a sketch and 'moving' is a transformation of the reinterpreted design elements. This cycle results in the generation of series of related sketches in which design elements are recognized, associated, connected, repeated and elaborated [6]. Therefore, by using the 'see-move-see' cycle, a designer can be inspired for further sketches. Reinterpretation is one of the essential elements in design exploration and in creative design [7], which may lead to emergence.[8].

Despite shape transformation and reinterpretation being vital in design exploration, most of available computer-aided design (CAD) systems cannot properly support designers in these processes.

Most of available computer-aided design (CAD) systems are used in detailed design stage rather than in conceptual design. Therefore, this research is aimed to bring the benefits of computer-based design systems into the early stage of design process–conceptual design, which is the most important stage in creative design process.

In this research, conceptual design signifies the process in which designers generate broad and various alternatives [9], therefore in this stage designers commonly cope with some activities such as generate ideas, record ideas and decide to continue to generate more ideas or prefer to explore the possibilities of the existing ones [10].

This research focuses on the sketching process of soft products like jewelry. This kind of product requires the use of computers more on the indefinable and intangible aspects such as styling, inspiration, creativity, value-addition, and human–machine interactions [11]. The sketching process of jewelry designers and the interaction of designers with their sketches have been investigated in the part of this research. These interactions are formalized using a finite number of generalized shape rules.

This paper introduces a generative design tool, which is based on the experimental data collected in the case studies and theories of shape grammar. The tool is to be used in generative design as a system supporting designers for design exploration in the conceptual design stage.

The paper was organized in five main sections. The next section, Section 2, provides the briefs of the related theories and works, which were reviewed for setting up the research experiments. Section 3 explains the methodology of this research. Section 4 provides the experimental results including discussions. Finally, the research works were concluded and provided in Section 5.

2. Related works

2.1. Sketching process

Sketching is a rapid freehand drawing technique, which is considered a quick way to simply record a design idea for later use. For example, it is used to try out various ideas and concepts, and to focus on the most important or interesting parts (elements) of shapes. In sketching process, a designer naturally proceeds in a see-move-see cycle [5]. When a designer is working with some visual medium, he visually records information and creates its meaning. The designer observes the existing sketches, represents a relation to them in new sketches, and then sees what has been sketched. This cycle of see-move-see creates a further series of related sketches.

Sketching is considered as a key factor for a successful creative design process [2, 4, 6, 12-18]. It represents the development of designs and has an interactive role and a vital effect in the mechanics of the design activity [19]. Sketching is a simple tool, which supports designers in idea or concept exploring, discovering, and generating, which are the most important parts in creative design. Sketching is also considered an external representation, which supports the imagery processes. [20]. Sketching helps designers to deal with re-organization, maintenance, transformation and evaluation of shapes. It can support the re-use of information in previously generated design ideas, which can assist in creating more links between ideas and thus reduce the cognitive load during the progress of the design activity.

Given the information above, it is desirable to develop computer-based tools for sketching in the early phases of design to support designers in shape and concept generation [14, 16, 21-27].

2.2. Generative Design

Generative design system is a tool that supports designers in design exploration and design generation. It can assist designers to explore a large design space, which provides a larger range of design possibilities than in manual production [27] and a set of designs that might have been unpredicted by designers [28]. Moreover the generative design tools can be utilized as teaching aids for novice designers [29].

One of the most important issues in a generative design system is user interaction. There are various models of user interaction depending on the objectives of the uses of the generative design systems. Chase [28] summarized user interaction paradigms in the following way: minimal user interaction using optimization techniques; tight control over rule application; and computer generation with user selection. He also described the possible interaction scenarios, which are classified into full control, partial control and no control.

Prats et al. [16] suggested that an effective design system should provide a communication channel between designer and the system. The generative design tool developed by Orbay and Kara [26] exploits partial control interaction model to guide conceptual design process. The prescribed engineering and ergonomic criteria are concurrently considered with form design. Agarwal and Cagan [30] developed a function-based grammar to design coffee makers. Partial control protocol was employed to design the interaction between designer and the system by allowing user to select design rules. Tapia [31] developed a grammar-based design system, which allows user to define and select rules, and also offers user the selection of control mode (user control and system control).

2.3. Shape Transformation

Shape transformations in sketches are an activity in which design elements are developed from one sketch to another. They have been studied to understand the design process and the mechanics of sketching in design [4, 16, 22, 24, 32, 33]. Prats *et al.* [16] have set up an experimental investigation to study how designers transform shapes and sub-shapes while exploring design alternatives. Shape transformations are used to describe connections between sketches. These transformations are explained using shape rules. Stiny and Gips [32] proposed a method of shape generation, where a shape is created using shape grammar. The process starts with a given shape and is iterated by successive applications of a set of shape rules. Shapes are formed by finite arrangement of geometric elements, for example, points, lines, curves, and planes, in which any element can be used multiple times with any scale or orientation.

2.4. Shape Grammar

Shape grammars function as production systems, which generate designs according to sets of shape rules. They perform calculations with shapes in the following order: recognition of a given shape and its possible replacements; compiling rules; and exploring the shape grammar [31, 32]. Shape grammars rationalize designs by formalizing the spatial relations between their elements [16]. Shape rules identify the particular shapes to be replaced and describe the process of replacement. Shape rules are used to describe shape transformations between sketches, according to schemas, in a formal and visual way [4, 16].

The general shape rules that resulted from the published experimental investigations [13, 16, 34] are sufficient to capture shape transformations in the observed experiments. These general shape rules are summarized in Figure 1.

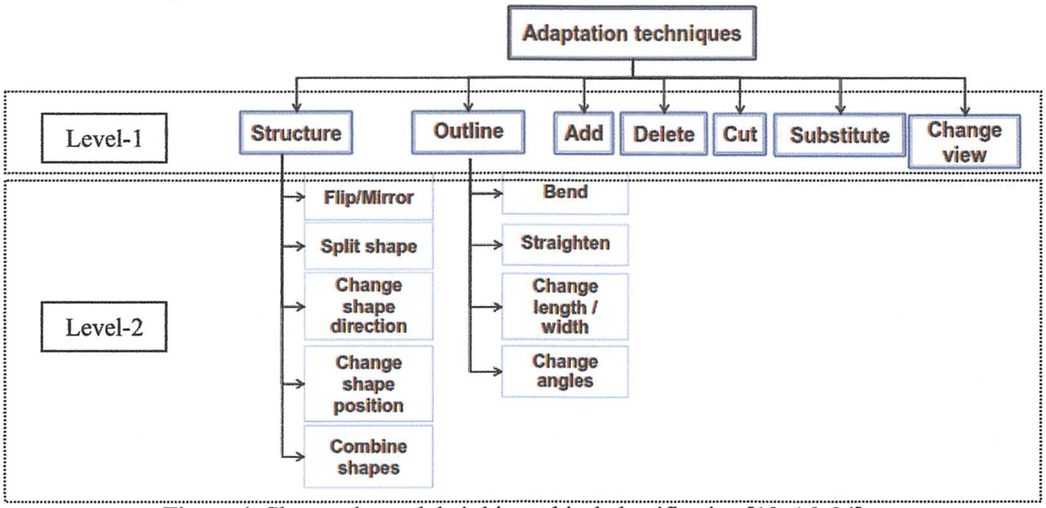

Figure 1. Shape rules and their hierarchical classification [13, 16, 34]

The shape rules in Level-1 (higher level) are Outline transformation, Structure transformation, Substitute element, Add element, Delete element, Cut element, and Change view rules.

Outline transformation rule indicates changing the outline of the shape as well as contour manipulation. It is subdivided into the rules in the Level-2 (lower level):- Blend, Straighten, Change length/width, and Change angles rules.

Structure transformation rule signifies changing structure and position of the shape. It includes Flip or mirror, Change shape direction, Split shape, Change shape position, and Combine shapes rules.

Shape transformations can be explicitly described and used for systematic generation of design alternatives using shape grammars. Prats [35] presented a new type of rule named 'piecewise line-rule' used in conjunction with the decomposition rule to describe and transform curved outlines. This technique can be used to systematically generate design alternatives.

3. Computational Shape Transformation for Jewelry Design

The Experimental investigations of the sketching process of jewelry designers were organized to observe and study how they transform shapes and design elements in sketches while exploring design alternatives. Shape transformations are employed to describe the connections between sketches according to shape rules.

In the case study, we started from analyze the elements of jewelry ring and attempted to capture shape rules, which jewelry designers exploit during developing shape or sub-shapes from one state to another, and then developed shape grammar of jewelry ring design. In this stage, we found several set of parameters, which have influence on transformation of shapes. Therefore, we studied on these parameters. The methodology of this research is illustrated in Figure 2.

The results of the study of sketching process were analyzed in terms of shape rules, and were used to develop a computational mechanism for an automatic shape generation tool, which is used for supporting designers in exploring design concepts, and as a source of inspiration.

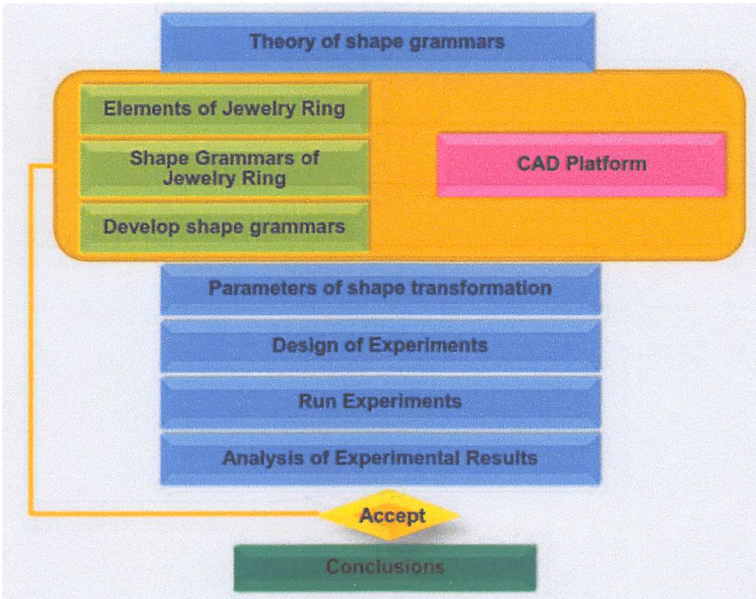

Figure 2. Methodology of the development of shape grammar for jewelry design

3.1. Experimental Investigation

The results of the observations and interviews are classified into the following three categories:

- Jewelry design sketching process;
- Sources of exploration and inspiration for jewelry design;
- Transformations of shapes in sketches.

Jewelry design, as any other industrial design process, needs to consider the balance of aesthetics and function. It involves creativity, analysis, and development. Jewelry design is an iterative process. It generally begins with design concepts, which are defined by either customer or a jewelry company. In the later case designers or marketing department define the design concepts. Designers transform this information into shapes and functions of products, and then create a series of sketches of conceptual design. In the current jewelry design process, designers mostly produce hand-drawn sketches and rarely work with a CAD system during the conceptual design stage. Detailed designs are often created in CAD system after screening the alternatives suggested in conceptual design. However, it depends on the production process used in the later stages, if model-making and production processes are controlled by computer technologies, and CAD models of the detailed design are requested.

After obtaining design concepts, designers make a series of sketches, and looking at them they explore and discover opportunities or obtaining inspiration for further sketches.

3.2. Shape Transformation Factors

We found from the observation of the sketching process in jewelry design that in principle designers create new designs based on the transformations of shapes and the adaptations of design precedents.

The major shape rules often used in the experiments are listed below:

- Moving a shape to another position – 'Translation';
- Turning or winding a shape around a centre or an axis – 'Rotation';
- Rotating a shape along a spiral line– 'Spiral rotation';
- Changing size with a particular proportion – 'Scaling';
- Cutting off or clipping the ends – 'Shearing';
- Reflecting a shape on a horizontal or vertical line – 'Mirror';
- Copying a shape and placing it in a pattern – 'Repetition', which can be done together with translation, scaling and rotation;
- Combining at least two objects to form a new whole – 'Combination';
- Altering or changing a part of shape.

Most of the resulting shape rules are based on affine transformations, such as, translation, scaling, rotation, and shearing [36], and some of them are similar to the general shape rules presented in Table 1 [13, 16, 34]. The sketches were in most instances manipulated using more than one shape rule at a time.

In one of the sketching experiments, a circle shape was provided as an initial shape to create a pair of earrings. Some parts of the sketches in the experiment are illustrated in Figure 3. The designer explicitly exploited more than one rule to transform the initial shape from one sate to the successive ones.

The shape rules exploited to transform Shape A to Shape B (A→B) are listed below:
Rule 1 → Copy a given shape (Number of copies = 1)
Rule 2 → Scale down both shapes with different factors.
Rule 3 → Change the relative positions of shapes
Rule 3-1 → Direction of position change – along Y-axis
The shape rules used to transform Shape A to Shape C (A→C) are listed below:
Rule 1 → Copy a given shape (Number of copies = 3)
Rule 2 → Scale down all shapes with different factors.
Rule 3 → Change the relative positions of shapes
Rule 3-2 → *Direction of position change – along a curve in XY-Plane.*

3.3. Computational Shape Generation Tool for Jewelry Design

The prototype system was developed using Visual Basic script in Rhinoceros 4.0 software [37]. The development of a shape generation system consists of two main parts [28]: shape grammar development, and shape grammar application.

Shape grammar development involves the construction of shape rules, control mechanisms, and object representation. Shape grammars and shape rules were derived from the experimental investigations of jewelry design and sketching. The shape grammars were tested, modified, and refined in order to produce a basic language of jewelry design. It is difficult to construct shape grammars, which can cover the whole range of jewelry design. Therefore, in this research we began with the study of shape grammar in the basic jewelry design rather than specific styles. Nevertheless, shape grammars of the specific styles could be developed and later incorporated into the system. Shape grammar application involves the determination of shape rules, and shape or sub-shape matching conditions.

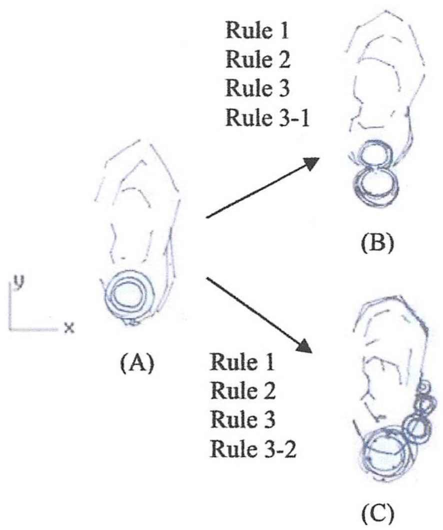

Figure 3. Sketches of an experiment using a circle to design earring

Scheme outline of the shape generation system is shown in Figure 4. A semiautomatic user interaction system with partial control is used [28]. The points designed for user interaction are shown in the box with solid lines. The process begins with a designer initially creating a shape or selecting a shape from shape database. In the next step the designer selects a rule, and defines position(s) where the rule is applied onto and the conditions, which the rule must follow.

The system then calculates shape transformations for all possibilities in the design space. The system applies the rule to the shape and then generates a set of possible shapes according to the predefined shape rules. Here, the designer can select a favorite shape to continue the process. If no shape satisfies him, he can track back to create/select a new initial shape or select a new rule, or define a new position/condition for new shape generation. The process runs iteratively until the designer terminates it.

In another mode, the system automatically generates a set of new shapes according to computational shape grammar.

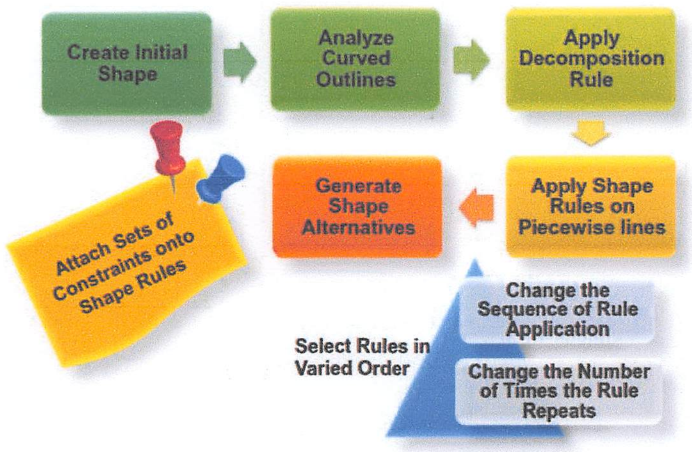

Figure 4. Shape generation process using shape grammar and shape rules

4. Results and Discussions

The results of the study indicate that shape transformations can be described using a limited number of shape rules. The shape rules used in this study are derived from the general shape rules [13, 16, 34], affine transformation [38], and the specific shape rules, which are often used in jewelry design. These specific rules mostly combine several rules into a complex one.

An example of shape transformation using the computation shape generation system is illustrated in the following paragraphs.

There are several ways to create a jewelry ring. In one of our experiments, we create a ring using cross-sections sweeping around a circle. In this case, the cross-sections are considered as initial shapes. In the first example, the system detects the curved outline and decomposes the outline into two sub-curves. Then the shape rules are automatically applied onto the upper curve based on shape grammar, while the lower line is fixed.

R_{Ba}, a shape rule for bending a line to be a convex curve is applied on the upper curve and the resulting shape is shown in Figure 5(a). While R_{Bb} for bending a line to be concave curve is applied on the same line with the resulting shape being shown in Figure 5(b).

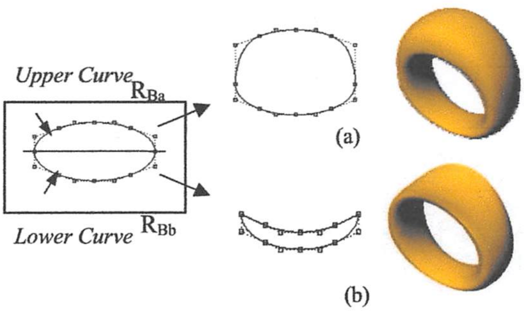

Figure 5. Shape rules of bending applied on the upper curve

A shape rule (for bending) can be successively applied on the upper curve. The resulting shapes are shown in Figure 6.

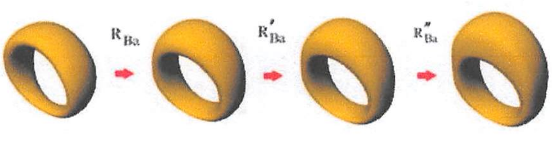

Figure 6. Shape rule (R_{Ba}) being applied successively on the upper curve

The inverse shape rule to that of the bend shape rule is the straighten (R_S) rule. This rule is used to straighten a curve, as shown in Figure 7.

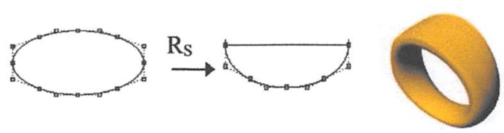

Figure 7. Straighten shape rule (R_S) being applied on the upper curve

The next shape rule is the split rule (R_{SS}), which is used to divide a line or curve into sub-lines or sub-curves. The example in Figure 8 uses the split rule (R_{SS}) to divide the line into two sub-lines and then applies the bend rule (convex) onto both sub-lines.

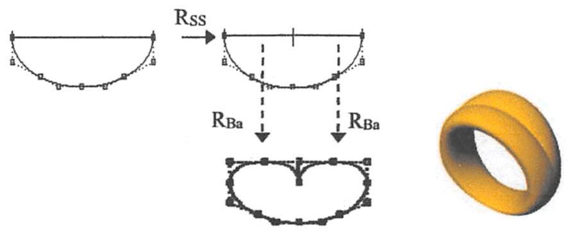

Figure 8. The use of two shape rules for splitting a line and blending sub-lines

The next example is similar to Figure 8, but one of sub-lines is transformed with R_{Ba} (bending for convex curve), while the other one with R_{Bb} (bending for concave curve). The resulting shape is shown in Figure 9.

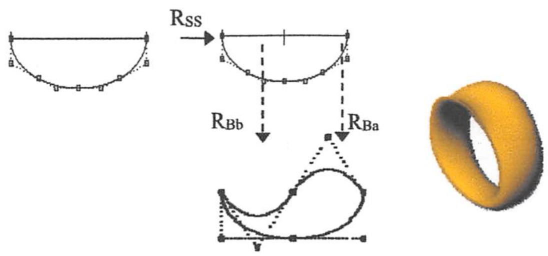

Figure 9. The use of split rule, followed by convex and concave bend

The split rule (R_{SS}) can be used to split a line into more than two sub-lines with different lengths. The example of this case is shown in Figure 10.

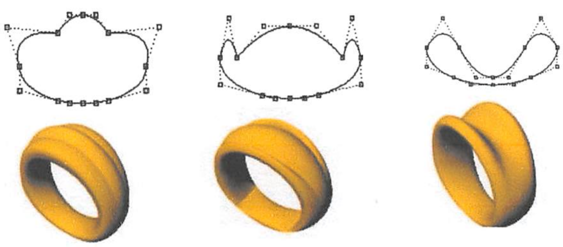

Figure 10. Examples of splitting a line into three different sub-lines and bending them into different curves

In Figure 11, an example of applying a different set of rules can generate the various ring design.

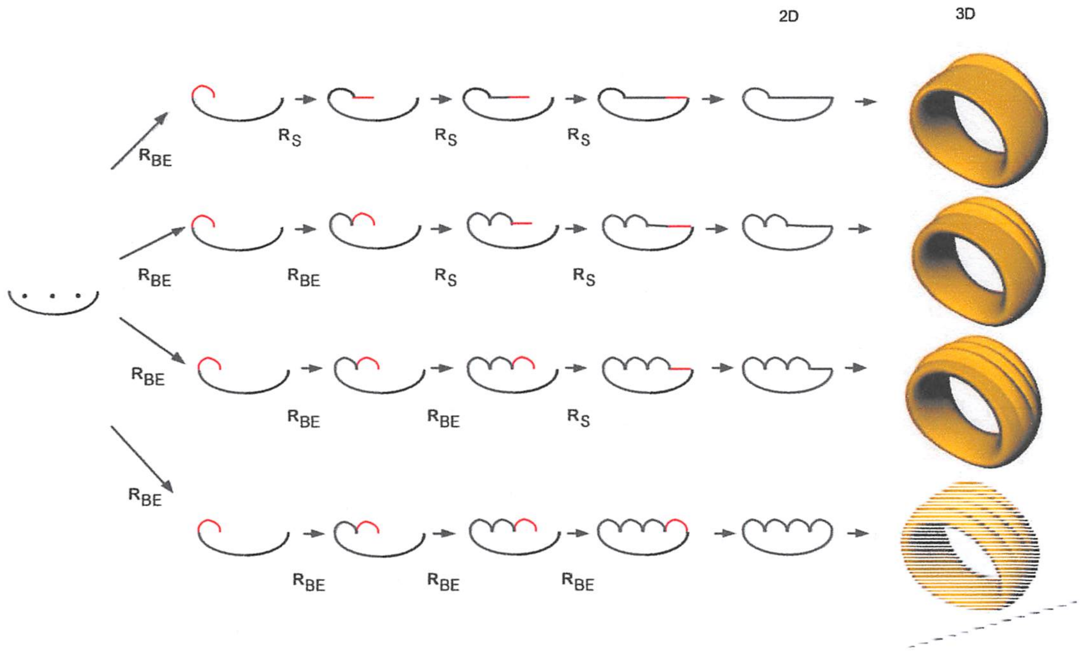

Figure 11. An example of applying single rule in different times

An example of randomly generated ring design by applying different set of rules is shown in Figure 12.

Figure 12. Some examples of generated ring using the proposed system

Shape rules that are often used in shape transformations are listed in Table 2. The shape grammar and shape rules used in this research are based on experimental investigations. They do not cover the whole range of jewelry design, but more grammar and rules may be added in future. This system could be a starting point for developing a shape generator based on various transformations. Such a generator could enlarge the design space by more possible alternatives within the specific objectives and constraints of a given project.

Table 2. List of important shape rules used for jewelry design.

Parameter	Name
R_{Ba}	Bend Convex
R_{Bb}	Bend Concave
R_{S}	Straighten
R_{CL}	Change Length
R_{CW}	Change Width
R_{CA}	Change Angles
R_{M}	Mirror
R_{CSD}	Change Shape Direction
R_{SS}	Split Shape
R_{CSP}	Change Shape Position
R_{COS}	Combine Shapes
R_{SU}	Substitute
R_{A}	Add
R_{D}	Delete
R_{C}	Cut
R_{T}	Translation
R_{RO}	Rotation
R_{CO}	Copy
R_{CS}	Change Scale
R_{CT}	Combinations of Transformations

Heuristic methods such as genetic algorithms are useful in optimization of solutions from a large solution space and they can also help in the construction of shape rules. Artificial neural networks can be applied to investigating the process of cognitive behavior during the generating of sketches [12]. Additionally it can be used to investigate designers' shape grammar systems from the observed sketches. This approach, however, requires a large amount of inputs. The other idea to improve shape grammar is to include the consideration on color and texture feature [39] of jewelry items.

User interface is one of the most important issues in a generative design system. The effective user interface should be simple, intuitive and visual. It should support user in selecting rules, defining constraints, exploring ideas, developing design languages, selecting alternatives, and stimulate visual thinking. This area will be further developed for the presented shape generation tool.

Shape generation systems can be useful for novice designers and design students. They can support them to easily transform shapes and design elements during exploration design concepts. At the same time these systems can help students and graphic novices in learning about shape grammar.

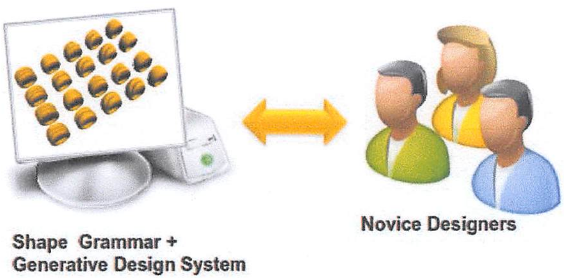

Figure 13. Use of generative design system for novice designers.

The advantages of the shape generation system are that can generate a huge amount of possible shapes to be used in design process; help designers to easily explore more alternatives; help in processing shapes; generate digital ideas which could be further used in embodiment design, despite the fact that the disadvantages are the limitation of data/shape representation limits some shapes and the evaluation is not adaptive and could not consider sub-shapes.

5. Conclusions

The research is based on experimental investigation into the sketching procedures of jewelry designers. This investigation was designed to understand transformations and developments of idea sketches. The analysis of the experimental data led to the definition of a set of shape transformation rules, which are frequently used in sketching. These results were used in the development of a computer-based shape generation tool.

The paper presents a shape generation design system, which consists of shape grammars, shape rules and a control mechanism. It is aimed at supporting designers in the early stages of design aiding them in exploring and developing design ideas. The results of our experiments reveal that the interaction between designers and their sketches can be represented by a finite number of shape rules. Those shape rules formalize the shape reinterpretation and transformations, and are used to develop the shape generation system.

The generative design system can assist designers to automatically create shapes based on algorithms and parameters. This paper explains how shape grammar system can be utilized in the sketching process of jewelry design. The generative design system is proposed as an external working memory for imaginary process, which can solve overload of visuospatial working memory. Emergence shapes generated by the system may play a part in solving idea saturation during conceptual design.

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