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Shape Exploration in Design: Formalising and Supporting a Transformational Process

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Abstract

The process of sketching can support the sort of transformational thinking that is seen as essential for the interpretation and reinterpretation of ideas in innovative design. Such transformational thinking, however, is not yet well supported by computer-aided design systems. In this paper, outcomes of experimental investigations into the mechanics of sketching are described, in particular those employed by practising architects and industrial designers as they responded to a series of conceptual design tasks,. Analyses of the experimental data suggest that the interactions of designers with their sketches can be formalised according to a finite number of generalised shape rules. A set of shape rules, formalising the reinterpretation and transformations of shapes, e.g. through deformation or restructuring, are presented. These rules are suggestive of the manipulations that need to be afforded in computational tools intended to support designers in design exploration. Accordingly, the results of the experimental investigations informed the development of a prototype shape synthesis system, and a discussion is presented in which the future requirements of such systems are explored.

1. INTRODUCTION

Creative design is an activity that involves exploration and development of design alternatives [1] This involves transformation of overall outline shape and parts of shapes [2]. Pictorial representations of designs, particularly sketches, support such transformations because they offer ambiguity and support reinterpretation [5]. Reinterpretation is a vital element in design exploration and is believed to be a vital element in creative design [25]. Despite its importance, the support offered by computer-aided design (CAD) systems for the reinterpretation of shapes has been poor. The research reported in this paper builds on the hypothesis that knowledge of the mechanics of design exploration employed during sketching may inspire new types of computational support, which are not available in conventional CAD systems [4]. Schön [5] and Goel [3] have described the interactive process through which designers produce fast graphic representations during conceptual design. The process of sketching can support the sort of transformational thinking that is seen as essential for the interpretation and reinterpretation of ideas in creative design [6]. This is particularly important where transformation of shape in product design is concerned [7]. Despite the importance of reinterpretation and transformation of shapes in design exploration, the ways in which designers typically manipulate shapes are not well understood.

The research described in this paper results from a broader research activity which aims to establish a common reference framework that can be used to inform the definition of future generations of computer aided design systems. The main research questions posed in the research reported in this paper were (i) How do designers, across a range of disciplines, generate shapes?; (ii) What similarities and differences in approach can be observed?; (iii) How might the ability to compute shapes enhance the act of designing itself?; and (iv) Can computer vision techniques be used to resolve the sub-shape detection problem in a shape grammar system? This paper reports on experimental investigations into the sketching processes of practicing architects and industrial designers. It reveals how the making of sketches assists the process of shape transformation and reinterpretation, and thus informs future computer based design systems with a computer-vision based prototype system.

2. FORMAL SHAPE EXPLORATION

Exploration in design can be investigated through an examination of the shape transformations used by designers when sketching and through an examination of designers' perception of shapes. Transformation and interpretation of shapes can be represented according to shape rules in a grammar [8], which provides a connection between cognitive processes and formal explorations of designs. Shape rules, used in shape grammars, are of the form $a \rightarrow b$, where a and b are both shapes, and are applicable to a shape S if there is a transformation that embeds a in S. A shape rule is applied by replacing the transformed shape a in S with the similarly transformed shape b, and shape grammars can provide quantitative information about the design produced [9]. Since their conception over thirty years ago, shape grammars have been applied in a wide range of fields. For example, in the 1970s, shape grammars were used to analyse paintings and decorative arts [10], and more recently have been applied as a tool for analysing and capturing the essence of existing designs as well as synthesising new ones [11, 12]. Moreover, the potential for applying shape grammars to generate designs in a particular style has been explored in areas such as architecture [13] and consumer products [14, 33], and the advantages of having an explicit generative representation of designs in a particular style or brand using shape grammars has been discussed [15].

While the concept of shape grammars provides a technical focus for our research, shape rules offer a valuable foundation for capturing shape interpretations – left-hand side of the rule – and transformations – right-hand side of the rule – in design. They may very well inform future generations of shape computation systems for design exploration. In this paper, shape rules are used to formally describe the shape transformations commonly used by designers during sketching. A number of professional designers were observed whilst sketching a series of conceptual designs, and their manipulations of the sketches were encoded via shape rules.

3. SKETCH OBSERVATION

Previous studies into the sketching processes of designers have largely been concerned with design reasoning [16], and with insights gained via interviews [17] and case studies [18]. Observation and recording of designers whilst conducting design tasks are often successfully used as a way to examine cognitive mechanisms used in design [19, 20], however, the focus of these studies is mainly concerned with what the designer is 'seeing' rather than the actions that follow. In the experiments described here, the main focus is on exploring the mechanics of shape transformation, that is, the actions used in sketching to transform shapes from one state to another, based on observation and recordings made during set tasks.

3.1. Method of the Experiment

The aim of this experiment was to identify shape transformations and manipulations employed by designers during sketching and formalise them via shape rules. Eight industrial designers and six architects participated in this experiment. Five of the industrial designers had been practicing for more than six years and the other three had between two and four years of professional experience. Of the architects, two participants had more than four years of professional experience, two participants had between two and four years of professional experience, and the other two participants were architectural researchers. The participants responded to a series of conceptual design tasks and produced an output of nearly 300 sketches. This data was supplemented by retrospective interview where the designers were questioned concerning their interpretation and transformation of shapes. Three tasks, with short design briefs and initial design proposals (see Appendix), were given to the participants. During the sketching process participants' activities were recorded via a video camera for hand gestures, a digital tablet which provided a native pencil-and-paper environment, and software for video screen capture which facilitated the recording of sketch stroke sequences. The two video clips – one from the video camera and the other from the video screen capture – were synchronised in order to gain further insight into the participants' design thinking, and to accurately interpret their movements whilst sketching as illustrated in Figure 1.

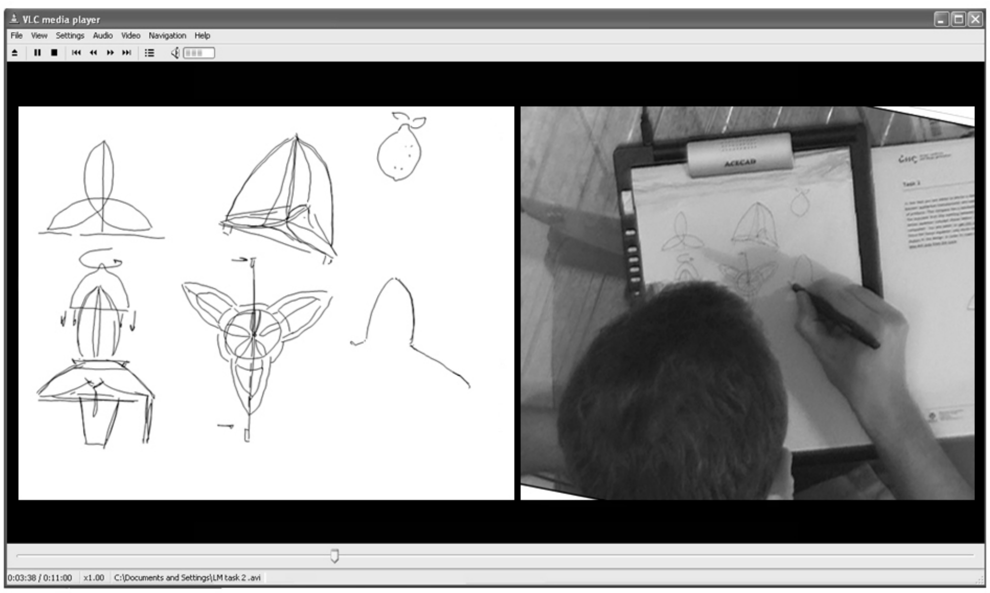


Figure 1: Synchronised videos. Left: Video screen capture of sketch stroke sequences made on the digital tablet. Right: Video of hand gestures via a video camera.

In this experiment, shape transformations were analysed according to three cognitive actions commonly used by designers when exploring ideas via sketches – Decomposition, Reinterpretation, and Design Families. In order to examine shape transformations it is necessary to compare two or more shapes that are related one another. While decomposition allows comparing shapes at a micro level and design families at a macro level, reinterpretation informs about the relationship between shapes. These three cognitive actions are defined as follows:

1. Decomposition: This is a strategy applied in shape analysis [21] and exploits cognitive perceptual mechanisms [22, 23]. During decomposition a shape is broken down into its constituent parts. These parts may be the parts it was originally composed of segmentation or constituent shapes that emerge from the combination of shape elements that were sketched. It can be observed through the various strategies of reproduction that result from applying different interpretations to ambiguous drawings [24], or from a designer's personal interpretation of sketches [7].
2. Reinterpretation: This is a change of interpretation of a shape that can be identified by comparing the strokes used amongst sketches that represent the same idea [7]. Studies [5, 16, 24, 25] have revealed that different interpretations of a given drawing can lead to different strategies in its reproduction, whilst Suwa and Tversky [19] indicate that new design ideas are frequently a consequence of reorganising and reinterpreting parts or elements in design representations such as sketches.
3. Design Families: In this study, a design family was considered to be a 'group of vertically transformed shapes' [7]. According to Goel [3], vertical transformations manipulate one idea into a version of the same idea whilst lateral transformations manipulate one idea into a different idea. Studies [3, 16, 26] suggest that designers rarely produce single and isolated sketches in the creative stages of design; instead, they often generate sketches in successive spells. Thus, most of the design concepts produced in the conceptual design stages are related according to close groupings of ideas or design families.

Three tasks with different grades of complexity were designed to explore the three cognitive actions. The first task used two simple abstract shapes, illustrated in Figure 2. These are adopted from the work of van Sommers [24] who used them to show that different interpretations of a drawing can lead to different strategies in its reproduction. In this experiment, the subjects were separated into two groups, and each group was given a different interpretation of two shapes and corresponding task descriptions which were based on the interpretations. The first shape (on the left of Figure 2) was presented either as a pair of crossed swords, with the corresponding task of developing a logo for a bank, or as a pair of kissing mice, with the corresponding task of developing a logo for a dating agency. Similarly, the second shape (on the right of Figure 2) was presented either as a cocktail glass with cherry or as a person with a telescope. The subjects were asked to begin exploring design concepts by first reproducing the given shapes, and then developing them according to the given design brief.

Figure 2: Left: Logo described as crossed swords or a pair of kissing mice. Right: Logo described as a cocktail glass with cherry or a person with a telescope.

The second task provided another abstract shape which is ambiguous and open to interpretation, illustrated in Figure 3. The design brief for this task was more complex and more time was allowed than for the previous task. Subjects were introduced to this shape either as a concept design for a lemon squeezer, for the industrial designers, or as a conceptual design of a building, for the architects. No further interpretation was provided and the designers were free to perceive the shape as they desired, for example as a top view or a side view.

Figure 3: Initial design proposal presented as a lemon squeezer (industrial designers) or a conceptual design of a building (architects).

The third task provided more explicit shapes as initial design proposals and offered less freedom of interpretation than was available in the other tasks. The shape on the left of Figure 4 was presented to the industrial designers as an initial design for a kettle design, and the shape on the right in Figure 4 was presented to the architects as a reference to a new building.

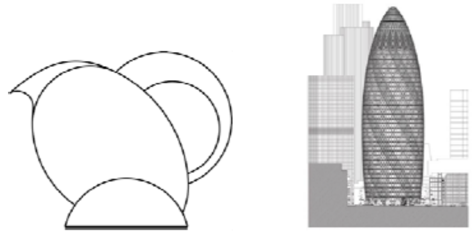


Figure 4: Left: Initial concept for a kettle (industrial designers). Right: St Mary Axe Building as a reference to a new building (architects).

3.2. Shape Rules from Identified Shape Transformations

In each task the participants produced series of sketches, which were summarised and analysed based on the above three cognitive actions. Design families were identified based on similarities recognised and exploited by the designers, which were made apparent during the retrospective interview. For example, Figure 5 demonstrates a sequence of sketches of kettle designs which were produced by a participant in response to the third task. The sequence does not linearly explore a single design family but instead jumps between two distinct families which were identified by the designer. These families are identified according to different features, which were identified in different reinterpretations of the sketches produced during exploration. For example, *design family A* was identified according to the similarity of handles whilst *design family B* was identified according to kettle bases.

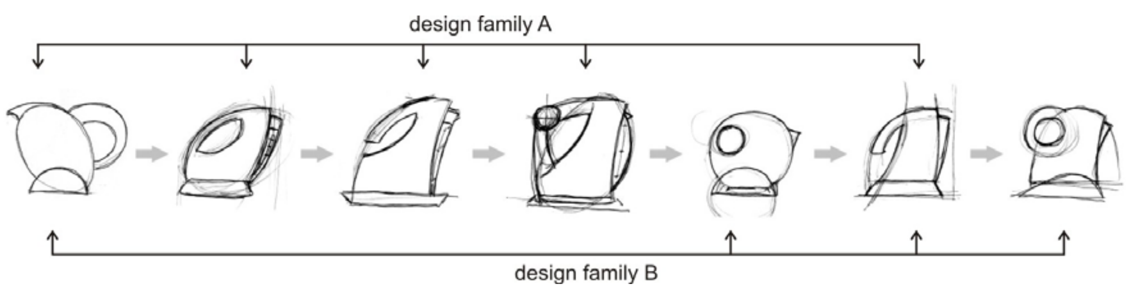


Figure 5: Example of design families.

An examination of how designers decompose and reinterpret designs and generate design families assisted in developing a better understanding of the kind of shape transformations used by designers during shape exploration. For example, in Figure 6, the sketching sequence in Figure 5 is observed in more detail and the shape transformations between sketches are described via shape rules. Some of the steps include multiple transformations whilst others include only one.

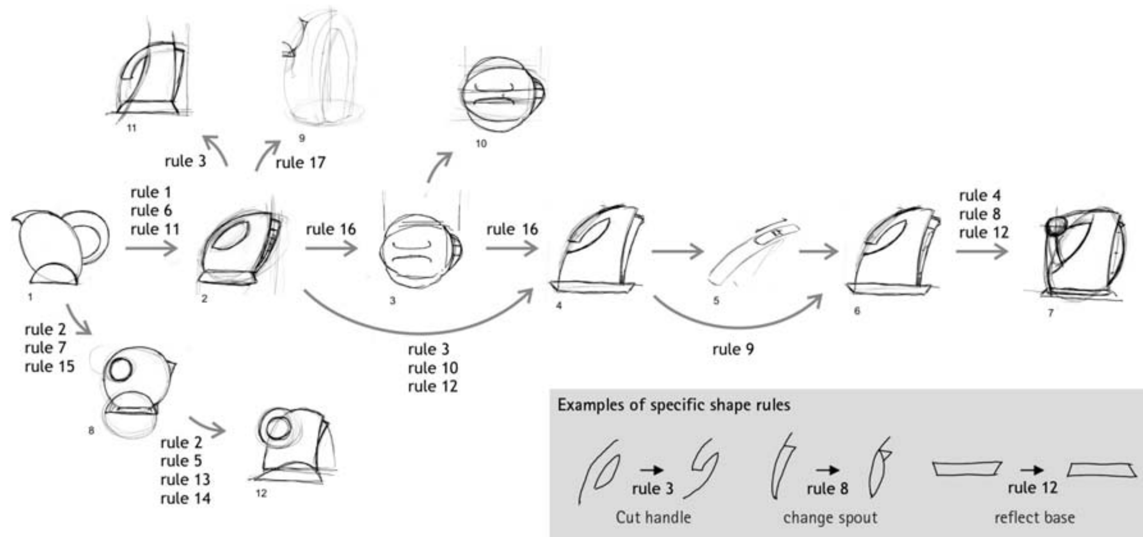
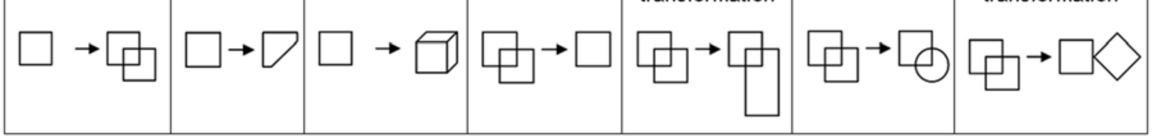


Figure 6: Examples of specific shape rules.

In order to describe all the shape transformations identified in the experiment it was necessary to define a large collection of very specific shape rules. These rules were generalised so that a smaller set of transformations could be identified, which would enable quantitative comparison amongst the different participants. In total, seven general shape rules were identified as presented in Table 1. While the general rules presented here may be sufficient to capture the shape transformations of these particular participants the list is not assumed to be complete. It is possible that further experimentation might result in additions to the list. Nevertheless, the general rules are: *Outline transformation, Structure transformation, Substitute element, Add element, Delete element, Cut element*, and *Change view.* Note that these rules express shape transformations in an abstract way and are not meant to represent the exact transformation of a shape.

Table 1: General shape rules.

Add	Cut	Change view	Delete	Outline transformation	Substitute	Structure transformation



3.3. Hierarchy of Shape Rules

The specific shape rules like those shown in Figure 6 and general shape rules presented in Table 1 are the two extremes of the hierarchy of shape rules presented here. In this research shape transformations between participants were compared in terms of general shape rules. However shape transformations can also be compared using a set of more specific rules within the hierarchy of shape rules. For example, Table 2 shows a set of fourteen shape rules that belong to a lower level in the hierarchy of shape rules. In this case, two general rules – *outline transformation* and *structure transformation* – have been deconstructed into four, more specific shape rules. The *Outline transformation* rule has been deconstructed into *bend, straighten, change length/width,* and *change angles* rules and the *Structure transformation* rule has been deconstructed into *flip/mirror, change direction, split shape (use both parts),* and *change shape position* rules. These more specific rules can be further deconstructed into even more specific ones. For example, the *bend* rule can be modified to apply specific transformations to the curvature of elements in a shape, e.g. soft radius, sharp radius, rising curvature and so on. These rules more accurately represent the shape transformations used by designers during exploration and can inform the manipulations that should be supported in a computer-aided design tool.

Table 2: Shape rules identified.

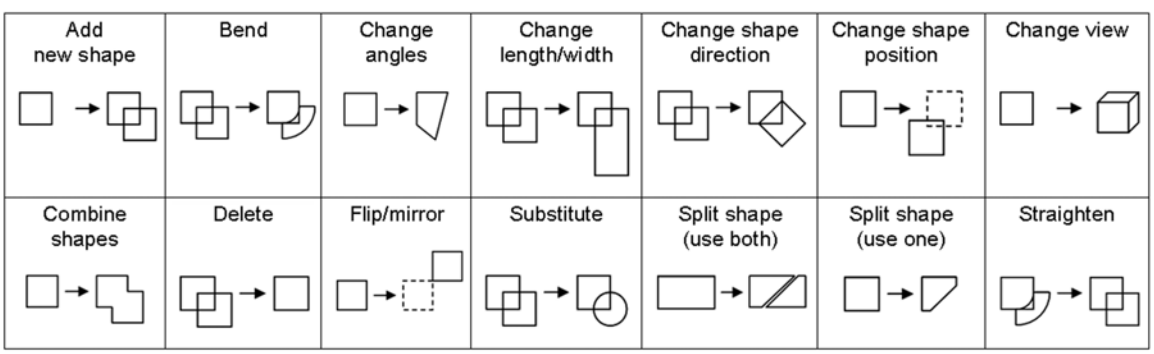
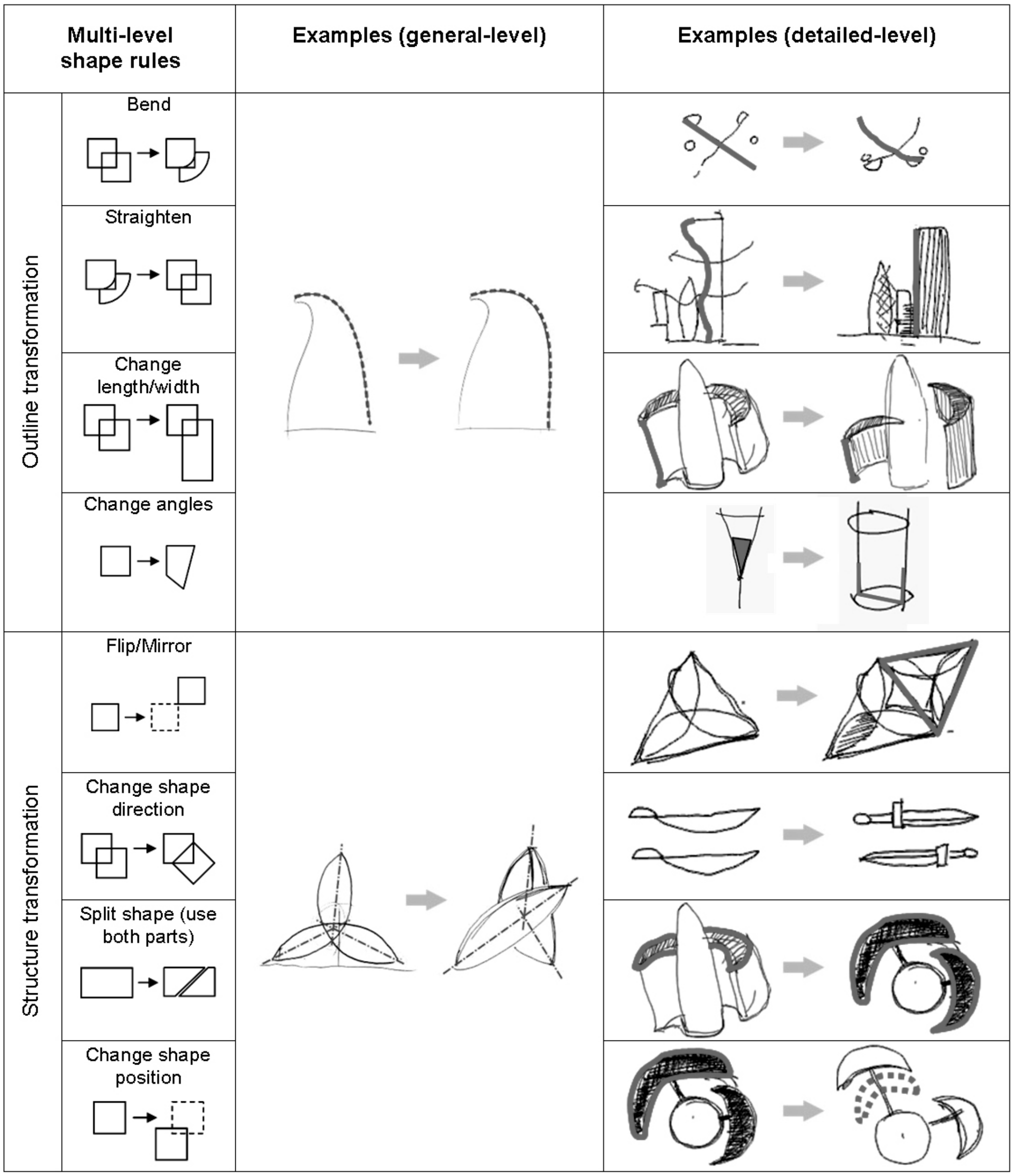


Table 3 shows a multi-level hierarchy of shape rules that describes each type of shape transformation in an abstract way, and provides examples of shape transformations taken from sketches produced by participants.

Table 3: A multi-level hierarchy of shape rules. Bolded (grey) parts are criteria for the identification.



3.4. Discussion

The research described here seeks to address the first two research questions, discussed in the introduction: (i) How do designers, across a range of disciplines, generate shapes?; and (ii) What similarities and differences in approach can be observed? The first of these questions is addressed by formalising the shape transformations used by participants during design exploration according to shape rules. These rules provide a means for describing how designers, when provided with an initial concept, proceed to generate shapes in order to explore design alternatives. However, the more difficult issue of how designers might generate an initial concept has not been addressed.

Shape rules also provide a means for addressing the second research question. With the shape transformations formalised according to generalised shape rules, it is possible to define quantitative data that can be used to compare the different approaches to design exploration used by designers of different disciplines. For example, in Figure 7 two charts are presented that enable the comparison of shape transformation use across tasks 2 and 3 and across the two design disciplines of architecture and industrial design. The results suggest that participants have a common preference for using certain types of transformations over others regardless of their design discipline. The most frequent shape transformations are, in order of relevance, Outline transformation, Change view, and Add element. Despite the similarities between the two design disciplines, the results also exhibit significant differences. For example, the data from task three suggests that architects focused more attention on Structure transformation than industrial designers. However, these results may not reflect design practice in general since the number of participants that took part in this study was small.

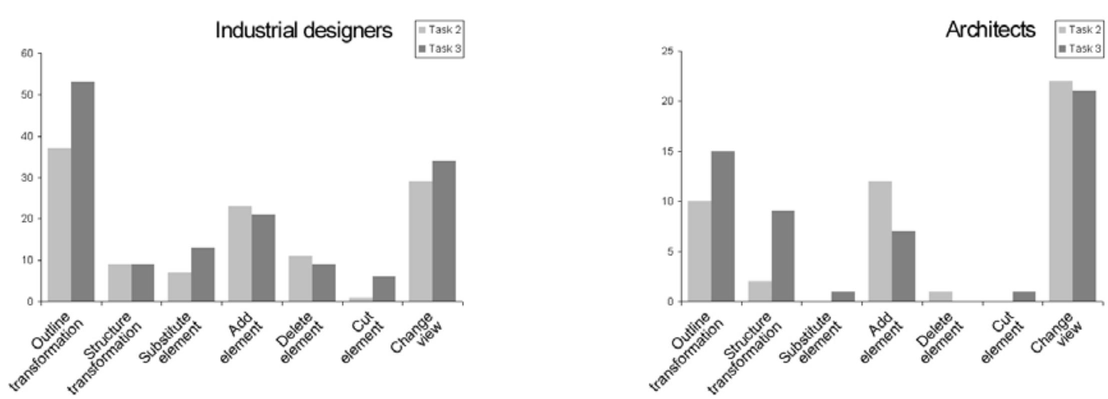


Figure 7: Comparison of shape transformations usage across design tasks and design disciplines

The use of shape rules to formalise shape transformations offers further possibilities with respect to customisable selection of design outcomes that are not available in conventional shape grammar applications. For example, consider that shapes S_1 and S_2 are composed from the application of a number of shape rules according to the following sequences: $\{S_1 \mid R_a, R_b, R_a, R_d\}$ and $\{S_2 \mid R_a, R_c, R_b\}$. If a designer considers that the shape rule R_a is most important to cluster an object, then the shape S_1 and S_2 could be classified in the same cluster. In all other cases, they would be classified in a different cluster. This can frequently happen when a designer and user are different. The customisable selection via different criteria might not only improve shape grammar system performance but could also provide more meaningful outcomes to designers [29]. It is suggested that this can be done by parameterisation of shape rules adapted from the method for numerical representation of vagueness [28], which parameterises vague geometric information to provide a fully customisable selection of geometric information.

In order to address the final two research questions in this research, i.e. (iii) How might the ability to compute shapes enhance the act of designing itself?; and (iv) Can computer vision techniques be used to resolve the sub-shape detection problem in a shape grammar system?, the outcomes of the sketching studies described in the previous section were used to inform the development of a shape synthesis system, as discussed in the next section.

4. A PROTOTYPE SHAPE SYNTHESIS SYSTEM

With the exploratory process of sketching formalised according to shape rules, it is possible to analyse the manipulations objectively that a designer uses when sketching. In addition to providing an objective means of analysis, shape rules are key elements in the definition of shape grammars which provide a means for formally generating and exploring different design alternatives within a design family e.g.[13]. Application of a shape grammar involves the repetitive task of matching and replacing sub-shapes under transformation and as such is well suited for computer implementation. Previous examples of shape grammar implementations have been concerned with formalising and generating designs according to a fixed set of rules e.g.[14, 33], or have been concerned with addressing the fundamental problem of detecting embedded sub-shapes in formally defined shapes e.g. [34]. We present a shape grammar implementation, which is intended to support shape synthesis in conceptual design, as discussed by McKay et al. [30]. This system, depicted in Figure 8, uses established techniques from the computer vision community in order to enable the detection and manipulation of embedded sub-shapes within a design. Figure 8 uses an example of car wheel design to illustrate how the program detects and manipulates outlines of sub-shapes (Figure 8a and b) and changes the structure of the design by manipulating emergent sub-shapes (Figure 8c and d).

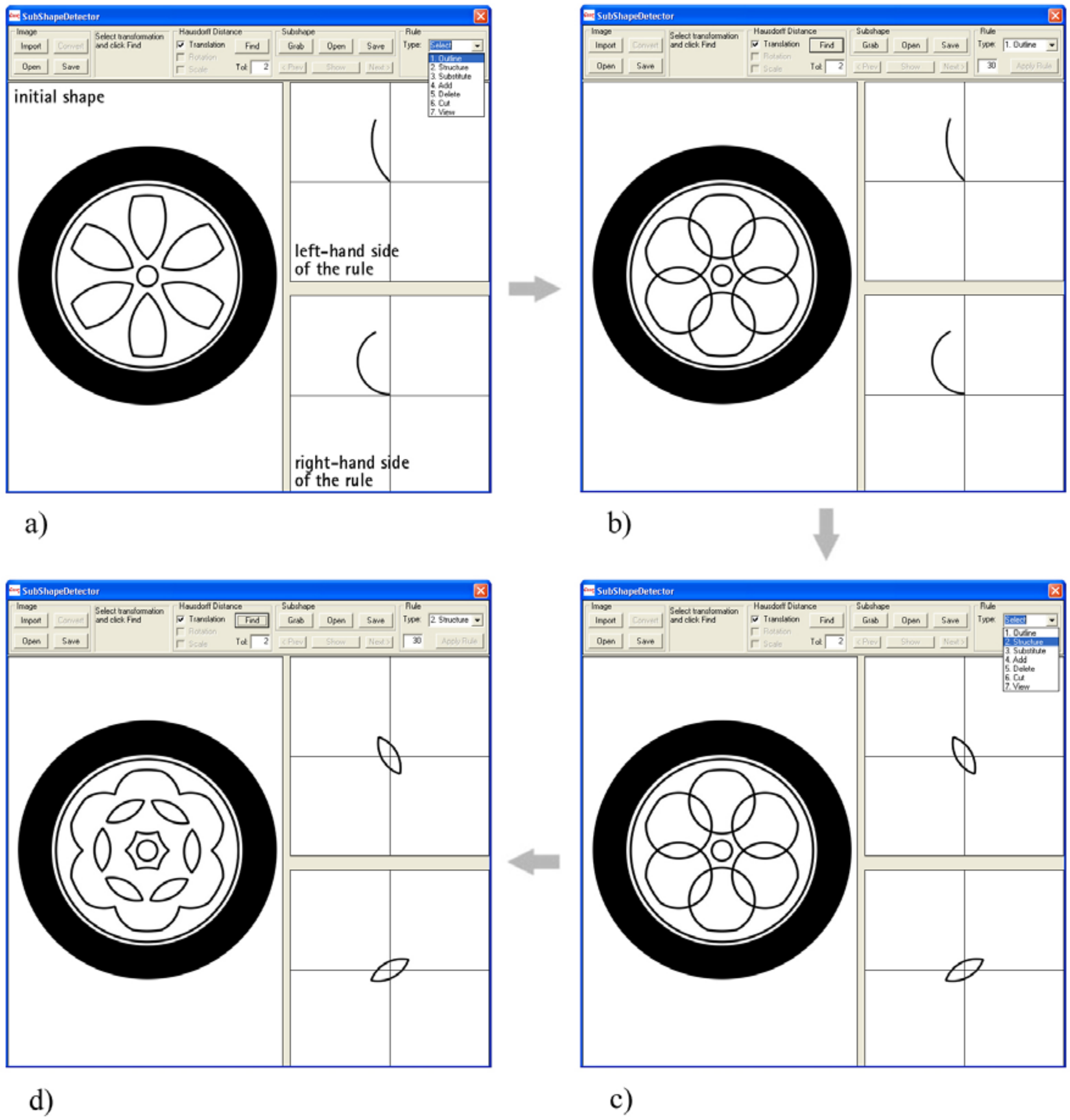


Figure 8: a) Definition of a shape rule to manipulate outlines, b) Application of the shape rule to the initial shape, c) Definition of a new rule which rotates the emergent petals, d) Application of the new rule

The system was developed with consideration of the experimental results, discussed above, and is intended to support the fluid interaction that designers employ whilst exploring design concepts via sketching. The system can be used to implement predefined grammars in order to generate and explore members of a design family according a specific set of shape rules. However, it can also be used to interact dynamically with developing design concepts. The system provides an intuitive interface which enables designers to define rules that formally recognise and manipulate perceived sub-shapes and structures in a design. This use of shape rules means that it is not necessary to consider alternative structures of a shape as it is being created and manipulated, as discussed in [31]. Instead, only a single structure is necessary which changes dynamically according to shape rules that reflect and formalise a designer's perception and intent.

The current system is a prototype intended to explore the possibilities of employing the shape grammar formalism to support fluid design exploration, as described in [32]. In future it is intended that the system will be developed such that it can support the definition and generation of design families, and the exploration of design concepts simultaneously. Such a system would capture all the benefits of the shape grammar formalism by allowing designers freedom to explore design concepts via manipulation of perceived sub-shapes; and also by presenting networks of design alternatives which can be generated via application of shape rules. This system would not replace the creativity of a designer by automatically generating completed design concepts but instead would assist the designer by suggesting alternatives, and possibly unconsidered avenues of exploration.

5. CONCLUSION

This research is aimed at supporting the early stages of design when shapes are explored and developed. Thus the research is in contrast to currently available CAD systems, and the models that underpin them (BIMs for architecture and product models for industrial design), which support later stages of product development processes. Early work is exploring how shape synthesis systems might be integrated with today's CAD systems. The research described in this paper addresses four research questions: (i) How do designers, across a range of disciplines, generate shapes?; (ii) What similarities and differences in approach can be observed?; (iii) How might the ability to compute shapes enhance the act of designing itself?; and (iv) Can computer vision techniques be used to resolve the sub-shape detection problem in a shape grammar system? Analysis of experimental data produced a number of general/detailed shape rules that formalise the shape transformations used by designers when exploring design concepts. Although the rules express shape transformations in an abstract way without representing the exact transformation of a shape, the analysis suggests that the interactions of designers with their sketches can be represented by a finite number of shape rules. The rules formalise the reinterpretation and transformations of shapes, e.g. through deformation or restructuring. The shape rules defined in this research are used to inform development of a computer-vision based shape grammar system, developed to implement our research. The system offers a fluid interaction with digital representations of design that reflects the modes of interaction observed in designers as they explore design concepts via sketching. The system also provides the potential to generate designs within design families via application of shape rules. The analysis reveals a possibility of a customisable selection of generated design outcomes which might not only improve shape grammar system performance but could also provide more meaningful outcomes to designers based on personal design intentions. The support of personal design intention with customised viewpoints that use hierarchical classification of shape rules with preference value for each shape rule is described in [29]. Future work is concerned with exploring (i) how the defined shape rules can be further detailed in a hierarchical manner, (ii) how the customised viewpoints that have been formalised can be further developed, and also (iii) how these results can be further integrated with the computational tool for conceptual design that has been developed for our research.

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Appendix: examples of the design briefs

The process of this study

This study includes three tasks that involve sketching. The first task contains two short sub-tasks of 3 minutes each in which you will be asked to redefine the design of a logo. The second and third tasks are more specific to your own design field and you will be given 10 and 14 minutes respectively to generate your design sketches.

In each task you will be given a proposed design which you will be asked to modify. You will be provided with sheets of A4 paper on which we would like you to develop your sketches. Your first sketch should be a copy of the proposed design and after that you're free to explore ideas of your own, leading to a single preferred proposal. We are interested in observing the development of your ideas through your sketches so please produce as many sketches as necessary. Since this is an early design stage we do not expect detailed drawings but would like to see the development of your ideas through rough conceptual sketches.

Task 1a *3 minutes*

You are asked to improve the logo for an organization known as '**VA Bank'**. The image below is the logo that was suggested by the bank's design consultant. The logo is composed of two crossed swords which symbolise safety and security. However, the bank also wants the logo to reflect the flexibility and dynamism of the services offered by their company, and they feel that this is not reflected in the current design. You are asked to incorporate the concepts of flexibility and dynamism in a new logo.

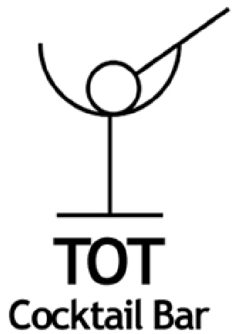
You are allowed to change the composition of the design, and to add or remove design details, but the final proposal should be composed of two swords. If you wish, you may ignore the lettering and focus on the graphic element.

VA BANK

Task 1b *3 minutes*

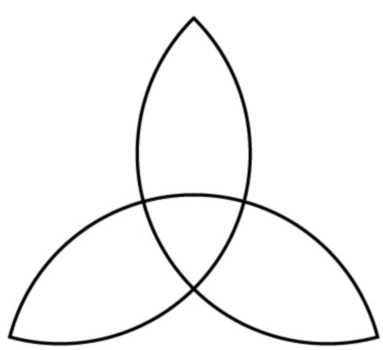
You are asked to improve the logo for a venue known as '**TOT Cocktail Bar'**. The image below is the logo suggested by the bar's design consultant which is composed of a cocktail glass and a cherry. The bar owners are happy with the brand concept but they would like to see the logo with another type of glass - with the exception of the classic Martini glass. You are asked to modify the <u>type of glass</u> in a new logo.

You are allowed to change the composition of the design, and to add or remove design details, but the <u>final proposal should include a glass with a cherry</u>. If you wish, you may ignore the lettering and focus on the graphic element.



Task 2 *10 minutes*

In this task you are asked to devise a design for a new **lemon squeezer**. Your 'client' is a kitchen appliances manufacturer who wants to introduce a lemon squeezer into their range of products. The company has a reputation for manufacturing <u>simple and effective designs</u>. The outcome from the meeting between the design and management departments was the lemon squeezer concept shown below. As this is only a conceptual design it needs to be completed. You are asked to <u>use this concept design</u> and make it a real design proposal. Since the lemon squeezer only works manually you should <u>not consider using any electrical motors</u> in the design. In order to make an effective design, the new gadget should <u>separate pips and pulp from the juice</u>.

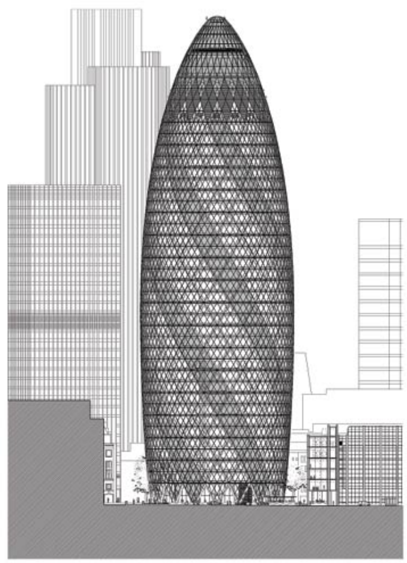


Task 3

14 minutes

In this task, your ‘client’ is the owner of the St Mary Axe building in London. The client recently purchased the site adjacent to the Axe building, and would like to build a second iconic building next to the Axe building. You are asked to design a **Multi-complex tower**, which contains various types of spaces, e.g. car park/sports centre in underground, a bank in the ground floor, shopping centres/offices in the middle and apartments for the rest, with the following requirements.

- The shape of the new building should be different from the Axe building, whilst retaining its <u>organic form and aesthetics</u>.
- The new building should be connected to the Axe building via an <u>aerial link</u>.
- The height of both buildings need not necessarily be the same.
- Consider that you are not restricted by the building law.



St Mary Axe Building