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Supporting Reinterpretation in Computer-Aided Conceptual Design

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Abstract

This paper presents research that aims to inform the development of computational tools that better support design exploration and idea transformation - key objectives in conceptual design. Analyses of experimental data from two fields - product design and architecture - suggest that the interactions of designers with their sketches can be formalised according to a finite number of generalised shape rules defined within a shape grammar. Such rules can provide a basis for the generation of alternative design concepts and they have informed the development of a prototype shape synthesis system that supports dynamic reinterpretation of shapes in design activity. The notion of 'sub-shapes' is introduced and the significance of these to perception, recognition and the development of emergent structures is discussed. The paper concludes with some speculation on how such a system might find application in a range of design fields.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [User Interfaces]: Interaction styles I.3.6 [Computer Graphics]: Interaction techniques J.6 [Computer-Aided Engineering]: Computer-Aided Design (CAD)

1. Introduction

Studies suggest that creative design is an activity that involves creation and exploration of design alternatives [Cro97]. Furthermore, it has been observed that when sketching designers often produce series of ideas that are ambiguous and open to reinterpretation. These design alternatives are explored visually by the designer and they can suggest patterns and associations that lead to new avenues of exploration. Schön and Wiggins [SW92] describe this as a 'seeing-moving-seeing' process where seeing a sketch can result in its reinterpretation according to emergent forms or structures, and this in turn informs the development of future sketches. Such reinterpretation is a vital element in the exploration of designs and is believed to be a decisive component of innovative design [Suw03]. However, despite the importance of reinterpretation in design exploration it is not readily afforded by current computational design tools.

The research outlined in this paper is concerned with gaining an understanding of the mechanics that underlie reinterpretation and transformation in design exploration, and with using this understanding to inform a computational tool that supports early design exploration. The work is based on experimental investigations of sketching, in which practicing designers were observed as they responded to a series of conceptual design tasks [LPCG08b]. In particular, the investigations were concerned with the mechanics of the process of 'moving' as defined by Schön and Wiggins. 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, defined within a shape grammar [Sti06]. These rules formalise the interpretations and transformations of shapes that are used during design exploration. As such, they provide a basis for the generation of additional design concepts which can suggest alternative avenues of exploration.

With these results in mind, a shape synthesis system was developed which, based on the shape grammar formalism, enables dynamic reinterpretation of shapes for design exploration [MJC*08]. This system is introduced, and via consideration of case studies derived from the experimental data, its application as a tool for supporting design exploration is investigated.

2. Background

Computational design tools, such as Computer-Aided Design (CAD) systems, are common in modern design studios and enable the creation of digital product models that are used throughout the design process, e.g. for evaluation or manufacturing. It is generally accepted that such tools do not support the early, explorative stages of the design process. For example, Tovey [Tov89] discusses the limitations of early CAD systems with respect to conceptual design and concludes that such systems do not support the flexible interaction that designers require when exploring design concepts. In spite of much research and technical development an incompatibility is still observable [Eva02]. As a result, digital product models are typically produced after the creative act of designing has been completed and there is a gulf between the explorative processes that result in the selection of a design concept and the creation of a digital model.

Computer-Aided Conceptual Design (CACD) systems are intended to address this distinction between design exploration and digital product definition. However, such systems have not yet been released commercially due to the many implementation problems that remain to be addressed. Much of the research in this area has been concerned with addressing problems that arise when ambiguous sketches are used as input to computational systems. For example, the problem of converting sketches into 2D or 3D models e.g. [IMT99], or the problem of shape ambiguity e.g. [Gro01]. Other studies have been concerned with the issue of user interface e.g. [WWA07] and prescribing the components necessary to support conceptual design e.g. [SGY07]. There has been little research concerning understanding the mechanics of design exploration so that CACD systems can support and enhance conceptual design.

A crucial difficulty in using computational tools in design exploration arises because such tools do not readily afford dynamic reinterpretation of designs according to newly perceived forms or structures. When a digital product model is created a specific structure is defined according to a fixed set of geometric elements, such as edges or surfaces. Reinterpretation of this structure in order to allow for newly recognised patterns and associations is only straightforward when these emergent forms conform to subsets of this set of geometric elements. Otherwise, reinterpretation of a model necessitates redefinition according to a new set of elements. A fixed structure such as this can lead to inconsistencies between what can be perceived in a design model and the manipulations allowed. Designers cannot easily manipulate all the sub-shapes that they perceive and cannot take advantage of emergent structures. As a result they are not free to explore the patterns and associations that emerge as a design is being developed but are restricted to manipulating shapes according to the structure by which the design was initially defined. Saund and Moran [SM94] present a system that seeks to address these issues by providing an image interpretation architecture based on token grouping. Tokens are organised into a lattice structure which enables perceptual interpretations of a sketched shape to be specified and manipulated according to simple gestures. In this paper an alternative approach is presented which takes advantage of the shape grammar formalism in which perceptual interpretations of a sketched shape are specified according to shape rules [Sti06]. The shape rules used are derived from sketching studies which were conducted in order to gain an understanding of how designers interact with shapes whilst exploring design concepts. Such an understanding can lead to formal representations of the mechanics of sketching which can then be used to inform development of CACD systems that facilitate creative design.

3. Supporting the Mechanics of Sketching

In conceptual design sketches are frequently used to explore design alternatives. A key benefit of sketching is that it assists designers in the development of various characteristics of products such as form and shape in a flexible and unstructured way. Studies of design suggest that there is a reciprocal relationship between designers' thinking and their sketches [Gol94]. This two way conversation between designer and sketch commonly leads to the generation of sequences of related sketches in which design elements are recognised and manipulated [PE06]. Much research has focused on the patterns and associations that designers see in their sketches, e.g. [ST97], and how recognition and manipulation of these patterns can be perceived as an externalisation of a designer's cognitive processes, e.g. [Law06]. However little effort has been expended in studying the mechanisms used to transform shape in sketches. Our research goes some way toward this goal, and has led to the development of a shape synthesis system intended to support design exploration.

3.1. The mechanics of sketching

An understanding of the mechanics of sketching was derived following a series of studies in which a combination of architects and product designers were observed whilst exploring design concepts, as illustrated in Figure 1. A detailed discussion of these studies is presented by Lim et al. [LPCG08b].

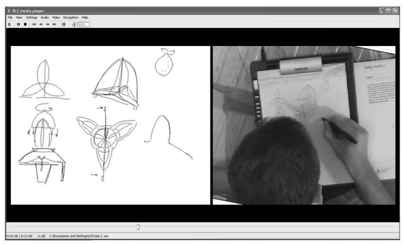

Figure 1: *Video capture of a designer exploring sketches*

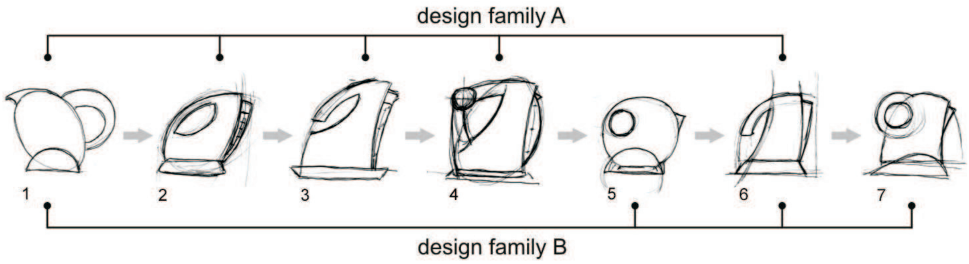

Figure 2: *A sketch sequence*

During the studies, the actions of the designers were captured using an overhead video camera and through the use of a tablet input device. In addition, this video is augmented by retrospective interviews in which designers were asked to elaborate on the interpretations and manipulations of their sketches. This data was analysed with the aim of formalising the shape manipulations that designers use as they sketch when exploring design concepts. By studying the video it was possible to determine the sequence in which sketches were created, as indicated by the horizontal arrows in Figure 2. In addition, by considering comments made by designers in interview, it was possible to derive the flow of ideas between sketches and also to group together concepts that are considered to be explorations of the same idea. These groups of similar concepts are termed 'design families'. For example, in Figure 2 two distinct design families were identified, each of which is derived from a different interpretation of the initial sketch. In design family A, the oval body of the kettle in the initial sketch was perceived by the participant as being the primary shape and the second, third, fourth and sixth sketches are different explorations of this concept. For example, when discussing the fourth sketch the designer stated "*Here I started with the same shape* (tracing the oval shape) *I had before...*". Alternatively, in design family B, the circular handle of the kettle in the initial sketch was perceived as being the primary shape, and the fifth, sixth and seventh sketches are explorations of a circular concept. To quote the designer when discussing the fifth sketch, "*To follow the* (initial) *concept I tried to use this circle* (tracing the handle of the initial shape) *to make this concept...*".

This example illustrates one way in which reinterpretation of a shape influenced the exploratory processes of participants in the experiments. However, this was not the only example that arose during the analysis. For example, in some instances a shape was interpreted as being a side view, and then was reinterpreted as being a top view. In other instances a single shape was interpreted as performing different functions. In each case, a particular interpretation played an important influencing role on the subsequent designs, and different reinterpretations often led to exploration of different design families. In many cases, this reinterpretation merely involved recognition and manipulation of different sets of sub-shapes embedded in the same design.

By studying the members of a design family in sequence, it was possible to begin to understand the manipulations that the participants used when moving from one sketch to another, and from one design family to another. For this study, these manipulations were formalised according to shape replacement rules. For example, Figure 3 illustrates a selection of the rules that were used to formalise the explorations of design family A and design family B in Figure 2. These rules specify on the left-hand side the sub-shape of a design that a designer intends to modify, and on the right-hand side the intended modification.

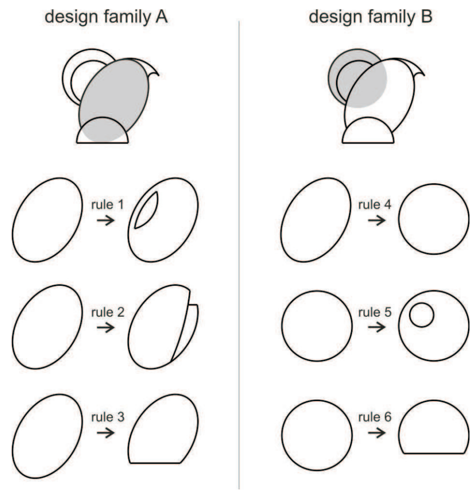

Figure 3: *Formal exploration with shape rules*

With the exploratory process formalised in this way, it is possible to objectively analyse the manipulations that a designer uses when sketching. For example, the rules in Figure 3 suggest that although the different interpretations of the initial sketch in Figure 2 led the designer to explore different design families, the transformations used to explore these families share strong similarities. Analysis of shape rules also suggested similarities in approach between participants. For example, the participants all showed a preference towards two types of transformations: the manipulation of the outlines of shapes, whilst keeping the topological structure constant; and the manipulation of the topological structure between sub-shapes without modification of the sub-shapes themselves. These rules are discussed further in Section 4. 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.

3.2. Shape grammars

Shape grammars [Sti06] embody the philosophy that a designer can recognise and manipulate any sub-shape or structure that can be perceived within a shape. As such, a shape is not composed according to a fixed structure but is structured according to whatever components a designer cares to see at any particular moment in time. Particular decompositions of a shape are formalised according to shape replacement rules which specify the structure of a shape by recognising and manipulating embedded sub-shapes. These shape rules provide a dual advantage to designers. Firstly they enable the perceived structure of a shape to be freely recognised and manipulated without adherence to a predefined geometric structure. Secondly, the rules formalise the creative process by which a design is generated and thereby enable the repetition of the process. As a result, it is possible to define a design family which contains the design alternatives that can be generated by the rules. For example, shape rules have been defined such that they formalise a specific style or brand, e.g. [KE81], and the resulting shape grammar can be used to generate and explore the appropriate design family. If required, exploration of design families can be automated according to qualitative criteria that reflect desirable qualities such as aesthetics, e.g. [LPCG08a].

3.3. Shape synthesis to support design exploration

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. [ACS00], or have been concerned with addressing the fundamental problem of detecting embedded sub-shapes in formally defined shapes, e.g. [Jow06]. We present a shape grammar implementation, which is intended to support shape synthesis in conceptual design, as discussed by McKay et al. [MJC*08]. This system, illustrated in Figure 4, uses established techniques from the computer vision community in order to enable the detection and manipulation of embedded sub-shapes within a design.

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 [SM94]. Instead, only a single structure is necessary which changes dynamically according to shape rules that reflect and formalise a designer's perception and intent.

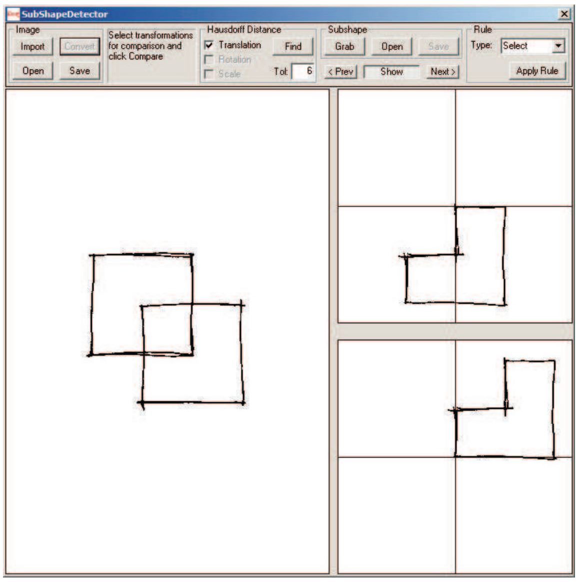

Figure 4: *A shape synthesis system*

Shape rules are defined according to two shapes, which are displayed in the system's graphic user interface (GUI). The left-hand side of the rule is displayed in the top-right corner of the GUI, and the right-hand side of the rule is displayed in the bottom-right corner. For example, the rule displayed in Figure 4 recognises and translates sub-shapes of a design in the form of an 'L'. These shapes can either be imported as image files, or can be created interactively within the system. For example, the left-hand side of the rule can be created by selecting a particular sub-shape of a design. The current design in a sequence is displayed in the main window on the left side of the GUI, and in Figure 4 is composed of two overlapping squares. The initial design is imported as an image file, and subsequent designs are generated by recognising and manipulating sub-shapes according to shape rules. These rules are not restricted to manipulating shapes according to the structure by which a design is initially defined, but can manipulate shapes according to any perceived structure. For example, the initial structure of the design in Figure 4 is constructed according to two squares, but the shape rule is able to reinterpret this structure as two 'L's and manipulate the resulting sub-shapes, as illustrated in Figure 5.

The current system is a prototype intended to explore the possibilities of employing the shape grammar formalism to support fluid design exploration. 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.

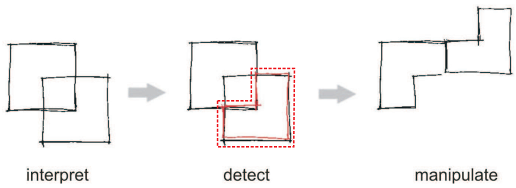

Figure 5: *Recognition and manipulation of 'L's*

4. Two Case Studies

The shape synthesis system discussed in Section 3.3 enables the formal exploration of design alternatives. This exploration is based on a 'seeing-moving-seeing' process as described by Schön and Wiggins [SW92], with shape rules carrying out the action of 'seeing' and 'moving' perceived sub-shapes in a design. In this section, this process will now be illustrated with reference to two case studies. These studies are both derived from data that was collected during the sketching studies described in Section 3.1. The first study, in Section 4.1, is concerned with explorations by a product designer, while the second, in Section 4.2, is concerned with explorations by an architect.

Analyses of the sketching studies suggest that designers use a variety of different types of shape transformations when exploring design concepts, and that these transformations can be defined according to generalised shape rules [LPCG08b]. Here, we concentrate on two types of shape transformations: outline transformations and structure transformations, as discussed in Section 3.1. The rules presented here do not aim to reproduce the actual sequence of sketches produced by participants but instead formalise the transformations they used when exploring, in such a way that additional design alternatives can also be generated within the same design families.

4.1. Case study 1: product design

In this first study, the objective was to produce a design concept for a manual lemon juicer. An initial abstract concept was provided, as illustrated in Figure 6a), and the task was to develop this further into a simple and effective design that would efficiently separate the pips and pulp from the juice. Given the initial concept, design exploration commences by 'seeing' patterns and associations which suggest avenues for exploration. For example, one participant in the study perceived the initial concept to be composed of truncated petal shapes and proceeded to explore by manipulating the resultant sub-shapes. These transformations can be formalised according to shape rules which detect and manipulate perceived sub-shapes. An example of this transformation is provided by rule 1 in Figure 6b), which recognises and stretches truncated petals. With this manipulation formalised it is possible for the shape synthesis system to repeatedly apply the rule in order to generate a variety of design concepts in a design family, as illustrated in Figure 6c). Some of the concepts illustrated were produced by the participant whilst sketching, but others were not and suggest alternative avenues for design exploration.

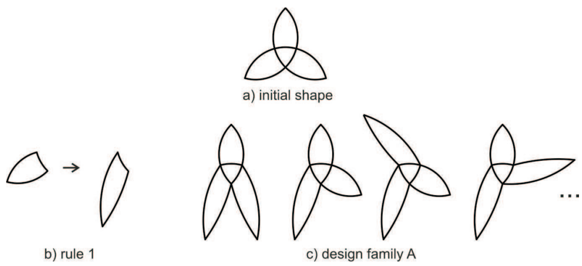

Figure 6: *Formal exploration of lemon juicer designs*

As previously discussed, whilst exploring designs it is common for designers to reinterpret previously generated concepts according to newly recognised forms or structures, and this reinterpretation can lead to the exploration of alternative design families. The shape synthesis system actively supports this reinterpretation simply by enabling the definition of new shape rules that recognise and manipulate newly recognised sub-shapes. For example, the initial shape in Figure 6a) can also be perceived as being composed of three overlapping petal shapes and this reinterpretation can be formalised according to a shape rule such as rule 2 in Figure 7. Following the reinterpretation an alternative design family can be generated as illustrated which further explores the initial design concept, and the concepts in design family A (Figure 6) according to the new shape rule.

Both rule 1 and rule 2 are examples of outline transformations since they change the outlines of shapes, whilst keeping the topological structure constant. An example of a structural transformation is given by rule 3 in Figure 7c), which recognises and removes a specific sub-shape in a concept, thereby changing its topological structure. Application of this rule results in the generation of additional design concepts in which further sub-shapes can be recognised and manipulated, as required.

At this stage, it is interesting to compare the concepts generated by the shape synthesis system with concepts developed by the participant whilst sketching. Three sketched concepts are illustrated in Figure 7 which bear a strong similarity to concepts generated by the computational system via application of the three shape rules. However, functional interpretation of the shapes in the sketches has led to two distinct design families. In design family C the petal sub-shape is interpreted as being the corrugated component of the lemon juicer, with the truncated petals acting as legs on which this component would stand. Alternatively, in design family D the petal sub-shape is interpreted as being the juice collector with one truncated petal acting as the corrugated component, and another truncated petal acting as a stand, or as a handle. This functional interpretation does not result from simple reinterpretation of shapes but instead is a product of the designer's creativity. However, it is theoretically possible to incorporate such functional explorations in a shape grammar, e.g. [ACS00], and as such could be incorporated in future shape synthesis systems. The current system can merely assist the creativity of designers by suggesting shapes and design families that designers may not produce themselves.

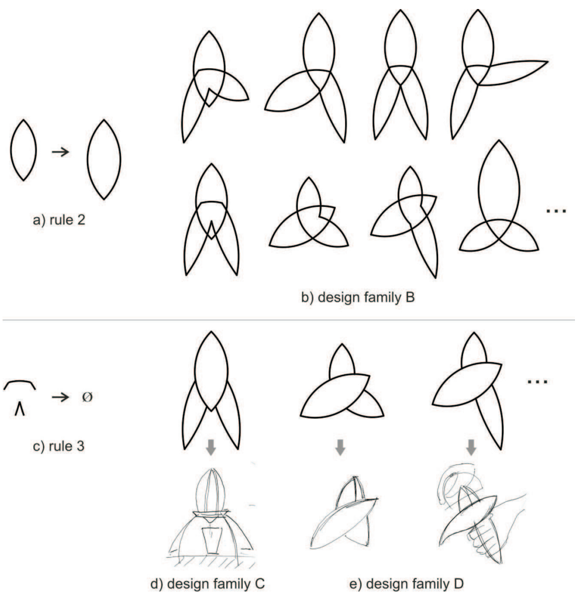

Figure 7: *Further explorations of lemon juicer designs*

4.2. Case study 2: architecture

In this second study, the objective was to produce a conceptual design for a building. The same initial concept was provided as for the product design study and the participants were free to explore with no restrictions. As with case study 1, exploration commences by 'seeing' patterns and associations in the initial concept but in this case when participants reconised a pattern in a sketch they often then repeated the pattern in future sketches. The transformations involved in this process are structural transformations but they differ from the structural transformations illustrated in case study 1 because they involve the addition of sub-shapes to a concept rather than their removal. For example, one participant was interested in exploring floor plans and took a petal sub-shape as an initial design. From this, the initial concept in Figure 6a) was systematically constructed, as illustrated in Figure 8a). This construction can be formalised according to a shape rule, such as rule 1 in Figure 8b), in which a circular arc is added to the tip of a petal shape. The rule can then be applied repeatedly in order to continue the addition process and explore design concepts. The members of the resultant design family all have the same underlying structure repeated a number of times, as illustrated in Figure 8c). When exploring design concepts via repetitive patterns such as this the shape synthesis system can further enhance the creativity of a designer since it is able to recognise avenues of exploration that a designer may have missed.

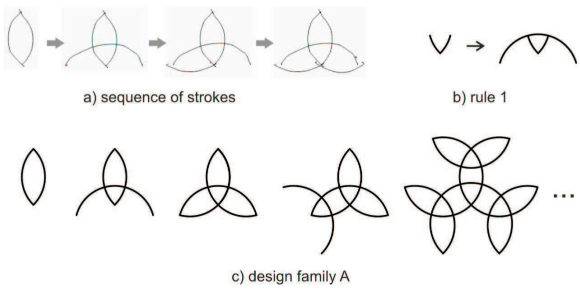

Figure 8: *Formal exploration of building layouts*

Design exploration continues with the addition of new rules which manipulate alternative patterns recognised in a design concept. For example, rule 2 and rule 3 in Figures 9a) and b) formalise shape transformations that the participant used during design exploration whilst sketching. Rule 2 reinterprets the circular arcs added to a design by rule 1 by dissecting the arcs into two segments. Rule 3 formalises a new pattern between petals of differing scale. The three rules can be applied in turn in order to explore a wide variety of designs within a design family, as illustrated in Figure 9c).

In the study, the initial concept was interpreted as a floor plan of a building composed of petals and the designs the participant explored involved experimentation with the patterns that emerged from petal sub-shapes. When happy with a particular floor plan, the participant then proceeded to explore the three-dimensional aspects of the building designs, as illustrated in Figure 9c). Here, the two sketched concepts on the left were produced by the participant, while the two rendered concepts on the right were developed based on floor plans generated by the shape synthesis system via application of rules 1, 2 and 3. The rendered designs were developed based on shape rules that were derived from the participants reinterpretation of two-dimensional plans into three-dimensional concepts. However, the current shape synthesis system works solely with two-dimensional shapes and does not support exploration of shapes in three-dimensions. Shape grammar systems have been implemented that generate three-dimensional shapes, e.g. [CCMdP04], and as such it is possible that future shape synthesis systems will be able to explore the reinterpretation of floor plans into elevations, along with other interpretations of perspective.

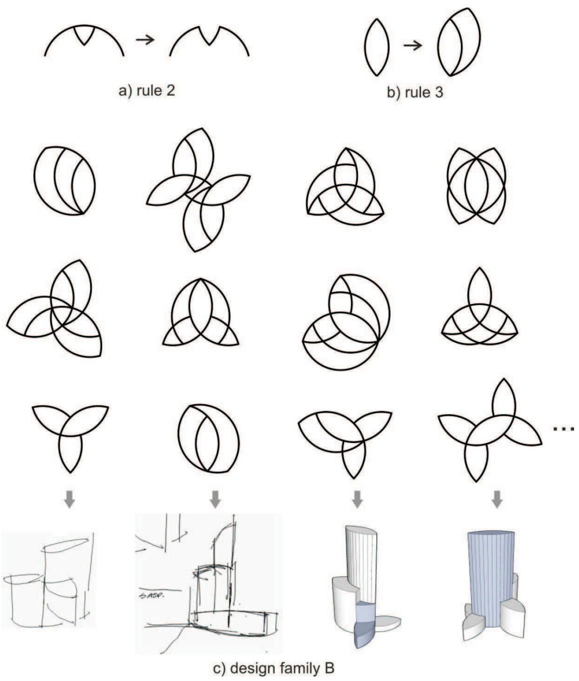

Figure 9: *Further exploration of building layouts*

5. Conclusions

Current CAD systems are generally not appropriate for use in conceptual design since they do not support the flexible interaction that designers require when exploring design concepts. As a result, there is a distinction between the development of design concepts and the production of digital design models. CACD systems are concerned with addressing this distinction but they do not currently support the dynamic reinterpretation of designs that studies have shown to be vital for creative design.

In this paper, a prototype shape synthesis system was presented which is based on the shape grammar formalism. Unlike other examples of shape grammar implementations, this system has been developed with the requirements of conceptual design in mind. Indeed, development of the system has been informed by studies of sketching in which designers were observed when exploring design concepts. The studies were concerned with formalising the mechanics of exploration in conceptual design, which can be summarised according to three steps: 1. the recognition of features and patterns in design representations; 2. reinterpretation of the structure of representations according to these newly recognised features and patterns; 3. transformation of shape elements in the representation according to the new structure.

The shape synthesis system enables reinterpretation of designs via application of shape rules that detect and manipulate perceived sub-shapes of a design. The shape rules formalise the transformations used by designers when exploring design concepts and provide two distinct advantages. Firstly, they enable reinterpretation of digital design models, thereby enabling dynamic interaction for conceptual design. Secondly, they enable repetition of the process by which a design concept was produced, and thereby the generation of design families instead of single design concepts, thereby providing alternative avenues for exploration. These advantages were illustrated with reference to two case studies concerning the design explorations of product designers and architects.

Acknowledgements

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