ANALOGICAL REASONING AND CASE ADAPTATION IN ARCHITECTURAL DESIGN: COMPUTERS VS. HUMAN DESIGNERS

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This paper depicts the studies of the differences between human designers and computers in analogical reasoning and case adaptation. Four design experiments are undertaken to examine how designers conduct case-based design, apply dimensional and topological adaptation. The paper also examines the differences of case adaptation by novice and experienced designers, and between human judgement in case adaptation and the evaluation mechanism by providing similarity assessment. In conclusion, this study provides the comparative analysis from the above observation and implications on the development of case-based reasoning systems for designers.

Keywords: Case-based reasoning, analogical reasoning, case adaptation, computer-aided architectural design

1. Introduction

Design cases were considered as the design solution or condensed knowledge of previous design experience (Dave et. al. 1992, Rosenman et. al. 1991). Cases are described as design stories, scripts, frames, etc. (Leake 1996, Oxman 1994). Kolodner (1993) defined "a case, which generally represents a concrete situation, integrates a multitude of complex information in a very concrete way." Reasoning with cases involves case retrieval, adaptation, and justification.

Analogical reasoning consists of (1) transferring knowledge from past problem solving episodes to a new problem that shares significant features with corresponding past experience, and (2) applying the transferred knowledge to construct solutions to new problems (Chen 1991). In the analogical reasoning process, case adaptation is the fundamental task for solving the problem. Case-based reasoning (CBR) is a research paradigm that also uses the adaptation machanism for solving a new problem from past experience. Analogical reasoning can be case-based reasoning, but is more general in the problem-solving process.

Furthermore, in the case-based reasoning process as shown in *Figure 1*, dimensional, topological, and other factors may affect the adaptation of design solution (Maher 1995, Hua et. al. 1992). To make case adaptation useful, justification need to be evaluated through similarity assessment.

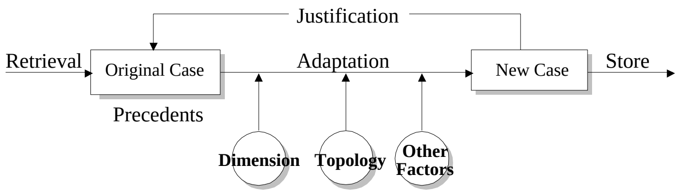

Figure 1. The Case-based Reasoning Process and Adaptation

In the following sections, ways of performing case-based design, making case adaptation, and a computational approach for case adaptation are explored.

2. Case-based Design

Design is a situated activity. The design process is considered as a learning process in which designers are learning from analogy by deduction and induction (Chen 1991). Two situtations may be occurred in adaptation as shown in *Figure 2*. In the situation A, one case may generate many new cases by analogical reasoning by deduction. In situation B, many cases may be retrieved and developed into to one new case by analogical reasoning by induction. In the adaptation process, dimensional or topological adaptation can be used.

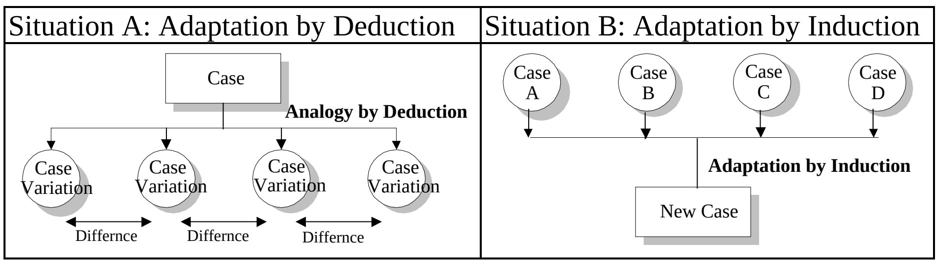

Figure 2. Two Situations of Case Adaptation

In the past three years, four case-related design experiments undertaken in NCKU are examined as shown in *Table 1*. These experiments provide the fundatation for the following discussion, i.e., the comparison between human designers and computers in case adaptation.

Table 1. Summary of Design Experiments

	Design Experiments	Contents	Objectives
1.	Elementary School Layout	Case-based Design	1.The role of case studies in design 2.Adaptation mechanism
2.	Color Museum	Case-based Design	Case adapation
3.	Urban Housing Design	Analogy by Deduction	Prototypes, generation, and variations
4.	Street Facade Renovation	Analogy by Induction	Transformation and substitution

2.1 The Role of Case Studies in Design

In the first experiment, the elementary school layout, the role of case studies play a critical factor for design. Cases are often used as "short-cut" for conceptualization and transformation of knowledge. For example, the spatial relationship of original design was reconfigured by adaptation from case studies as shown in *Figure 3*.

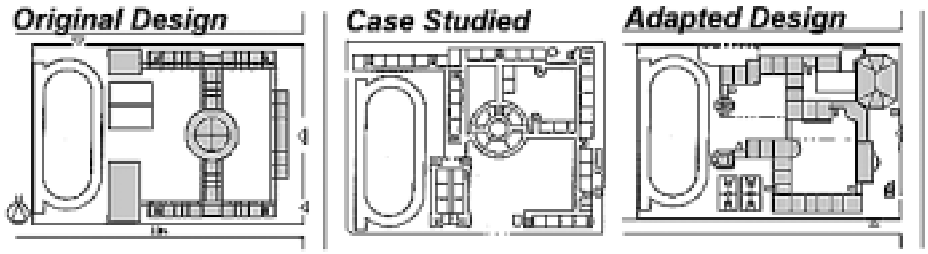

Figure 3. Case Adaptation in Elementary School Layout

2.2 The Use of Cases in Design

The second experiment, the color museum project, adopts case-based design approach which designers retrieve cases for initiating conceptual design. Cases selected are driven by the concept, the structure, and the form. Detailed descriptions can be found in (Chiu 1997). For example, Frank Gehry's Vitra Design Museum was chosen because of the form. While the site is different in size, new design was generated by abstraction of initial case, and dimensional and proportional change, followed by topological changes, as shown in *Figure 4*.

The above two experiment provides why and how cases can be used in design. More importantly, adaptation are applied by analogical reasoning. To make the demonstration explicit, we conduct two other design experiments based on two situations as mentioned. Each experiment is assigned to two testing groups. Group A consists of novice designers who have no previous design experience and Group B consists of experienced designers.

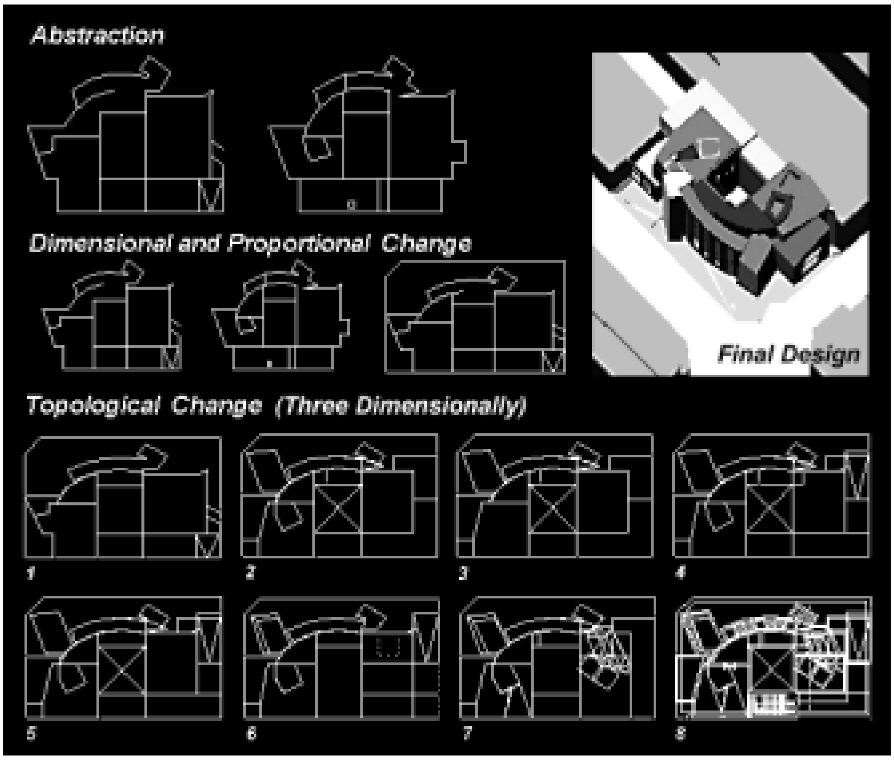

Figure 4. Case-based Design in Color Museum

Therefore, four steps are undertaken: (1) first examines how designers apply dimensional adaptation and topological adaptation; (2) continues the previous experiments and explores the differences of case adaptation by novice and experienced designers; and (3) finally examines the differences between human judgement in case adaptation and the evaluation mechanism by providing similarity assessment.

2.3 Dimensional and Topological Adaptation

The third design experiment of a housing project was given to Group A for exploring the dimensional and topological adaptation. Details are given in (Chiu 1996). Prototypes are derived from design knowledge and developed as a conceptual model (Gero 1991). Two prototypes of each housing unit are given to designers. Based on their preference and judgement, designers can only choose one prototype and try to fit into different sites of incremented width of 1.5 meter from 6 meter to 10.5 meter, as shown in *Figure 5*.

The design result indicates that one third of designers basically maintain the original structure, one third maintains the structure with minor changes of width, and one third change the structure greatly. Dimensional changes, including change of proportion and scales, work easily within the 1.5 meter incremental range, and topological changes are occurred beyond the range. Designers tend to give up further development beyond the 3 meter range. Only few designers are able to change dimension and topology simulateously. The most difficult task for designers is to maintain the characteristics of the prototype.

Case	6m	7.5m	9m	10.5m

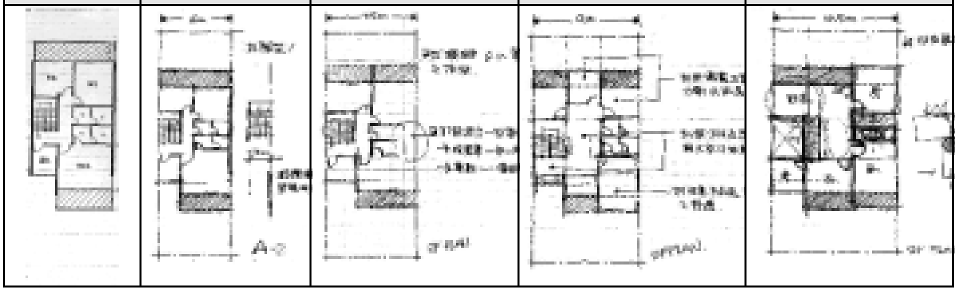

Figure 5. Changes of The A-Type Unit Plan in Various Widths

Parameter adjustment is a technique for interpolating values in a new solution based on those from an old one. The above adaptation process can be modeled as the parameter adjustment of the housing unit. The SAR (Stichting Architecten Research) theory was applied for defining the structure (Wiewel 1976). The supports (the structure and the partitions) and the infills (space units) are shown in Figure 6. As accepted and feasible solutions, most of the developed schemes by designers can be simulated by parameter adjustment. Therefore, new cases can be developed by dimemsional and topological adaptation. However, the limitation of dimensional and topological adaptation is clear as shown in the experiment.

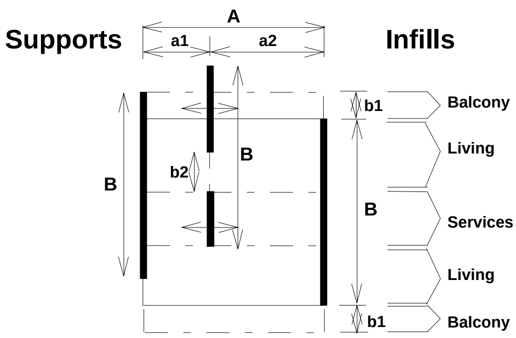

Figure 6. Parameter Adjustment of A Housing Unit

2.4 Substitution and Transformation

The fourth experiment is also given to Group A for exploring the substitution and transformation in case adaptation. Reinstantiation is used to instantiate an old solution with new objects for suggesting substitutions. Transformation is a process of adapting an old solution for a new problem by structurally deleting, inserting, substituting, or adjusting parts of the solution.

Environmental changes in Taiwan are acclerated because of economic development. The focus on contextual influence was given to traditional row houses which are rapidly demolished and needed to be infilled. *Figure 7* demonstrates the facade of the Di-Hwa Street in Taipei. *Figure 8* illustrates a new problem and a possible new case based on the analytic structure.

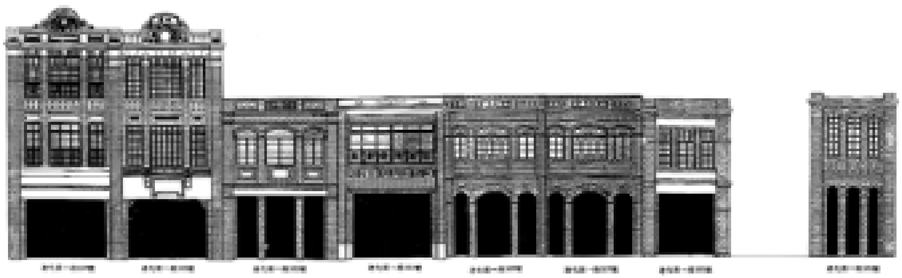

Figure 7. The Original Facade of the Di-Hwa Street in Taipei

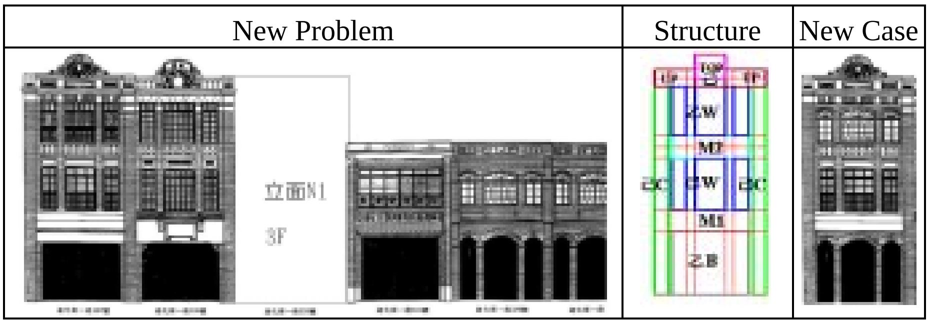

Figure 8. The New Problem and New Case in the Di-Hwa Street

Furthermore, various situations which are mixed with two-story and three-story houses are simulated. Designers are requested to infill the empty block in each situation based on existing conditions. Case retrieval and selection is critical to adaptation. *Figure 9* demonstrates the adapation of facade C derived from neighbour A and B, i.e. components of A and B are retrieved. In the case of substitution, facade A is selected, partial substitution is implemented by using compents of facade B. In the case of transformation, a two-story building can be tranformed into three-story building by inserting the middle section.

Reintantiation of an old solution may be used when the structure of the solution to the problem and an old case are the same, but roles in the problem solution may be filled differently than roles in the old case. Local reinstantiation may be applied when only parts of an old soultion need to be reinstantiated. As shown in *Figure 9*, the supports of the street facade is connected to certain contexts. Based on the present of certain features, each building facade as precedent can be organized and retrieved. Coyne and Yokozawa (1992) indicate that a connectionist approach can be used for automating the classification and designing with precedents.

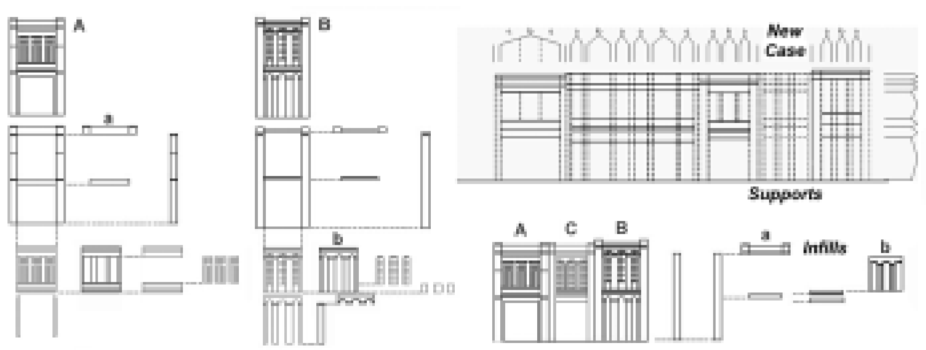

Figure 9. Case Adaptation by Substitution and Transformation

The result of 17 designers from Group A shows that most of designers conduct analogical reasoning based on the direct neighbours (right and left sides) of the empty blocks. Few designers are based on all facades in the street. This phenomena can consider that designers tend to use partial substitution of the all facade. Meanwhile, all designers are based on supports and infills to construct the basic frame, while few rules are implemented and constraints are imposed.

3. Case Adaptation by Novice vs. Experienced Designers

3.1 Preliminary Comparison

The above design experiments were also given to the second group of designers, i.e., experienced designers. In the third experiments, the results show that experienced designers are more capable to resolve topological adaptation, and topological adjustment generally follows dimensional changes. The reasoning time of experienced designers is usually shorter than the novice designers. Meanwhile, novice designers occassionally misuse cases. Generally, in Group A, the ability of topological adaptation is weaker than the dimensional adaptation. On the other hand, in Group B, experienced designers are more capable to conduct dimensional and topological adaptation simultaneously.

In the fourth experiements, experienced designers typically have individual intentions and consideration based on semantic relations. More importantly, attitudes toward historical and environmental context vary, and could be harmony, neutral, or constrast to the existing situations. *Figure 10* demonstrates two examples by experienced designers in the street facade experiment.

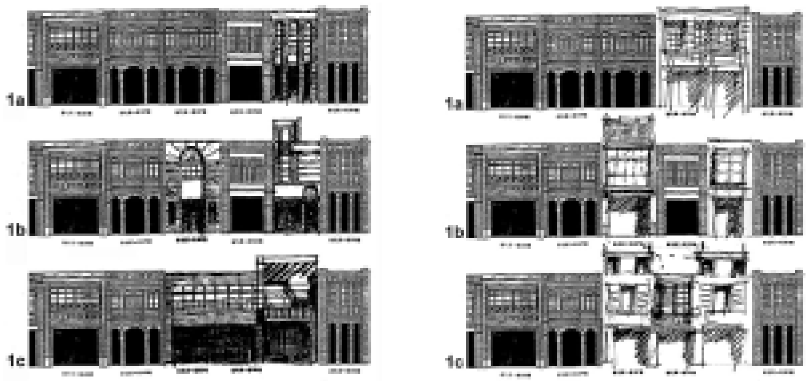

Figure 10. Two Street Facades Designed by Two Experienced Designers

Can CBR systems provide innovative or creative design become an interesting issue? Innovative design may arise during routine design when a new requirement is introduced that takes the design away from routine, requires new components and techniques. Since some design knowledge remains constant, designers do not have to re-develop a new design schema, parts of the original building are transformed while some new parts are built. Often designers modify other architects' schemata because their design requirements are almost identical.

3.2 Case Similarity Assessment

Furthermore, similarity is addressed by most designers in the design experiments. Therefore, similarity assessment is a major concern in adaptation. Apparently, the selected street facade is built in the same period. The building styles can be said as similar or uniform. Designers tend to retrieve adjacent cases for developing the new cases. It would be interested to examine in the semi-uniform or hetrogeneuous situation of the street facade. However, no designers want the new cases to be identical to the old ones. Variation are generated in the substitution and transformation process. When rules or contraints are applied, the level of variation can be manipulated.

Case-based research assumes that cases whose solutions are most similar to a new solution will most likely be useful in designing it (Dzeng 1995). Generally, a new case is developed and retrieved by key features (the structure or components). The similarity assessment by human judgement may be inconsistent due to the complexity of contexts and designers' intentions.

Kolodner (1993) argued that some classes of matches, "easy-adapted" matches, should be referred over "hard-to-adapted" matches during retrieval. This study uses nearest neighbour retrieval in case retrieval instead of using the index-based method which have been studied in most CBR research. Typically, the query case (Q) and a case (C) in the case-base S(Q,C) is the weighted sum of similiarity of each attribute: ΣWi * s(Qi,Ci) / SWi, where Wi is the weight of the attribute, s(Qi,Ci) is a similarity between the value of the i-th attribute of Q and C. Traditional implementations would compute the similarity value for all cases, and sort cases based on their similarity. However, this is a time consuming task as computing time increase linearly as the number of cases in the case-base and as the number defined attributes.

If the user can specify and assign similarity value, then the differences between human judgement in case adaptation and the evaluation mechanism by computers is quite narrow. Therefore, for each assessment, a similarity value will be assigned using similarity between values of attributes specified by the user and values of case created in the previous stage. Calculation is similar to weighted nearest neighbour, except that not all attributes are involved. Then computation time will be saved. While design computation will be beneficial from converting heuristics into mechanism, problem-solving requires the transformation of non-routine problems into routine problems (Maher et. al. 1995).

4. A Computational Approach

Learning from the findings of design experiments, we have implemented a case match system as shown in *Figure 11* for examining case adaptation mechanism.

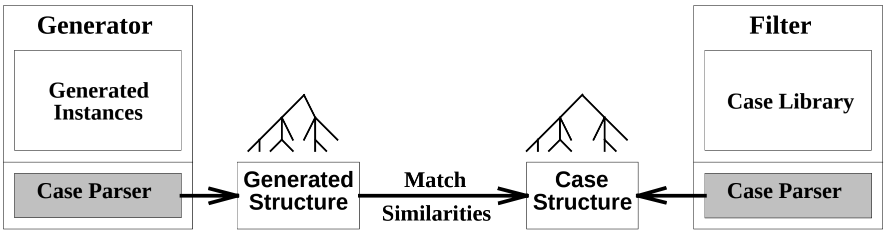

Figure 11. A Case Match System

4.1 Adaptation Algorithms

In most situations, solutions from retrieved cases needed to be adapted so they can solve a new problem. Generally, case adaptations are considered as a constraint satisfaction problem in design computation. Kolodner's (1993) case-based reasoning textbook describes ten methods by which adaptation can be done. Among these methods, adaptation algorithms fall into four categories: (1) substitution, (2) transformation, (3) special-purpose adaptation and repair, and (4) derivational replay.

More than one of these algorithms may be used in the CBR system. Different systems implement their algorithms of each category differently. This paper focuses the first two categories, i.e., substitution and transformation methods. Substitution methods substitute values appropriate for the new sitution for values in the old solution. Reinstantiation and parameter adjustment are frequently used by CBR systems. Transformation methods are used to transform an old solution into one that work in a new situation.

4.2 Search Mechanism

The elementary school layout project is used to do experiments on case adaptation. The SAR design method is also used to define problem spaces that can be systematically enumerated using various search strategies. In the design process using SAR method, a layout problem is structured into a system of supports, which divides the layout site into zones and sectors by analyzing environmental factors; and infills, which are the components to be placed in the layout. Various layout alternatives can be systematically generated and tested according to the relationships between infills and supports.

The system of supports and infills as shown in *Figure 12* defines a problem space that can be enumerated in various ways. Each way of enumeration imposes a structure to the problem space, on which the positions and relations of all derived layout alternatives can be defined. Based on the notion of positions and relations defined in this manner, major issues in CBR such as case similarity and adaptation can be formally discussed and experimented. *Figure 13* demonstrates alternatives generated by the forward search process.

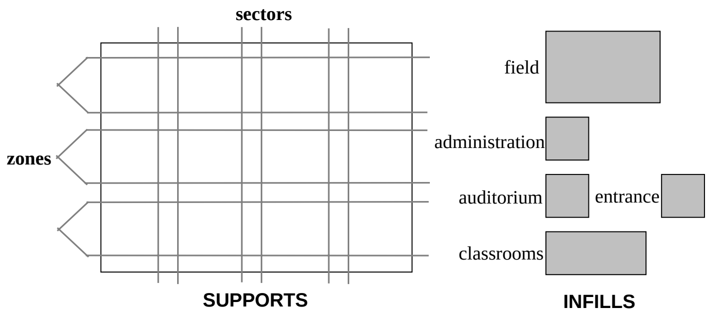

Figure 12. A System of Supports and Infills.

Two types of enumerative processes are used to study CBR in the domain of school layout planning using SAR design method. The two types of enumerative processes can be distinguished as first, generation by insertion and second, generation by replacement. In the process of generation by insertion, a sequential order is introduced to the layout components so that the entire problem space can be enumerated by traversing all possible insertion of layout components following that order. Each different order of layout components defines a lattice structure upon the problem space. The similarity of two different layouts can be measured by calculating the distance of the shortest path through their closest common ancestor in the lattice. Case adaptation can be executed by systematically examining layout variations that are most similar to the original case. In the process of generation by replacement, a layout alternative can be transformed by insertion, deletion or replacement of layout components. The least operations that are required to transform one layout to another can be used as a measurement to the distance between cases. Case adaptation is then carried out by searching through the closest neighbors of the original case. Based on these two types of operations, variations of search methods can be derived.

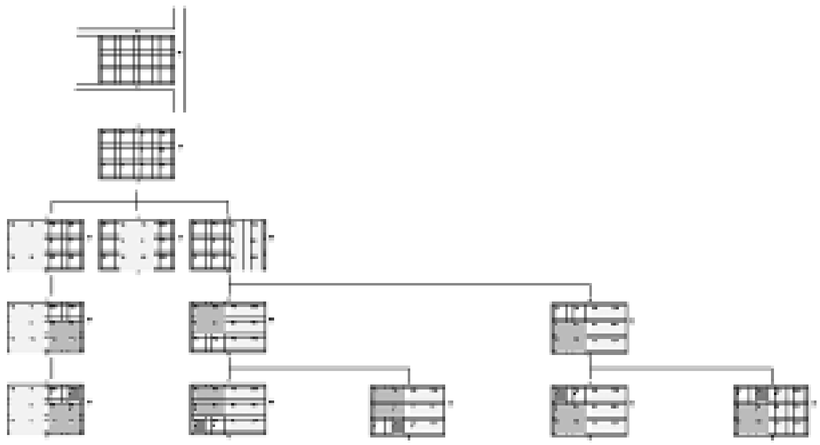

Figure 13. Forward Search of School Layout

The diagrams in *Figure 14* illustrate three methods of case adaptation. The first method, is basically a process of back-tracking, according to an order imposed to the layout components. The component that is most critical to the solving of the new problem is reallocated first, and the least critical component is reallocated the latest in the search hierarchy. The second method does not distinguish different component in separated levels of search hierarchy, although weights may be imposed to calculate case similarity. The third method is a combination of the first and the second methods, it switches strategies according to the result of evaluations. Upon the problems defined for our experiments, all of the three methods are capable of deriving layout alternatives that solve the given layout problem if solutions do exist.

As shown in *Figure 15*, generation of school layout by the forward search and backward search method increases the alternatives quickly. Detailed descriptions can be found in (Hsieh 1997). While alternatives generated from the system facilitate the design development, further comparison of these methods of case adaptation are yet to be investigated.

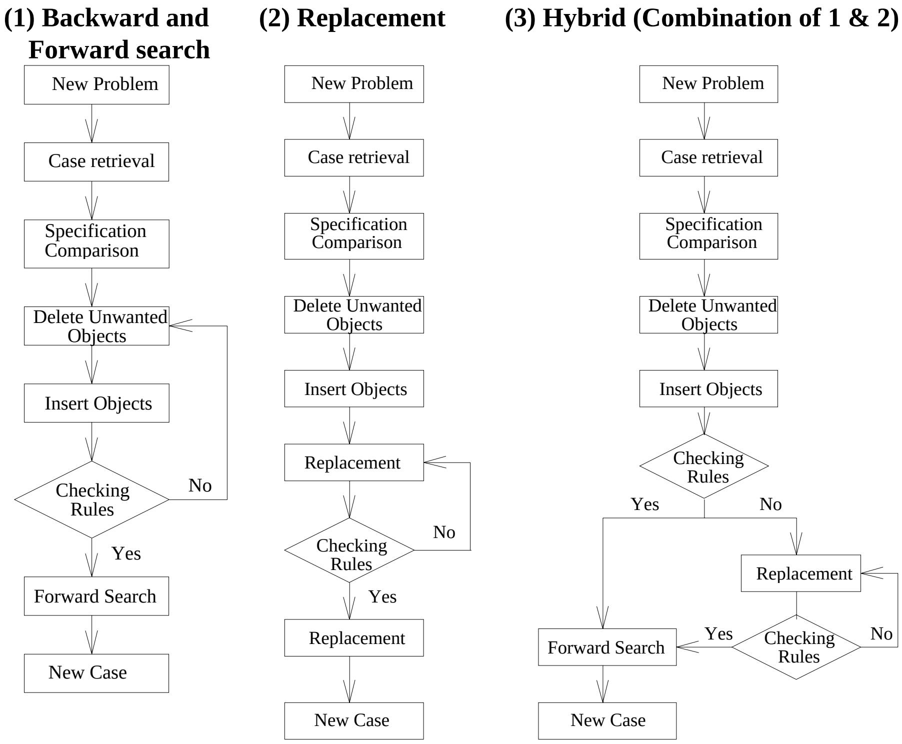

Figure 14. Case Adaptation Models

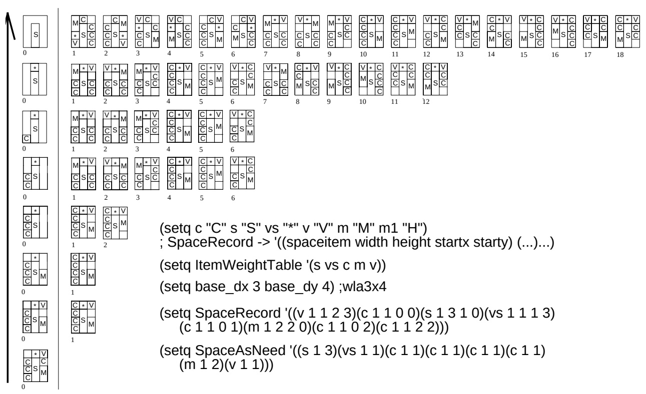

Figure 15. Generation of The Elementary School Layout by Backtracking

5. Conclusion

This paper provides a basic understanding of the human design and computers in case adapation by observation from design experiments. The findings indicate the limitation of dimensional adaptation and the complexity of topological adaptation. Case adaptation by novice and experienced designers are different in approaches of dimensional adaptation and topological adaptation. While design computation will be beneficial from converting heuristics into mechanism, problem-solving requires the transformation of non-routine problems into routine problems. If the user can specify and assign similarity value, then the differences between human judgement in case adaptation and the evaluation mechanism by computers is quite narrow. Without an understanding of how these above conditions are met, further study of what computational tools are needed for case-based design and reasoning cannot be reached.

In general, the complexity of design case adaptation has been underestimated, with a tendency for it to be modeled as the manipulation of simple algorithms and heuristics. From the preliminary observations, existing CBR systems are constructive tools which produce correct answers but not necessarily good ones because:

(1) They do not consider characteristics of an individual user or the problem. The outcomes are standardized regardless of problem constraints and the context of the domain.

(2)They do not address semantics and design justification. Architectural plans are usually constrainted not only by their dependency relationships through spatial reasoning, but also by the designer's experience and heuristic rules.

In conclusion, design is a significant human activity. Computers open up new realms of possibilities for design assistance. However, a computer is not a designer. It is best understood as useful tools which provides means of storing information and carrying out potentially useful computations (Sun 1993). The research indicates that case-based design in architectural design can proceed effectively through the cognitive science of views for proceeding future research.

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