Design Case Bases: Graphic Knowledge Bases for the Design Workspace

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Cases in the domain of architecture and engineering are commonly stored and presented as graphical representations in the form of drawings. The way creative designers fit and adapt graphical representations through drawing and re-drawing is still one of the least understood phenomena in design. Modeling such processes 'ears to be a key to graphic knowledge base integration in CAAD environments. This *paper reports on a new approach to modeling design adaptation in a graphical environment. This approach is based upon a theory of creativity, the Representation -Re-representation Hypothesis which is here employed in the formalization of design adaptation. A 'multi-layer re-representational model' which assists in the adaptation of design drawings is developed and presented. The model is based on the transformation of chunks of knowledge in design cases into explicit re-representational structures which can support creative design in a graphic environment. This model is utilized in our current work in development of a prototype graphical case-based CAAD system.*

Keywords: adaptation, case-based CAAD, case-based design, creativity, graphical case-bases, representation, re-representation.

1 Introduction: Graphical knowledge bases in CAAD workspaces

Capturing, representing and exploiting experiential knowledge of prior significant designs is a long-standing focus in design computation. As part of this research effort, the concept of a 'design case base' in the domain of architecture and engineering is beginning to emerge as a computational resource for design in CAAD systems. Work in the area of casebased design has already accomplished much towards the development of case-based design systems [1] [2]. In these systems, cases are commonly stored and presented as graphical representations in the form of drawings and textural material. However, while providing new ideas, concepts and graphical images, these systems generally do not integrate the active use of the case-base in designing.

In order to accomplish such an integration between a CAAD environment and a graphical design case-base, we require a theoretical basis related to the employment of graphical case representations in the design process. From a research point of view, work in the sub-area of case adaptation within CBR is beginning to provide such a basis. The work on design case adaptation which is presented in this paper reports on a new approach to modeling design adaptation in a graphical environment. This approach is based upon empirical research in the modification of graphical design representations during design, one of the central processes of design. The paper reports on the theoretical foundations, the empirical research, and work on the development of an integrated, casesupported, design environment.

The research has employed the psychological theory of creativity through the re-representation of graphical images as a theoretical underpinning. The introduction of the theory has provided us with a powerful tool to crystallize research thinking on case-based adaptation of graphical representations. This has been a central problem in formalizing and modeling adaptation processes in design. The way designers fit and adapt graphical representations through drawing and re-drawing is still one of the least understood phenomena in design. Modeling such processes appears to be a key to graphic knowledge base integration in CAAD environments.

In the following sections, we develop the relevance and utility of the rerepresentation hypothesis [3] in creativity studies to the formalization of design ac[aptation. As a result of application of this new theoretical foundation, we develop an approach to graphical case-based design adaptation. We present a multi-layer representational model which assists in the adaptation of design drawings. This model is based on the transformation of the knowledge in design chunks in cases into explicit representational structures which can support designers working in a graphic environment. This model is utilized in our current work in development of a graphical design workspace in a prototype case-based CAAD system.

2 Design adaptation as a re-representation process

2.1 Concept expansion in re-representation and transformation

One way to approach the problem of the use of cases in design is to model conceptual exploration in the modification of an existing graphic case. Adaptive reasoning in design can be explicated through research on creative reasoning in the representation and re-representation of drawings. In our modeling of the adaption of graphical representations we employ the Representation Re-Representation Hypothesis (RRH) [3] which is a psychological theory of creativity. We a pl it t mod ling the processes of images in design. RRH theory is a cognitive approach that explains creativity as an act of conceptual exploration through re-representation. In addition to supporting an adaptation model of design, it is also relevant to formal models of design creativit , since it deals directly with issues of representation and re-representation as a creative skill. RRH theory has demonstrated that one way in which human beings explore new conceptual spaces is by developing explicit mental representation of knowledge they have already possessed in an implicit form. The capability to transform knowledge into representational structures underlies the ability to make novel modifications and Enges in those representations. The ability to transform knowledge to representational structure enables modification and change, or in our terms, the adaptation of the graphical representations. The establishment of the right representation is considered to be a creative act and invention follows as the result of a degree of behavioral mastery of the process [4].

Another body of ideas which underlies the exploitation of re-representational theory in modeling design adaptation is termed, concept exploration and expansion [5] In practicing design skilled creative designers develop cognitive abilities which enable them to exploit prior knowledge in new conceptual directions. One way to approach the modeling of re-representation is to formalize how new conceptual spaces are developed during design. A conceptual space can be mapped, explored, and can be fundamentally transformed. The result--of-such transformations is the appearance of a new space of possibilities. According to Boden, creativity could be explained by such an approach showing how conceptual spaces can be accessed and transformed in novel ways.

Researchers in RRH theory, have introduced relevant results from psychological research with young children in a graphical domain [3]. Transformations of graphic representations and tweaking of conceptual spaces are familiar phenomena in the drawing of children. By asking young children to draw innovative figures such as a 'house that does not exist' or a 'funny man' researchers discovered that children have an internally propensity to re-represent implicit, domain specific procedural knowledge, e.g., drawing of a house, as explicit, abstract, declarative, knowledge, e.g. the schema of a house. Initial representations which are procedural e .g., house generation procedure, are not flexible for manipulations until they are turned into explicit declarative re-representational form. Knowledge is not just a matter of what is done, but also the manner it is represented and represented. Similarly, we can assume that in design, exploration through transformations on existing representations is guided by high-level conceptual structures. It is the cognitive ability to map this conceptual structure into a graphic representation that underlies the creative generation of variations through conceptual expansion of the specific representational structure. There is direct relevance of these findings to adaptation in design. If we are to model design as an adaptation process of re-representation, we require the ability to model the case through its declarative abstractions. Therefor, we assume that the process of transforming graphical case representations can be supported in a graphical case base by the representation of the case according to the declarative knowledge of domain-specific representational structures. An example would be the abstract representation structure of the functional, as well as the formal, contents of a particular design in a way that concept exploration and expansion can be enabled by rerepresentational operations on that structure.

2.2 Re-representation and transformation in design as a creative act

It is been further suggested that the selection of an underlying representational structure which guides a re-representation in a specific domain can constitute an "epistemic advance of a distinctly creative type [5]. That is, the recognition of the conceptual space of the particular representational structure is a creative act, which underlies the ability to expand conceptual spaces.

It has also been found that representational structures tend to be domain specific and task specific [5]. For example, the system of orthographic representations which support architectural design, and the underlying representational structures which support the generation of plans, or elevations, as a design task. These graphic representational structures support reasoning processes within the task domain. A formulation of the task structure is also required in order to support adaptive reasoning. This is particularly relevant in design domains, since the graphical representation and its re-representation is an essential medium for exploration and innovation. The function of sketching and drawing during design has been recognized as an externalized representational medium which enables designers to `reason` with their representations. Referring back to Boden`s conclusions regarding the exploration and expansion of conceptual spaces in design, it is the identification of the underlying structure of a task-specific design representation (for example, plan study, or elevation study) which is the epistemic advance, or the creative step. Further extrapolating these findings to our own research, a graphic case base should provide these underlying structures within the graphic representation of the case, if it is to support the adaptive re-use of the image.

Emergent Form [6][7] is a research field which is also relevant to the recognition of representational structure and its re-representation. In contrast to work on emergent form, we are interested in the recognition of task-specific representational structures which can support the adaptive re-representation of case representations. Case knowledge, in this sense, is viewed as the domain-specific knowledge structures which support the rerepresentation of the graphic case. In the following section we apply the theory of concept exploration and re-representation to case-based design and develop a theoretical approach to design adaptation.

3 Concept expansion within the framework of CBD

The general model of case-based reasoning evolved through structuring the several stages of reasoning among them, retrieval, problem definition, and adaptation [8]. Within CBD, we can classify current approaches to concept expansion according to the stages in which the expansion of conceptual spaces occurs. Current research work on retrieval is focused on the selection of cases, case memory organization, and related issues of indexing and retrieval. Most of these systems function as design-aid case-library systems and do not address adaptation, leaving it for the human designer [1][2]. In other CBD systems, the expansion of conceptual spaces occurs during problem-statement [8]. Such systems employ case knowledge in order to achieve an expansion of the problem definition. Finally, other CBD systems emphasize the expansion of conceptual spaces during adaptation. This is still the least well-developed stage of CBD which has currently become a major theoretical and research problem in case-based reasoning in design.

3.1 Concept expansion in Case-Based Design and design adaptation

CBD offers a model through which ideas of concept expansion can be applied and implemented. How has CBR looked at adaptation until now? Current systems apply strategies of problem solving such as constraint satisfaction to adaptation [9] or use modifications which are based on procedures such as typology, dimensional adaptation etc. [10], or view the adaptation process as a process of replay [11]. In general, this work has been able to deal only with routine design [10]. We propose that the problem of adaptation in CBD can be formulated as a problem of re-representation. This differs significantly from current approaches. We will demonstrate that formulating adaptation as a rerepresentational process has particular meaning which can enhance the implementation of adaptation knowledge as a form of design support in a graphical case base. Adaptation knowledge in our approach to graphical case bases is implemented within the graphical representational structures underlying the case representation.

The re-representation approach within the framework of structured case representations supporting adaptation will enable exploration of variations and manipulations that would not be possible to produce with routine compiled procedures. Furthermore, the theory of RRH provides new dimensions to current research work which may help us to model creative adaptation in case-based systems. In applying this theory to adaptation in CBD, it is suggested that in creative design, concept exploration and expansion may also be modeled as a process of re-representing the knowledge structures of existing cases with new structures.

The manipulation of graphic representations in design is also a problem of preservation and the exploitation of internal consistency of a holistic design, we propose that the subject of re-representation in an adaptation model in CBD is a key to the understanding of design as well as to the realization of potential CBD systems.

4 A formal model of re-representation in case adaptation

In the following sections an approach to modeling graphic case transformation through re-representation in case-based design is presented. The computational implementation of this model is discussed, and the implications of this work for the development of graphic case-based CAD design environments is considered. The proposed approach to adaptation is based upon the employment of re-representation as a medium of design case modifications. Beyond routine design, adaptation is also viewed here as a creative act in which the exploration of new conceptual spaces is effectuated through the construction of new re-representational structures. Modeling the mechanisms for the expansion of conceptual space within the framework of RRH and the achievement of unique designs through adaptive transformations has been a main focus of the research. That is, the proposed model is considered to be valid both for routine as well as innovative and creative design adaptation.

In order to develop a computer-based re-representational approach to adaptation, we have constructed the adaptation model based upon an empirical study of adaptive design. The study is described in detail elsewhere [1]. The objective of the experiment was to study the way designers manipulate graphical symbols in design drawings, and to model the knowledge needed to enable these processes computationally. The research findings helped to define the central issues in modeling graphical adaptation in design, to develop a re-representational adaptation model, and to provide guidelines for the implementation of the model in a CAD environment. The empirical study is briefly described in the following section.

4.1 Empirical study

The experiment was conducted to model design adaptation in the architectural domain which is strongly dominated by graphical representation. Adaptation was defined as the task of transforming a given design to meet new constraints. The chosen task domain was spatial configuration in design. The main goal of the experiment was to observe and record through self-protocols how designers actually manipulate given design case representations in re-representational processes of adaptation. The aim was to provide an account of the kind of representations employed by human designers, analyze and categorize the kinds of representational modifications, the strategies and operations employed and the way they interact in an adaptation process, and, finally, to postulate the structures of representation which make graphic re-representation possible. That is, each of the designers in the experiment formulated those conceptual structures in the representation which, for him, enabled the making of changes in a graphic representation. Thus the representational structures that were employed by the human designers were identified and procedural manipulations were effectuated within those domain specific re-representational structures. Subjects were asked to construct explicit representational structures, and to record each of their graphical manipulations and rationale. At a later stage, the group of participants contributed in the development of a joint model.

Human designers were found to be able to extract various abstracted explicit representations of the existing design based on their own domain knowledge. For example, these abstractions included organizational principles, morphological principles, functional relationships, etc. The subjects were also able to externalize and categorize their graphic manipulations conceptually despite the fact that architectural drawings tend not to support such decomposition. Thirdly, they were able to re-represent implicit procedural domain specific knowledge as explicit, declarative abstract knowledge. This abstract knowledge may be considered an inter-related system of representational structures. This finding is most relevant to the problem of appropriate representations for design cases. According to our findings, each case must have multiple representations, if it is to support adaptation. Another of the most interesting observations was the contingent quality of the adaptation process. It was possible to observe how each new (modified) representation of the design case introduced new modification strategies and operations, and even new structuring concepts. Maintenance of the internal consistency of the system of abstractions was found to be a characteristic of designer's cognitive ability.

4.2 A formal model of re-representation of case adaptation

Based on our empirical study we have developed a re-representation adaptation model. This model consists of multiple stages: retrieval, multi-layering of representations, change, evaluation and modification (figure 1). The description of the multi-layered representation adaptation model is organized by the following stages and steps.

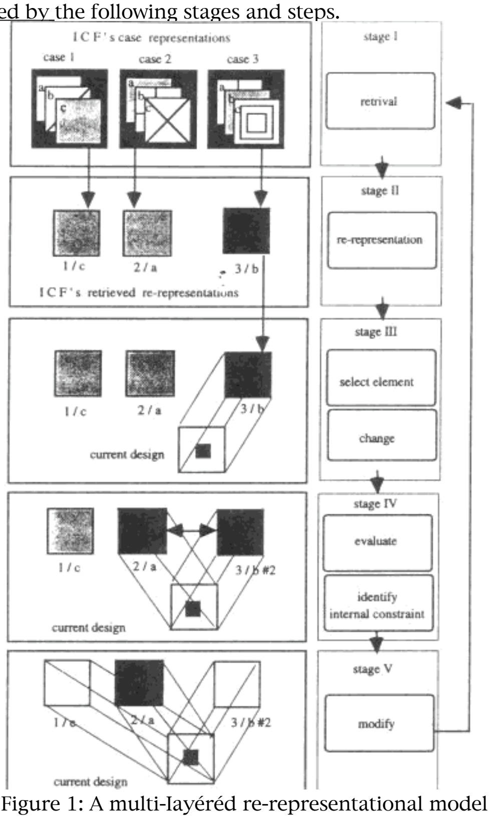

Figure 1: A multi-Iayéréd re-representational model of design adaptation

Stage I - Access of representational structures

Step 1 Retrieval of representational layers: representational structures which are relevant to the requirements of the current design are indexed and retrieved by the design requirements. They are retrieved as graphical layers are retrieved from a design casesystem.

The diagram illustrates possible representational structures of the case which may be retrieved (labeled a,b,c) . For example, a typological layer - functional organization, c is retrieved from case #1. A symmetry layer - underlying structure a' is retrieved from case #2. And a zoning layer - organization of plan elements and spaces, b in case #3, is retrieved. Each layer is a different abstraction of the detail of the case plan which is relevant to a particular design issue, and it is retrieved by the specific design issue of adaptation. For example, in a housing design, the typological layer may be relevant to functional design of a bedroom; the symmetry layer may be related to the expansion of size while maintaining planning principles; the zoning representation may be relevant to design requirement of through ventilation. Layer retrieval is a recurring process. It supports each step of re-representation. For each subsequent modification, layer retrieval is performed to extract the conceptual structure of the current state of the design representation. After retrieving the multi-layered representation system, each layer is separately mapped onto the representation of the current design.

Stage II - Re-representation

Step 2 - Selection of relevant design layer: As a result of the mapping, one layer is selected as a basis for re-representation. The representational layer is selected according to identification of an issue to be solved, for example, the symmetry layer.

Stage III - Change

Step 3- Select element: first element is selected for change

Step 4- Change: design element is changed to meet external constraints

Stage IV - Evaluation

Step 5 - Check consistency: consistency in current layer, and consistency between the various layers is checked. For example, in a typological layer, a failure may be caused because room is smaller than type of furniture. Step 6: identification of constraint type -identification of the type of constraint that causes a consistency failure. The nature of constraints affect the way the next modification step is performed. Modification is invoked in response to constraint violations in which the a value is rejected. Constraints may invoke a new representational layer as part of the adaptation process.

Stage V - Modification

Step 7- Activation of transformational methods and operations - the design can be modified employing any particular layer. Through an addition of layers the design can be re-represented. For each class of layer, (typological, topological, parametric, formal, etc.) there are strategies and operations which can produce modifications. A modified method is activated and design is modified. This process is succesively repeated.

This has been a description of a simple model of the adaptation of cases through the application of the concept of representational layers of a design case, and the concept of re-representation. Certain internal constraints of a re-representation may necessitate the accessing of a new layer in a new case. This is concept expansion in design. It is a "breaking out" of the constraints of the particular layer. Depending upon how the concept expansion occurs, when new case is retrieved, what concepts it contributes in the retrieved representations, etc. This models the explorative processes which are among the characteristics of design creativity.

5 Implementation of the model: computational issues

The objective of this section is to discuss possible implementational directions based upon the proposed model. In the following section, we review computational issues related to implementation.

5.1 *Accessing relevant representations*

The main goal in developing a computational system is to assist the human designer to access conceptual representations in graphic cases. To achieve this, there are two current directions. Research work in full atomization suggest the development of computer algorithms that model creative processes as re-representation. For example, a system may be considered creative, if it can re describe knowledge in terms of accessible structures derived from lower level structures of knowledge. [4]. Another approach explores how procedural knowledge may be reformulated as declarative knowledge, which then become a manipulated structure for a system. Knowledge which is implicit in a procedure of a system becomes available as an explicit data structure to the system and thus it is manipulable and flexible. Finally, a third approach explores the conceptual spaces of a structure that is defined by a set of rules of a generative system, and generates an indefinite number of structures lying within the relevant conceptual space [6].

A different direction suggests the development of computational support by placing the designer in a knowledge-rich environment. In such an approach, the user explores the conceptual space by browsing. This approach has recently been much exploited by the case-based design community [2]. In our work we employ a computational model of a memory structure of design precedents [1]. The memory structure and related indexing system enhances search and cross-contextual browsing for the exploration of new conceptual spaces. The model is composed of distinct chunks of knowledge called design stories. A formalism for the design story which represents the linkage between design issue, concept and form termed ICF'. These ICFs are structured in memory according to a semantic network. Each form description of this formalism in case-libraries is a unique representational layer.

5.2 *Mapping and re-representation*

In developing a computational system another main issue is the decomposition of drawings into different explicit abstract representational structures. Various approaches have begun to address the role of decomposition of drawings in case-based design systems and to demonstrate their utility in adaptation. There can be different kinds of generic abstractions (typological, topological, morphological, functional, etc.) underlying the holistic representation of drawings. Such abstractions include grammar-based descriptions, geometry-based descriptions of spatial aggregations, topological descriptions of spatial relations, [10].

Certain of these systems have a fixed priority relationship of design representations. However, such a predetermined set of representations does not allow for the insertion of new re-representational structures. A set of representational structures in a case library should be flexible and rich enough to support concept expansion through accessing new representations which suggest new types of modification and change. The computational issue is how to allow for a flexible multiple representational system in which new representations may interact with current representations.

5.3 *Adaptation and modification strategies*

How to implement adaptation and modification and how can it be implemented in a graphical case base. An underlying assumption in our work is that each representational structure contains its own generic modification strategies and methods. In a computational environment, in order to support adaptation processes there must be an integral relationship between types of manipulations, and their underlying decomposed representational structures. How can this knowledge be accessed while working on a current design? The issue raised is how to activate modifications strategies, methods and constraints which are associated with underlying generic representational structures when making a change. In such an approach, should representations activate their associated generic transformations and operations. Or can adaptation strategies be represented independent of cases, as specific agents? For example, would a particular strategy come with a specific case-representation? or is there a symmetry agent that might have reasoning capabilities? In the proposed system, a re-representation introduces a constraint which suggests a modification strategy.

5.4 *Evaluation*

We have identified three kinds of constraints relevant to evaluation: external given constraints, domain knowledge constraints and internal derived constraints. External constraints are imposed from the problem definition, and are explicitly represented in the problem statement. For example, constraints between context, such as site, and case [10]. Domain knowledge constraints are those types of implicit constraints which are based on domain knowledge. Their role is to keep the consistency of the internal representations. Internal constraints, are derived as a consequence of an earlier design manipulation. Internal constraints are usually propagated by other constraints. In addition to the modification of structures and components of designs, the ability to manipulate constraints can be regarded also as a significant kind of adaptation knowledge.

The ability to handle consistency by the modification of structures, components and constraints at any time that characterizes the dynamic nature of the process of adaptation. However, the manipulation of holistic structures which underly a design may effect the unique arrangement of components and their relations which results in internal constraints. If the design is to remain consistent, it should satisfy both external and internal constraints. Without a mechanism for checking the impact of internal constraints between layers, the internal consistency of a design undergoing adaptation (layer by layer) cannot be maintained. Facilitating evaluative procedures between layers by the exploration of internal implicit constraints between representations is a significant system behavior.

6 The GCB-CAD system

The GCB-System (graphical case-based system) is a prototype system which is currently under development. The system is intended to provide a graphic case knowledge resource for design. The objective of the system is to integrate design case knowledge within a CAD environment, (AutoCAD/AutoLisp development module). The goal of the system is to assist processes of design adaptation through the use of existing graphic cases which are stored in the system. The retrieval of relevant layers in cases is accomplished by the system, and search and retrieval continues as changes are made in the workspace. When making a change in a current design, the system identifies internal constraints and suggests possible modifications and new representational layers which may solve conflicts in innovative ways. Representational layers provide underlying structures which control generic modifications.

In the following section we describe the behavior of the system by demonstrating a typical design session illustrated by a simple example. Figure 2 and 3 illustrate typical workspace system screens of this example.

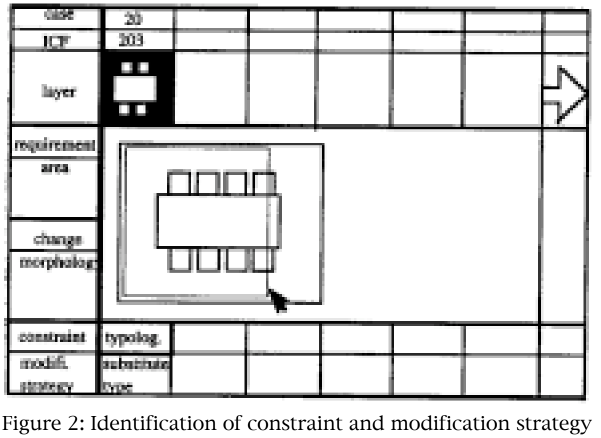

Figure 2: Identification of constraint and modification strategy

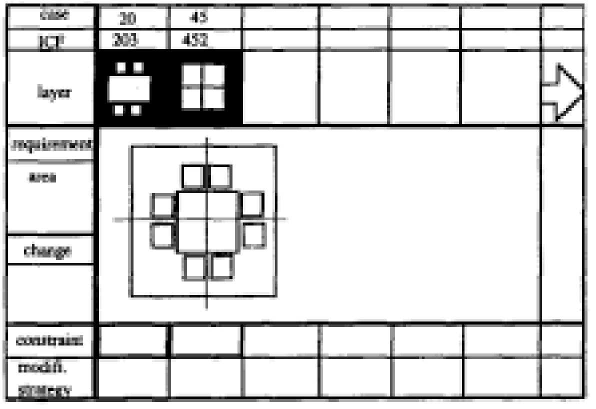

Figure 3: Re-representation of a symmetry layer is suggested by ICF

The user defines his requirements and activates the ICF box. ICF assists in the exploration of a relevant representational layers in cases according to design requirements and constraints. Through the ICF' box, an expanded version of PRECEDENT [1], representational layers of cases are retrieved. Retrieved representational layers are accessed and appear as icons on the upper box of the screen. An evaluation module is activated arid ensures the consistency between the different layers when change takes place in the workspace. The current constraint is identified and modification strategy is suggested. External constraints are checked consistently and are explicitly represented until solved. The Internal constraints are derived as a consequence of changes and modifications. They are identified and reported sequentially in the lower box of the screen. Each constraint suggests a modification strategy. The modification component provides generic strategies and operations as part of the representational layers. Given a constraint violation the following set of transformational methods and operations are activated:

(a) concept or typological substitution retrieve typological schema and refinement methods

(b) a change in relations retrieves topological operations such as delete and insert

(c) a change in value retrieve value-modifiers such as parametric operations, enlarge, reduce, etc.

Figure 2 illustrates a typological layer which is retrieved by its functional requirement. The icon of the layer appears on the upper box with its ICF and case numbers. The typological layer suggests arrangement of a rectangular sitting area. When the designer is making a morphological change to fit the design to a specific requirement of size and area, (dotted line on the screen of figure 2) internal typological constraints are identified and a modification strategy for substitution of a table and seating arrangement is suggested. These appear in the lower box of the screen. Recognizing the square morphology created by the designer, a new symmetry layer is suggested by the ICF module (see figure 3). The icon of the new layer appears on the upper box, and if the designer agrees, symmetry operations may be activated. In this way, new concepts are introduced to the designer as he develops and changes his design. The design is constantly evaluated and former layers and modifications for keeping consistency are proposed. When no more representational new representational layers are introduced and consistency is achieved among all layers, the design may be regarded as finalized.

7 Summary and conclusions

The objective of the work reported here has been to establish the theoretical foundation and implementational possibilities of integrating case knowledge actively in the workspace of a CAD system. Graphic design case libraries may be directly linked to a CAD environment. This can potentially lead to a powerful generation of Case-Based CAD stems, a development which we believe is the realization, in design, of the potential of BR . The purpose of such systems would be to provide design aid through, and in, the dynamic manipulation of explicitly structured graphic and textual representations of case designs. The re-use of prior designs, their storage, retrieval and modification for current design problems appears to be a concept which has obvious practical significance for the practice of architecture, as well as other design fields. While the idea of an electronic library of prior designs appears to be most attractive and accessible, it is the utilization of prior design knowledge in supporting current design activities within the actual design workspace which focuses on a set of challenging theoretical, research, and implementational issues.

The key to transcending the paradigm of the case-based design systems has been our approach to the representation of the knowledge of a prior design as decomposed into chunks, each of which is embedded in a design task related layer. If a design precedent connotes a prior design which has something to teach, this proposed structure of multiple layer representation responds directly to this functional definition of the design case.

Within the framework of these concepts, all design may be viewed as a complex process of adaptation of graphic representations. We consider our exploitation of the RRH theory to help in the modeling of design adaptation as among the important theoretical contributions of this work. The theory has helped to formulate design as a creative process of graphic representation and re-representation. Considering this as the medium within which concept exploration and expansion occurs, has provided a promising theoretical format for formal models of creativity in design.

There remain several problems to the complete implementation of GCB-CAAD systems. Domain knowledge, namely, form manipulation in graphical representation, which is highly significant' n architecture must be explored and understood. Developing a generic model of formal adaptation in the engineering and architectural design domains will improve our understanding of formal manipulation in design and will contribute to a sound theoretical basis for the developments of such systems. A future research goal is to achieve atomization of 'plan recognition and decomposition' as an extended project of our pattern recognition research, in order that there can be a seamless relationship between the case screens and the designer's graphic work space. Despite these limitations in our current pilot system, there appear to be many important areas of potential for the ideas which we have proposed. Among these, the important concept of layered and chunked knowledge in design cases. Furthermore, it provides the intriguing possibility to view design as a conceptual process, and to encode the relationships between concept and form. The implications of semantically rich graphic environments appear to be highly significant to the future of CAD systems.

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