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A Human-Computer Framework for Schema-Driven and Precedent-Driven Visual Analogy in Design.

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Design problems are said to be ill-structured, non-routine, and as such no algorithm or automatic procedure is possible to be used for finding a suitable solution (e.g. Goel, 1995; Simon, 1984). This is one reason because the use of analogy, and visual analogy in particular, is seen as a powerful strategy for dealing with design problem solving. Visual analogical reasoning entails the use of visual information from a known situation (termed source) in such a way that makes possible to solve a specific problem (termed target) (e.g. Gentner, 1983). Throughout the design process, and particularly in the early stages of the process, designers are exposed to vast collections of visual displays, which provide them with helpful references. Thus the use of analogy in the visual modality is considered to be a most suitable aid for design problem solving (Goldschmidt, 1994).

Reasoning by analogy deals with two main cognitive approaches. The first one is concerned with schema-driven analogy, which is defined as the use of abstract experiential knowledge that can afford a design solution to a familiar problem type (e.g. Chi, Feltovich and Glaser, 1981). In this case, the use of schematic knowledge which demands a large domain-based experience, can be automatically identified and applied as an abstract solution procedure to the problem at hand. The second paradigm has to do with case-driven analogy, and it is distinguished by the use of a concrete prior design problem whose major components and its corresponding relationships could be explicitly mapped onto the problem at hand (e.g. Kolodner, 1993). In contrast to schema-driven analogy, this paradigm entails effortful and explicit analogical reasoning processes concerning contentful rather than abstracted knowledge.

Empirical studies on the use of analogy showed that expert designers, who have developed and well-integrated knowledge structures tend to apply more schema-driven than case-driven analogy. On the other hand, novices, who lack such developed knowledge structures, showed the opposite pattern of analogical reasoning (Ball et al., 2003).

Despite the importance of visual analogy in any of the two modalities, only a small number of studies have dealt with the use of visual displays as an aid in design (e.g. Casakin, 2002; Casakin, 2003; Casakin and Goldschmidt, 1999; 2002), and few researches have tried to model computerized tools (Casakin and Dai, 2003).

In order to support the use of visual displays in design, both as schema-driven and as case-driven cognitive strategies, a computerized model that applies artificial intelligence technology for supporting visual reasoning is developed. Through a human-computer interaction, it is explored how the proposed computerized model supports the use of visual analogy by designers with a different level of expertise. The design process is automated to the maximum extent through the management of tacit design knowledge (often in intangible form), and explicit knowledge of designers (through well–understood processes). Tacit knowledge is more influential on schema-driven design process where explicit knowledge is used to support case-based reasoning directly.

Computing technologies are borrowed from an existing knowledge management framework (Rubin and Dai, 2003), and adapted to support various requirements of the reasoning process within the design framework. An unique advantage from this research is that designers are equipped with an innovative design tool that allows them to explore the design process in a new way. Once tacit and explicit design knowledge are well understood and managed, the aid provided by the computerized tool is expected to lead to improved productivity, and an enhancement in the quality of the design outcome. Through appropriate organizing and managing design knowledge, designers can virtually direct the behaviors of computing systems such as design systems in any way as they wish. Improved design knowledge or design process can lead to a knowledge update that can be eventually beneficial to other designers.

A human-computer framework for schema-driven and precedent-driven visual analogy in design

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Abstract

The use of visual analogy is considered to be a most suitable aid for design problem solving. Reasoning by analogy deals with two main cognitive paradigms. The first one is concerned with schema-driven analogy, which is defined as the use of abstract experiential knowledge that can direct a design solution to a familiar problem type. The second paradigm has to do with precedent-driven analogy, and is distinguished by the use of a concrete prior design problem whose major components and its corresponding relationships could be explicitly mapped onto the problem at hand. In order to support the use of visual displays in design through schema-driven and precedent-driven cognitive strategies, an interactive computerized framework that applies knowledge management practices as well as artificial intelligence technology for supporting visual reasoning is proposed.

1 Introduction

Design problems are generally viewed as typical examples of ill-defined problems (Goel, 1995; Simon, 1984). A main characteristic of these is that they are non routine and ambiguous. This is the reason because their goals cannot be clearly formulated, and the number of possible solutions can embrace a large number of unknown and unexpected possibilities (e.g.; Suwa et al, 1999). This is why the use of analogy, visual analogy in particular, is seen as a powerful strategy for dealing with design problem solving. Visual analogical reasoning entails the use of visual information from a known situation (termed source) in such a way that makes it possible to solve a specific problem (termed target) (e.g. Gentner, 1983; Holyoak, and Thagard, 1995). The identification of commonly shared relationships between the known relations in the source domain and the potential relations in the target domain leads to the creation of an analogy. The success of a visual analogy depends on the way that the knowledge needed to solve a problem is accessed and retrieved from a source, then mapped, transferred, and applied to a design problem (e.g. Novick and Holyoak, 1991). Reasoning by analogy deals with two main cognitive approaches. The first one is concerned with schema-driven analogy, which is defined as the use of abstract experiential knowledge that can direct a design solution to a familiar problem type (e.g.; Chi, Feltovich and Glaser, 1981). In this case, the use of schematic knowledge which demands a large domain-based experience, can be automatically identified and applied as an abstract solution procedure to the problem at hand. The concerned knowledge is called tacit knowledge, i.e. knowledge in abstract form. The second paradigm has to do with precedent-driven analogy, and is distinguished by the use of a concrete prior design problem whose major components and the corresponding relationships could be explicitly mapped onto the problem at hand (e.g.; Kolodner, 1993). In contrast to schema-driven analogy, this paradigm requires more effort and explicit analogical reasoning processes that involve focussing on detailed rather abstracted knowledge which can be more effectively dealt with by explicit knowledge. In order to support the use of visual displays in design through both schema-driven and precedent-driven cognitive strategies, an interactive knowledge management framework for design that applies artificial intelligence technology is developed. The design process is automated to a maximum extent through the management of tacit design knowledge (often in intangible form), and explicit knowledge of designers (through well-understood processes). Computing technologies are borrowed from an existing knowledge management framework (Rubin and Dai, 2003), and adapted to support various requirements of the reasoning process within the design framework. Key aspects of design knowledge according to the principles of knowledge management are considered.

2 Visual analogy and design

Visual thinking strategies have usually been considered as fundamental aids in design problem solving. During the generation and development of forms, the design process is frequently supported by visual sources of information, which contains cues that can potentially prompt new forms (e.g., Goldschmidt 1991). Visual displays are seen as major sources to stimulate the use of visual analogy. Researchers such as Beveridge and Parkins (1987) Gick and Holyoak (1983), and Novick (1988) carried out empirical studies regarding the use of visual analogy in the cognitive domain. In the design domain, empirical studies were achieved by Verstijnen, (1999), Casakin (2003), and Casakin and Goldschmidt, (1999; 2000). Major findings showed that visual analogy can be considered as an efficient cognitive strategy in design problem solving. However, spontaneous access, recall and transfer of analogical principles were seen to be highly dependent on the availability of some type of hints provided to the designer. On the other hand, other investigations demonstrated that the spontaneous use of analogy is largely dependent on the information contained in the source and target situations (e.g. Holyoak and Kohn, 1987; Sweller, 1980). An analogy is generally established when 'within-domain' displays (involving sources that are very close to the problem at hand) are available (Visser, 1996). Despite the vital role played by analogical reasoning in creative thinking, the use of visual analogy has still not received enough attention in design problem solving.

2.1 Analogical reasoning: schema driven and precedent-driven paradigms

Schematic knowledge embraces abstract conceptual representations of problems. Schemas allow for the recognition of problems according to main categories, and embody procedural knowledge concerned with the best ways for solving problems of that particular type (Anderson, 1989; Blessing and Ross, 1996; Ball et al., 2003). Empirical studies carried out by Chi et al. (1981) found that schema acquisition and schema application were related to the level of expertise of the problem solver. Accordingly, experts were able to represent a problem correctly in terms of relevant knowledge. This facilitated the access to an appropriate schema, and the mechanical recall of a successful solution. In contrast, novices showed restricted capabilities to identify and bring on appropriate problem-solving schemas for a task at hand. The schema-based approach has also been considered in the design domain (e.g. Gero, 1990; Ball et al., 1994). Under the difficulty to access schema-based solution knowledge, it was observed that designers made their efforts to find an analogical source that may share surface commonalities and solution principles with the problem target. This process is known as precedent-driven analogical reasoning. Ball et al. (2003) also showed that when the schema-driven approach cannot be successfully applied, designers seem to be ready to apply precedent-driven, also known as case-driven strategies. This is in part due to the ill-defined nature of design problems that not always makes possible to effectively use routine processes, to deal with unfamiliar design problems. Inversely to novice designers, experts revealed more schema-driven analogy than case-driven analogy. This supports the view that the development of problem solving skills is strongly related to a crucial shift from an initial dependence on concrete examples or cases, on the way to a final reliance on schematic knowledge.

3 The interactive knowledge management framework

The aim of the interactive knowledge management framework is to provide an environment where design knowledge can be effectively managed and applied. During the design problem solving process, new knowledge may also be created. The services offered from the framework include: design knowledge creation, capturing, maintenance and application through the use of both precedent-driven and schema-driven visual analogy. Knowledge plays a central role within the framework. There are two types of knowledge, i.e. explicit and tacit knowledge. Explicit knowledge can be described in tangible forms and often in clearly understood steps. For our interest, this is normally applied to the prescription-based design practice. Tacit knowledge is often in intangible and not easily understood forms, and cannot be easily associated with computing logic. It is often related to performance-based design practice. More details of handling explicit and tacit knowledge can be found in Dai et al. (2003). The support for managing the above different types of knowledge aims to meet a variety of design objectives and to tailor the computing-based design practice according to a designer's skills and background. In order to effectively process the design knowledge, the framework has different inference strategies in place, i.e. goal directed inference and event driven inference. Event driven strategies are behind precedent-driven analogy process, while goal directed inference is often applied in the schema-driven analogy process. All these inference strategies are implemented in modular forms so that there can be different combinations to deal with the tasks at hand. Once tacit and explicit design knowledge is well understood and managed, the framework is expected to be serving designers for improved productivity and quality in design.

3.1 Computing services available to designers

In the schema-driven analogy approach (generally related to routine problem solving), design problems can be faced with known type of solutions offered by the computerized service. Design solutions are organized and classified according to the major categories of visual knowledge, embraced in an instance derived from a prototype (e.g. Gero, 1990; Clark and Pause, 1996). Since what matters is the solution principle itself as part of the analogical process, one or more prototype instances that contain similar abstract solution principles can be considered while establishing an analogy with the problem at hand. For example, the way that the two facades meet in one corner can lead to prototypical instances (See figure 1). In the schema-driven paradigm, visual design sources (design prototypes) are already in a high level of abstraction. Therefore, a high level of expertise is needed to use a design principle from a prototype and to establish analogy with the problem. Since expert designers generally know what kind of knowledge is needed to tackle the design problem, their design actions are normally directed by those prototypes that may have applied a useful design principle.

Figure 1 about here

In the precedent-driven analogy approach, a design problem is seen as being similar to an instance of a prior problem or situation, and can be solved in allusion to such similarities (generally related to non-routine problem solving). In this approach, the computerized service can endow the designer with one or more design instances or design precedents (prior designs generally produced by master designers) containing different solution principles that can help solve the problem at hand (e.g. Kolodner, 1990; Clark and Pause, 1996.) Rather than considering a particular design principle, detailed design precedents are considered as starting points of the design process, from which different principles can be retrieved to establish an analogy. For example, the 'Wolfsburg Cultural Center' building designed by architect Alvar Aalto embraces a number of design principles such as 'hierarchy', 'linear circulation system', 'plan section relationships', etc., which can be considered as potential analogs (See figures 2 and 3). Since design cases are represented through higher level of detail, analogies are easier to be established with the problem at hand. This is the main reason for which novice designers usually prefer this cognitive approach. However, precedent-driven analogy is heavily concerned with making additional abstraction to the visual sources. In contrast to the schema-based analogical paradigm, where designers' actions are normally directed by those prototypes that may contain a specific design principle, in the precedent-driven paradigm designers are unaware of what design principles may lead to a successful design solution. Therefore, a selected design precedent can lead to new design cases sharing a similar principle. Alternatively, a design principle can guide the designer to further design cases containing new principles. Eventually one of those principles may help to establish analogy with the design problem.

Figures 2 and 3 about here

3.2 Computing supported interactive scenarios

In this section we present a computing framework that automates the key design processes proposed earlier. A technical diagram of the framework is described in figure 4. The key aspects that drive and support the computing services are the design resources that include: a design knowledge base consisting in Tacit and Explicit Knowledge Source (KS), and a Visual Analogy Data Sources (VADS). The VADS consists of an accumulated set of design objects such as different kinds of design representations.

Figure 4 about here

The computing framework supports both schema-driven and precedent-driven design practices through the core functions of the knowledge management module. The module has the following capabilities:

Tasks analysis and classification – verifications of designers' intentions and objectives;
Invocation of plan generator for solution strategy – selection of suitable knowledge according to tasks features;
Invocation of plan executor – application of the design knowledge from the plan.

3.3 Management of explicit and tacit knowledge at computing levels

Management of explicit knowledge can be accomplished through the use of existing facilities (Dai, 1996). For handling non-computable knowledge, multimedia technologies will play a major role (Dai et al, 2003). The invocation of specific data set depends on the tasks and knowledge involved. Invocation of visual displays is driven by computable design knowledge (either tacit or explicit). The screen display consists of digitized design knowledge information that provides principle guidance, and various visual data (e.g. design images) to assist intuitive design activities. The visual displays are always centered on the current state of design, and are changeable from state to state. Therefore visual displays are often relevant to particular aspects (e.g. objectives) of the design problem. The framework always has the capacity of fine-tuning the gap between the current design state and the desired state on the screen. The usefulness of the retrieved visual data for designers will depend on the type and level of computable design knowledge that has been captured. Based on a series of interactive cycles with the design framework, knowledge concerning explicit and tacit aspects of the design practice (e.g. within-domain visual sources such as design precedents, and abstract analogical principles) was captured into modular knowledge component (which stores business logic in industry context) to support design requirements during the analogical process.

4 Discussion and conclusions

In this paper, we investigate the issues of incorporating the processes of design science into an interactive design framework through knowledge management practice. The design processes (especially those standardized frequently used ones) can be mapped into related computing rules to be processed within the framework. The framework supports design problem solving through the use of visual analogy. According to the research performed in a non-computing environment, it was found that designers are not always inclined to spontaneously apply visual analogy. The retrieval, transference and application of relevant knowledge from analogical sources are largely dependent on the way the knowledge is represented, and on the level of expertise of the designer.

In order to help both novice and expert designers effectively apply the available knowledge, an interactive design framework supported by knowledge management techniques has been proposed. Designers in such situations are knowledge workers who apply professional knowledge in their jobs, and at the same time users of the framework. The framework provides a work environment where the design knowledge can be effectively and innovatively utilized on associated design problems. To support effective interactions with designers, knowledge module (a plug-and-run component of the framework) is offered to the designers where knowledge can be managed (e.g. through various maintenance activities) and applied according to design objectives.

A number of services are proposed through a computerized framework to support schema-driven and precedent-driven analogical approaches in design. Computerized services dealing with the precedent-driven paradigm are considered to have the potential to support non-routine problem solving, as well as processes carried out by novice designers. The framework supports both schema-driven and precedent-driven design practices. The computing framework used in this research is based on an enterprise applications integration project supporting advanced user centric applications at Victoria University, http://www.staff.vu.edu.au/PHOENIX/phoenix/. From computing aspects, this research focuses on tailoring computing services to meet design requirements. The research has a practical impact in improving productivity and design quality for designers.

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Figure Captions

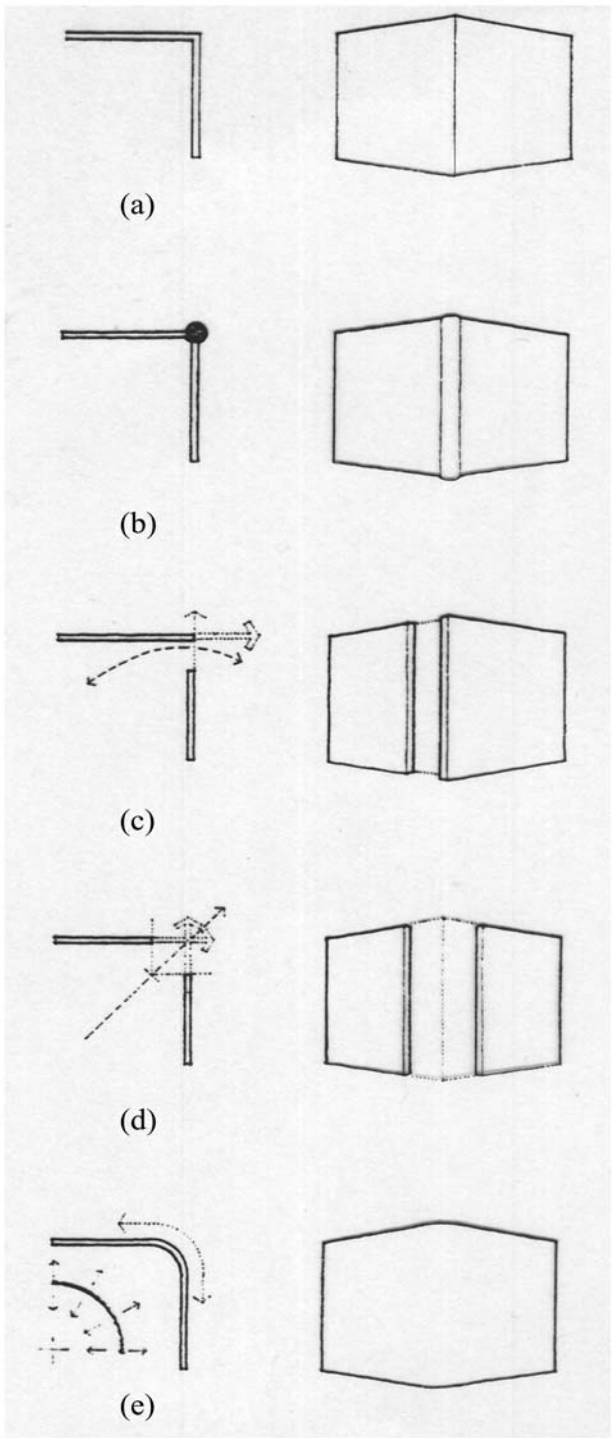

Figure 1: Prototypical solution principles of corners (a) two facades meeting by an edge; (b) two facades meeting by a third element; (c) one façade bypassing the other, while an opening is located in one side of the corner; (d) two facades meeting by a volume of space, while an opening is located in the two sides of the corner; (e) two facades meeting by a rounded off corner.

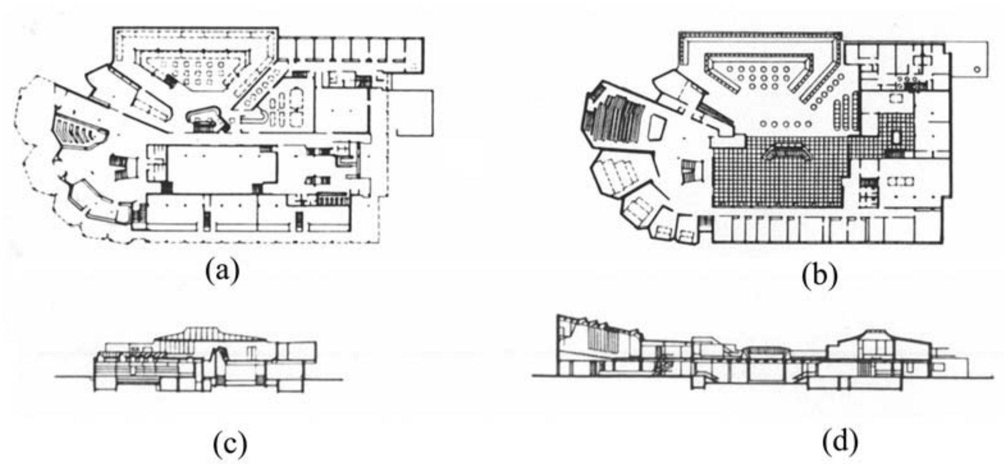

Figure 2: Cultural Center Building by Arch. Alvar Aalto, Wolfburg, Germany, 1962. (a) lower floor plan; (b) upper floor plan; (c) transversal section; (d) longitudinal section.

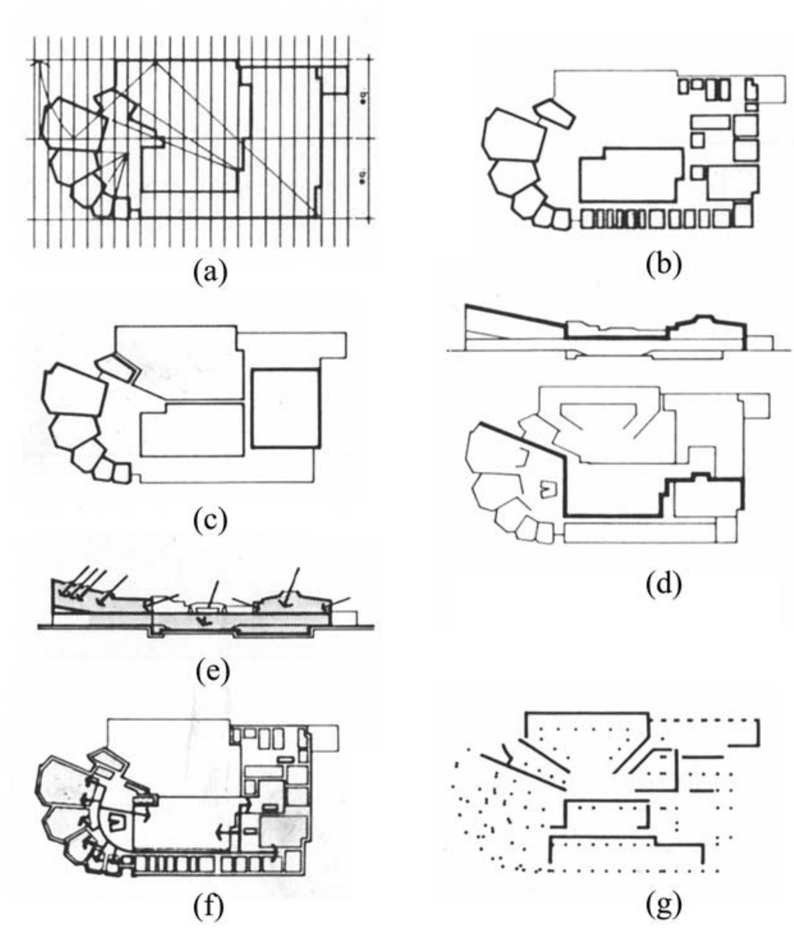

Figure 3: Design principles from the Cultural Center Building by Arch. Alvar Aalto, Wolfsburg, Germany, 1962. (a) relationship between polar and orthogonal grids;

(b) relationship between repetitive and unique elements; (c) hierarchy; (d) relationship between plan and section; (e) lightning system - skylight; (f) circulation system- linear; (g) structural system - independence between columns and walls.

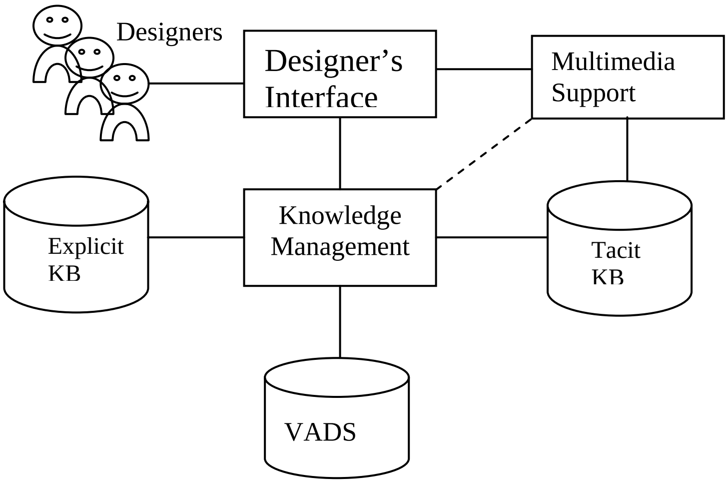

Figure 4: Interactive knowledge management framework supporting design