AN EXPERT SYSTEM FOR CONCEPTUAL DESIGN OF BUILDINGS

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ABSTRACT

In the conceptual design stage of a building the number of possible configurations is enormous. Configurations selected in this stage affect the building cost much more than any decision made in subsequent design stages. Currently there is no analytic method for selecting the best solution, and designers base their decisions mostly on experience and intuition. This process is not algorithmic and therefore the best possible design is not guaranteed.

In this paper the process by which a human expert arrives at a conceptual design is briefly analyzed and an automated knowledge-based expert system to aid in the conceptual design stage will be explained.

INTRODUCTION

Most of the time and the effort put into a building design are spent on details such as the sizes of the beams or the shapes of reinforcements. Usually a much smaller part of the design effort is dedicated to the first stage, the conceptual design stage. However, the performance of a building, functional as well as economical is mainly determined in the conceptual stage, while decisions made in the detailed design stage have secondary effects (Swinburne 1980, Steyert 1972).

The conceptual design stage of a building can be generally described as the stage where all the relevant data is collected and assessed, the projet objective is defined, and a configuration for major building systems is determined.

A building project is normally a financial enterprise. A developer of such a project aims at minimizing the costs and maximizing the benefits of the project. In that respect, a building design, the conceptual and the detailed designs, can be viewed as the process of selecting the optimal configuration that maximizes the developer's return within given constraints. However, the relations between the building components and the design objective are difficult to formulate. It is quite easy to calculate the costs of different building components; many construction data bases hold this information. It is difficult, however, to estimate the benefits of the building components. Attributes of a building such as privacy, circulation, view, acoustics, and appearance all affect the market value of a building.

Some authors claim that design is not a process of optimization at all, but a process of selection (Gross and Fleisher 1984). Others suggest that design is evaluated in terms of satisfactory fit between the system and the users (Oguntade and Gero, 1981). The following section will show that although the knowledge about the relation of the design objective to the building systems is still lacking, the conceptual design's ultimate goal is to optimize an objective function, and thus the design process is best described as an optimization process.

THE PROCESS OF CONCEPTUAL DESIGN IN PRACTICE

When an owner initiates a building design, the specifications given to designer explain the objective and some guidelines for the design. The design objective is usually to maximize the project's net present value. The nature of the guidelines needs clarification. Owner's guidelines may be divided into the following categories:

1. Crisp constraints,
2. Fuzzy constraints,
3. Preferences.

Crisp constraints limit the choices designer can make. The owner constraints formalize two things: (1) his concept of the form the building should take for its destined purpose, and (2) his heuristic knowledge of how to maximize the project's objective. "Net floor areas is 50,000 sf" is an example of the first type. "The facade is to be of marble" is an example of the second type.

Fuzzy constraints do not set absolute limits on the choice of building components. They are used when the knowledge that the owner possesses is not definite, but nevertheless can serve as a guideline to the design. An example of a fuzzy constraint is "Story net height should be large"; or "Bays should be of regular shape."

A preference is a formalization of heuristic knowledge about optimal design. Unlike a constraint it does not set limits on variables, and it may use fuzzy language. The essence of a preference is the ranking of two or more building components in view of their benefit to the project's objective. An example of a preference is "A concrete frame is considered more prestigious and therefore preferred to a steel frame."

After the owner gives his specifications, the process of conceptual design follows these steps:

1. Recognition of all constraints and preferences relevant to the project.
2. Estimating the relationships between the building attributes and the design objective.
3. Generation of several possible structural configurations that comply with the constraints and preferences, and are considered optimal by the designer.
4. Evaluation of the selected alternatives. In this stage a rough estimate is made of the costs and benefits comprising the objective function.
5. If the best solution found in the previous steps is satisfactory, the conceptual design stage is completed. Otherwise, the above procedure will be repeated by selecting different building components until a satisfactory solution is found.

Step 3 in the above list is the core of the conceptual design process. This is where the ingenuity, expertise and intuition of the designers are manifested. It was mentioned before that the effect of the building components on the objective function is difficult to quantify. The constraints and the preferences are often contradictory, and the number of possible structural configurations is very large. Nevertheless, designers select from this multitude of possibilities only a few promising solutions. In this process, obviously not all feasible alternatives are evaluated.

The conceptual design involves compromises. There is a tradeoff between different building attributes, for example, between the natural illumination and energy conservation. Eventually the components selected are those that are believed to optimize the complete building, not necessarily an individual building system. This compromise is not reached arbitrarily. The interaction of different building systems is complex. The designer's expertise is used to find the compromised values which are assumed to maximize the objective of the project.

The design evolves as follows: A compromised value is selected for a variable in order to reduce the size of the optimization problem. The designer then tries to optimize the reduced problem. If the reduced problem is still too difficult to solve, subsystems such as floors or the foundation are optimized locally. An optimal solution for a subsystem is searched for in the same way as for the main system; that is, by selection, separation, and optimization of reduced problems. Whenever a building component is selected, as opposed to optimized, the designer usually examines several alternatives. Consequently, more than one design is usually created. These designs are evaluated, and the best one is selected for a detailed design.

The above description of the conceptual design process shows that it is indeed an approximate optimization process. The optimization is achieved by an iterative process of selection, separation, and subsystem optimization.

CONCEPTUAL - AN EXPERT SYSTEM FOR CONCEPTUAL BUILDING DESIGN

Engineering, and especially civil engineering is a suitable domain for expert systems. Civil engineering has always been a domain where exact scientific methods are used with rules-of-thumb and judgment. There is a large number of structural engineering problems that are ill-structured and either not amenable to an algorithmic solution, or the algorithms are too cumbersome and restrictive. The experienced engineer deals with them using judgment and experience (Sriram, Maher and Fenves 1985).

The conceptual design problem is ill-structured, the space of feasible building configurations is too large for an exhaustive search, and the expertise in the field is vast and much of it is heuritics. Therefore, conceptual design is particularly a suitable domain for an expert system solution.

In the following section, CONCEPTUAL, a knowledge-based expert system, developed for conceptual design, is explained. The objective of the system is to optimize one of the major building systems - the structural system. The optimal solution is defined as the structure with the minimum initial cost.

CONCEPTUAL is schematically described in Fig. 1. A consultation starts with the user's input. This input consists of the general description of the building, the user's constraints, the user's preferences, and the user's best estimate of the optimal building configuration. The core of the system is the search module. The graph to be searched is shown in Fig. 2. The graph is part of the system's knowledge; however, the user has the option of deleting part of the graph if he has information that enables him to start with a smaller search space. In the search module, paths through the graph are generated, and then evaluated using the knowledge from the knowledge-base. The most promising paths are pursued. When a path represents a complete building structure, the path is passed to the module of component selection and cost estimating, where the total cost of the building is estimated. If the design is not satisfactory, the search continues. The explanation module provides the search status and the reasoning that resulted in the system's solution. Explanations can be provided whenever required. The output lists the five top configurations found by the system and their cost. The user may stop the consultation any time, and ask for the output. If not satisfied, the search can be resumed.

THE SEARCH ALGORITHM

The CONCEPTUAL search algorithm makes use of several types of knowledge. These are:

1. Hard constraints.
2. Heuristics.
3. Owners preferences.
4. Cost of bulding categories.
5. Costs and loads of building components.

The following section defines each knowledge type, explains its source, and the way it is represented in the system.

Hard constraints.-These are either permanent knowledge built in the KB, or input from the user for a specific design. A hard constraint, when entered by the user, makes the program delete the unwanted nodes from the search graph.

Heuristics.-Much of the knowledge in the conceptual design domain is not definite. The knowledge is in form of recommendations, rules of thumb, statistical inferences, and personal judgment. Such knowledge cannot be represented by definite rules of the form "if conditions then conclusion." Rather, experts use phrases such as "suggests", or "lends itself to", or "lends credence to." In CONCEPTUAL this knowledge is encoded by soft constraints. The heuristic knowledge in CONCEPTUAL comes from several publications, such as Moore et. al. (1980), Lin and Stoterbury (1981), Maher (1984), Iyengarr (1981) Dallaire (1983), Fraser (1970), Cassie and Napper (1966).

Cost of Building Categories.-When a building is identified as belonging to a standard building type (e.g., Means System Cost, 1984), an estimate can be made of the lowest possible unit cost of this building. This bound on the cost is used in the CONCEPTUAL's search to prune unpromising branches.

Costs and Loads of Building Components.-A full path through the search graph defines the following properties of a building: (1) geometry, (2) type of building systems, (3) materials. More information than this is required to estimate the cost of the structural system of a building. The required additional data is the load and cost of the various building components. A source of this information is Means Systems Costs.

Owner's Preferences.-Usually, in problems where a least-cost path is searched, a cost is assigned to each node. The optimal path is the one that the total cost of all itsnodes is minimal. The problem becomes more complicated when a user wants to incorporate subjective preferences into the search. How would then be the optimal path defined? In a map-crossing problem, for example, one may prefer going through city X even if it means straying away from the optimal route.

In this study the solution proposed to a search problem with preferences is as follows: when a user has a personal preference, his objective is a combination of two variables of different dimensions. One dimension is cost, the other is a personal value. To combine them, the two should be brought to the same scale. This can be done by transforming the user's preference to a cost value. The user is therefore required to state his preference and the value of this preference to him. In the example of a map crossing, when a user declares that he prefers city X, he has to state by how many miles is he willing to extend the road in order to visit city X. His objective function will be

$$\text{minimize } \sum_i (l_i - \Delta l_i)$$

where l_i is the length of road to city i and Δl_i is the price the user is willing to pay for visiting city i.

This analysis applies to CONCEPTUAL as well. The purpose of CONCEPTUAL is to find a configuration that has the least cost. In CONCEPTUAL, the cost of the building components is obtained from the system's DB; however, in a particular case a user may know a certain building component is less costly to use than what is specified in the cost data base. In such a case, the user should specify a preference for that component. Even when a preference is because of intangible factors, the user is still required to state how much is this preference worth to him. Therefore, the user's objective function would be

$$\text{minimize } \sum_i (C_i - \Delta C_i)$$

where C_i is the cost of system i, and ΔC_i is the dollar value of the preference of component i.

COMBINING AND PROPAGATING KNOWLEDGE IN CONCEPTUAL

The knowledge types of CONCEPTUAL were described in the previous section. This knowledge is used in several ways to guide the search for a solution. Hard constraints decrease the search space. Knowledge about different building types is used to prune uneconomical paths from the search graph. Owner's preferences are combined into the objective function, and costs and loads of building components are used to estimate the total cost of the building. The soft constraints are combined to estimate the measure of the promise of a node in the graph. The mechanism for drawing inferences from the constraints and the heuristics will be discussed subsequently.

CONCEPTUAL's inference mechanism is based on Shaffer's theory of evidence (Shafer 1976) and MYCIN's certainty factors (Buchanan & Shortliffe 1984). In CONCEPTUAL, a path is the smallest element that its validity has to be estimated. The validity of a path is, in other words, the measure of promise that the path is part of the optimal solution. To evaluate a path, only the KB rules applying to the full path are invoked. At every step in the search, the question to be answered is what is the best subsequent node to move to.

COMPONENT SELECTION AND COST ESTIMATING

In common optimal-path problems, such as the travelling salesman problem, there is a unique cost assigned to each node in the graph. This is not the case in CONCEPTUAL. Here the cost of a node is a function of the full path. For example, the cost of the node "steel column" cannot be calculated unless the number of floors, the span, and the flooring system are known. In CONCEPTUAL, after a full path through the graph, the building geometry, type of components and material are established. This data is passed to the costing module for estimating the total cost of the building.

USER INTERFACE

The user is initially asked for his/her constraints, preferences, and the best judgment about the optimal solution. During a consultation he may be asked for additional information. The output of the system consists of five best structural configurations found and their estimated cost. A user may inquire why a certain building configuration was selected to be optimal, and he/she will be presented with all of the reasoning that resulted in the selection. In addition to that, a user may stop the search at any time and ask for the best solutions found so far. If not satisfied with the solution, the search may be continued.

The program was developed on a microcomputer using prolog language.

SUMMARY AND CONCLUSIONS

The large number of possible building configurations and the difficulty in quantifying the benefits of building components, make an exact optimal solution to the conceptual design impractical. In practice, the conceptual design is an approximate optimization process. The optimization is achieved by an iterative process of selection, separation, and subsystem optimization.

The nature of the conceptual design problem makes it particularly suitable for an expert system solution. In this study, a prototype expert sytem, CONCEPTUAL, was developed. In CONCEPTUAL, the conceptual design process is modeled as an informed search in a solution graph. The information used by the program consists of owner's constraints and prferences, structural and architectural constraints, common practices in building construction, and building systems costs. The program's knowledge comes from published technical books and articles. Means Building System Cost book is the source of the cost data base. The program is written in a microcomputer based prolog language.

The development of CONCEPTUAL resulted in a better understanding of the conceptual design process, the formalization and automation of this process. As a practical design tool, CONCEPTUAL is still lacking. The number of possible alternatives to each building system should be increased, and the KB expanded. In addition to the structural system, other building systems should also be included.

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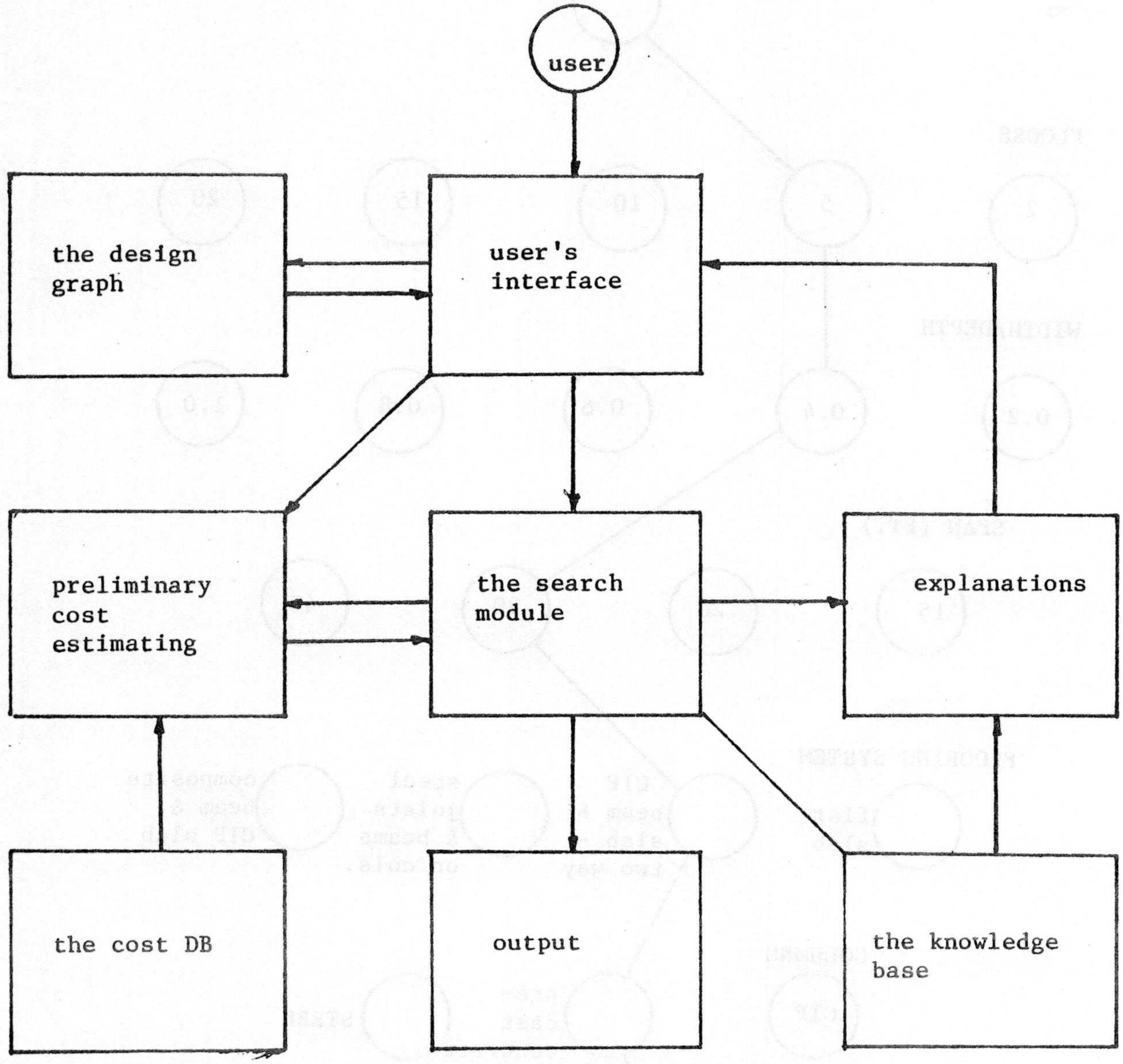

Fig. 1. - General Structure of the Conceptual System

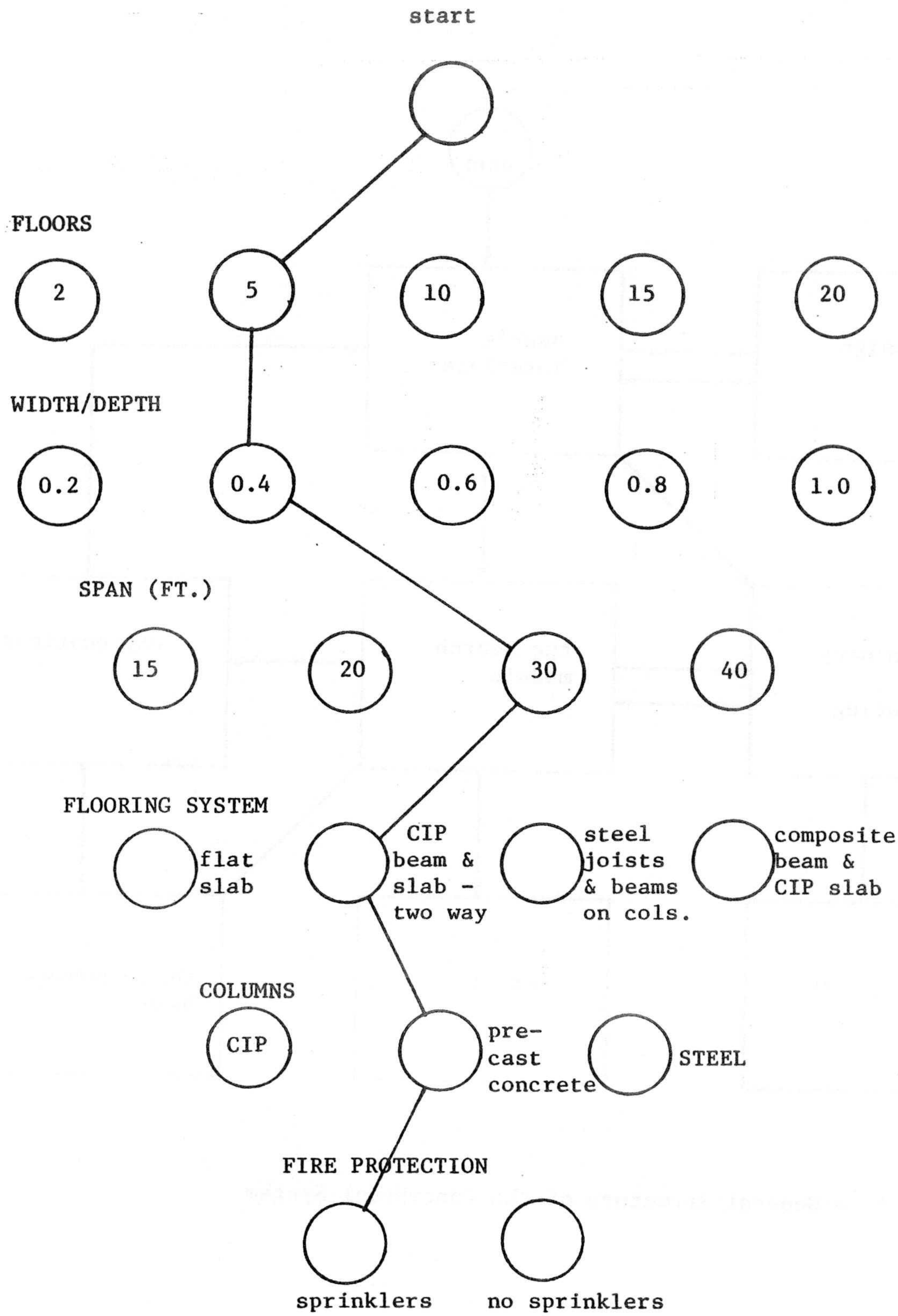

Fig. 2. - The Search Graph and an Example of a Path