THE USE OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN PRELIMINARY STRUCTURAL DESIGN

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1. Introduction

Computer aided design (CAD) has increased by orders of magnitude the power of design tools available to the engineer. Advantages of CAD include the reduction of computation time and therefore its cost, the elimination of the amount of tedious and error-prone detailed calculations done by the engineer, and the ability to develop and analyze much more complete models of structures. All present applications of the computer to structural design deal with later stages of the design process, namely, analysis, proportioning and drafting. With the advancements of a section of computer science called artificial intelligence it is now conceivable to create a knowledge-based system to automate or assist in the early, preliminary stages of the structural design process. The purpose of this report is to explore the potentials of such a system.

2. Civil Engineering Background

2.1 The Design Process

Design can be viewed as the general process in which an idea is developed into detailed instructions for manufacturing a physical product [5]. The design process starts with a definition of a need. The activities that follow can be grouped into four phases [9]:

1. synthesis : the clarification of the input parameters and their interaction to create a structure that will meet design requirements.

2. analysis: the modeling and solving of equations to predict the response of a selected structure.

3. evaluation: the activity of placing a worth on the structure where worth may be cost, safety, or energy consumption.

4. optimization: the search over the range of possibilities to improve the design as much as possible.

Preliminary design is considered to be part of the synthesis phase. In preliminary design alternative structures are developed, a structural configuration is selected, and the preliminary parameters of components are determined.

In the present practice of preliminary design very little optimization is done and selection is based on rough calculations. Computer assisted preliminary design would provide opportunity for optimization by consideration of a much larger range of alternatives. It is possible that computer assisted preliminary design could free the engineer from the implementation of existing structural schemes and allow him to pursue new schemes.

2.2 Computer Aided Design

To begin a discussion of CAD, a distinction will be made between computer aided design and design automation. In computer aided design man and machine work together on a problem using the best characteristics of each. In design automation the computer deals with all the demands and constraints without recourse to the designer [33. The latter may be suitable for design of components, but the method is inherently inflexible and the exclusion of the designer often leads to dissatisfaction. There are two schools of thought regarding the consequences of CAD. For one, computers remove the repetitive tasks and make room for creativity. The opposing view is that computers stifle creativity by distancing the designer from design. An optimum CAD strategy would be to remove the repetitive tasks without creating a large gap between the designer and the design process.

Today, CAD in structural engineering involves almost exclusively analysis, proportioning of structural components, and production of drawings and schedules. There are very few applications to conceptual and preliminary design. Conceptual and preliminary design are considered the creative aspects of design. Yet, generally the preliminary design process is not new design but redesign, where redesign involves the application of existing structural ideas to a particular design. New design implies the development of a new structural configuration, e.g. new concepts in structural design. Redesign actually is the application of a set of rules to assign values to predefined variables. Thus, it appears that preliminary structural design process may be placed in a knowledge based system, where IF THEN rules are used to instantiate values in a data structure.

A knowledge based program is developed using the knowledge of experts. Once the program is developed there should be close interaction between the designer and the computer. The computer should be able to respond to queries on the design process as well as accept additional information. Since a design prepared by the computer follows a limited number of rules, close supervision by the designer is necessary. In this way the designer will realize inadequacies in the existing set of rules and make revisions or additions to the rules when necessary.

3. Artificial Intelligence Background

3.1 Artificial Intelligence

"Artificial intelligence is the study of ideas which enable computers to do the things that make people seem intelligent." [10] Ideas are being developed to facilitate the creation of knowledge-based systems using the experience and knowledge of experts; for example, Nii and Ailo are developing a program to write knowledge based programs [4]. The following is a description of some of the applications of artificial intelligence.

> Knowledge based systems can do geometric analogy tests (see figure 3-1). The object is to relate A to B and then choose 1,2, or 3 as having a similar relationship to C The program can do this using a method of describing how A becomes B, then how C becomes 1,2, and 3, and choosing the similar transformation.
>
> Knowledge based systems acquire knowledge or learn ideas similar to the way people learn. The study of how knowledge based systems learn can provide insight into the way people learn and vice versa. Learning new concepts may be through sequences (see figure 3-2). Learning may also be done through the acquisition of procedural knowledge.
>
> Knowledge based systems can understand simple drawings, simple language, and do expert problem solving. There are programs capable of doing integration problems (MACSYMA), understanding mass spectrograms (DENDRAL), and helping physicians diagnose and treat bacterial infections (MYCIN). Knowledge based systems can also do industrial work (i.e., robotics) and model psychological processes.

One approach to the development of knowledge based systems is heuristic programming. (Heuristic is defined as serving to guide or discover.) A model may be developed in the form of a goal tree. In a goal tree a goal is achievable if certain subgoals are achievable; a subgoal is achievable if certain of its subgoals are achievable, etc. A goal is considered achievable if certain constraints are satisfied, where a constraint enforces a relationship among entities. Steele and Sussman [7] contend that physical systems are usually specified as sets of constraints on several variables.

Waterman [8] discusses a rule based approach to knowledge acquisition. The idea is to represent the knowledge of an expert in an information processing model. He describes a rule-based software system, RITA, where a RITA rule consists of

```
IF premises  THEN actions.
```

A collection of rules constitutes a rule set. In a rule based representation for procedural knowledge acquisition the domain dependent knowledge (or premises) is placed in a data base that directs the execution of a rule set.

Some existing applications of artificial intelligence techniques are AGE and SACON. AGE is a knowledge based program for building knowledge based programs. AGE is an attempt to formulate the knowledge used in constructing knowledge based programs and put it at the disposal of others. [4] This is a development in 'knowledge engineering'; the process of writing application programs using primary artificial intelligence methods.

SACON is a knowledge based consultant for structural analysis [1]. SACON is an "automated consultant[91]; it advises engineers in the use of a general purpose structural analysis program, MARC MARC offers a large choice of analysis methods. The typical length of time for a person to learn how to use all the options in MARC is one year. In SACON a rule based approach similar to RITA is used. An example rule of SACON is:

```
IF  1) The material composing the sub-structure is one of
       the metals, and
    2) The analysis error (in percent) that is tolerable
       is  between 5 and 30, and
    3) The non-dimensional stress of  the  sub-structure
       is  greater than 9, and
    4) The number of cycles the loading is to be  applied
       is between  1000 and 10000

THEN It is definite that  fatigue  is  one  of  the  stress
     behavior  phenomena in the sub-structure.
```

SACON is an example of the use of AI techniques in structural design in the analysis phase. The study and development of knowledge based systems should enable the structural designer to incorporate AI techniques into the other phases of design.

3.2 Frame Representation of Data

As viewed by a knowledge based system, the preliminary design process is the accumulation of information. This information describes the design alternative that is selected. As a means to represent this information in the computer the frame concept of Minsky (see figure 3-3) is presented [10].

In the original concept described by Minsky, a frame is a data structure for representing a stereotyped situation. There are different types of information associated with each frame, such as how to use the frame, what one can expect to happen next, and what to do if expectations are not confirmed.

A frame is a network of nodes and relations. The top levels are fixed and represent things that are always true. The lower levels have 'terminals' to be filled by instances of data. These terminals may actually be subframes. This representation allows multiple levels of detaiL

Each frame includes data needed to specify a subassembly at one level, but not details from lower levels. A frame may include conceptual information as well as numerical information. Before the design begins the frames contain titles without associated values. As design progresses values are assigned.

The design of the frames themselves should be done by the designer. Preiss discusses the idea of computer assembly of frame representation. A frame is created to suit a goal. For a general design all constraints are not known ahead of time, and more constraints may be discovered as design continues. Due to the fact that a computer's data base is bounded, there may be no alternative to man-made (possibly computer assisted) frame construction [5].

The frame representation combined with heuristic programming ideas provides a versatile design model. The frame representation is defined by the designer and may be refined when necessary. With the proper interaction between the designer and computer, queries may keep the designer in touch with the design process and allow new heuristics to be added.

3.3 Acquisition of Data

3.3.1 Introduction

The acquisition of the values to be stored in the frame representation (or any data structure) is generally done by the execution of rules. The organization and form of the rules varies with different programming techniques. This section describes two concepts for the development of a knowledge based system. The first is an and/or tree that uses plausible inference to pass certainty factors up the tree. The second is an operating system that will accept a set of rules and a set of facts and provide the resulting actions.

3.3.2 Tree

An and/or tree is a tree that may have the branches out of a node connect nodes that must either all be acceptable (and) or have only one acceptable node (or). The lowest level of nodes are the input parameters. The root of the tree is an hypothesis. This model is used by the program MYCIN (see figure 3-4). In this particular type of and/or tree there is a certainty factor associated with each node. The certainty factor is a number between 0 and 1. The user specifies a certainty factor with each input parameter. With the use of plausible inference these certainty factors are passed to higher level nodes until a certainty factor is associated with the root of the tree [10].

Another application of this concept is the PROSPECTOR programs [23. PROSPECTOR is being developed to provide consultation on problems of mineral exploration. In PROSPECTOR each tree is a model of an ore deposit. The model is a collection of rules of plausible inference. A typical inference rule is:

```
IF E1 AND E2 AND... AND EN
    THEN (to degree LS.LN)  H.
```

The variables EL E2, ..., EN represent pieces of evidence, H is an hypothesis. The factors LS and LN "represent how encouraging it is to find the evidence present and how discouraging if the evidence is not present The two numbers LS and LN must be provided by the expert for each rule. PROSPECTOR assumes a model to be acceptable until the certainty factors imply another alternative should be pursued.

In order to clarify this model assume the root of a tree is a particular structural alternative to be developed in preliminary design. There will be a tree associated with each possible alternative. The lowest level of nodes will be the initial information collected by the designer to be used in developing alternatives. The system works with one alternative at a time and selects the most likely alternative for the problem at hand. At this point the designer may revise the input parameters (if possible) and/or the initial certainty factors. In this way, the designer may optimize the selection of an alternative.

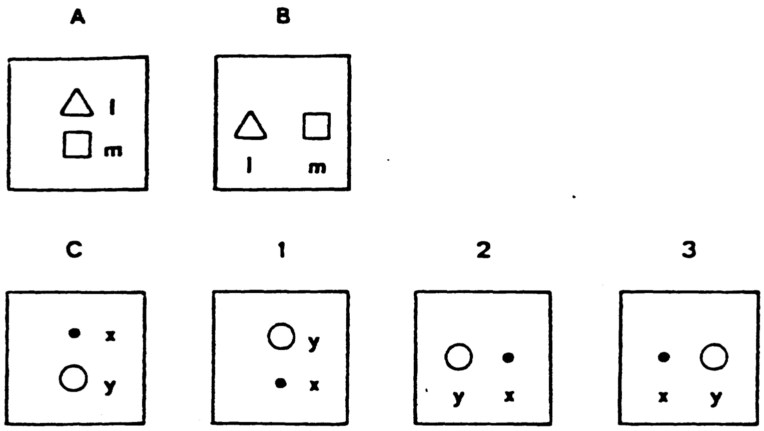
3.3.3 Operating System

The second concept for knowledge acquisition is an operating system [6]. This system will accept a set of rules to be stored in production memory. These rules may be stored in any order. The user can supply a set of facts (similar to the input parameters described above) to be stored in working memory. These facts are compared to the premise part of the rules to produce actions. Then these actions are added to the list of facts to be premises in other rules (see figure 3-5). The result may be one fact or a group of facts. In preliminary design applications, the resulting facts would describe the structural alternative to be implemented.

3.3.4 Conclusion

The operating system described may be an application of the and/or tree where the program itself does not have to know the hierarchy of the rules. However, different applications may presume the use of the operating system or the tree. In preliminary structural design the and/or tree may be used to determine the alternatives to be pursued. The operating system may be used to pursue the alternatives and evaluate their worth.

Figure 3-1: Analogy Tests



RULE	PART 1	PART 2
A → B	l ABOVE m	l LEFT m
C → 1	x ABOVE y	y ABOVE x
C → 2	x ABOVE y	y LEFT x
C → 3	x ABOVE y	x LEFT y

Figure 3-2: Learning Through Sequences

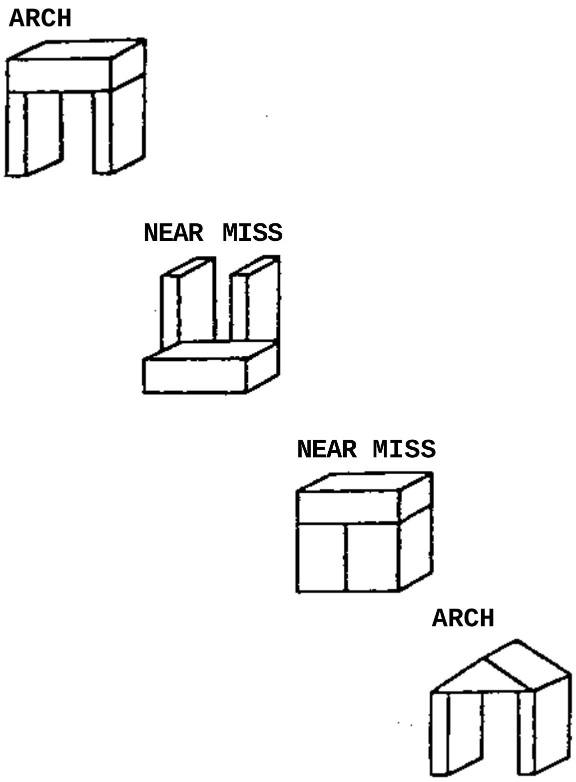


Figure 3-3: Frame Representation of Data

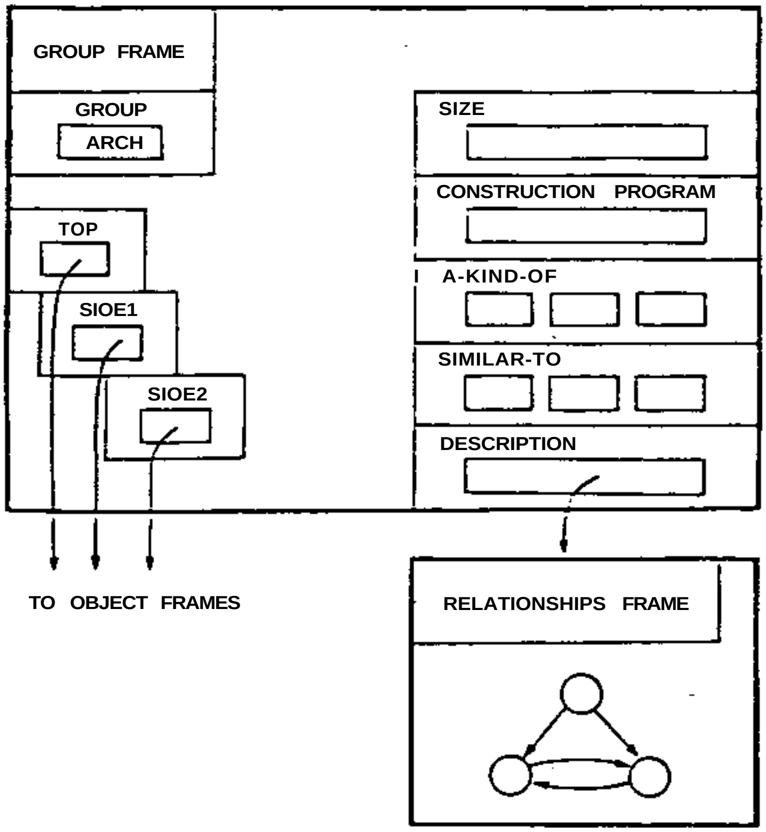


Figure 3-4: MYCIN And/or Tree

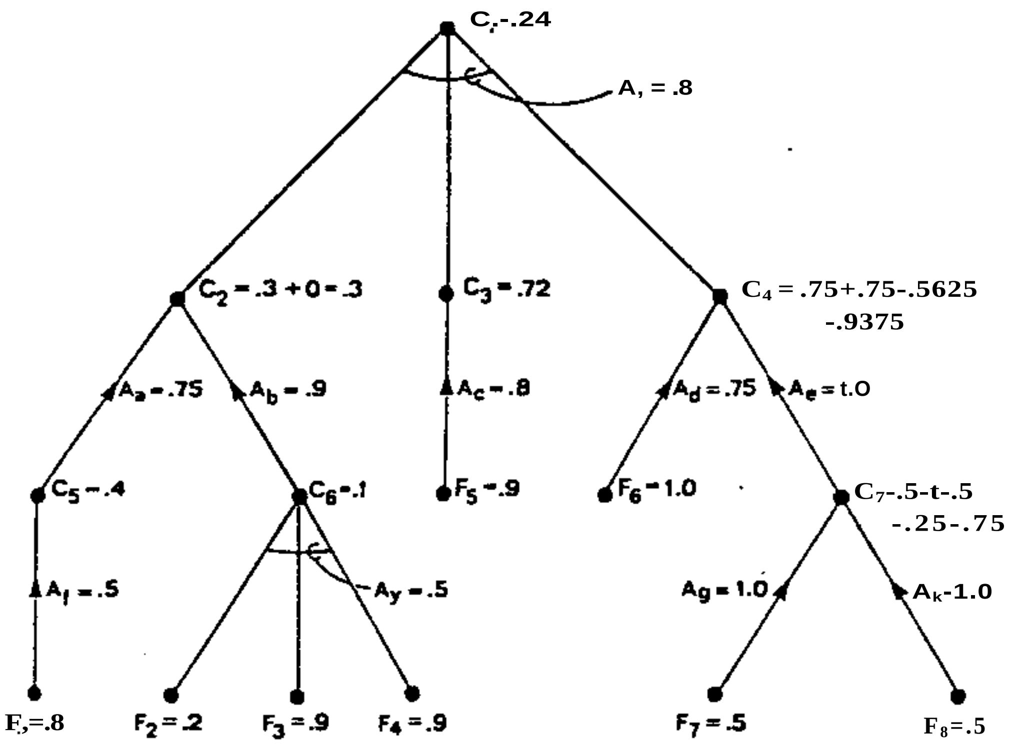
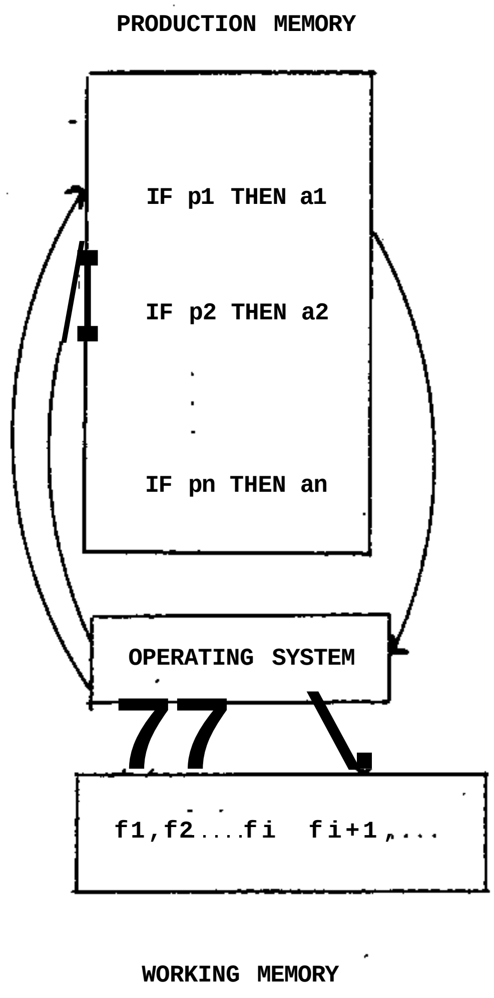


Figure 9-3 MYCIN uses a simple theory of plausible inference to pass certainty factors up the AND/OR tree from the given facts. The Fs are the cenainty factors attributed by the user to the facts he supplies, the Cs are the certainty factors computed for each conclusion made, and the As are the •'attenuations'* that indicate the inherent reliability of the productions. Cenainty factors are computed at the AND and OR nodes according to straightforward formulas. The truth of any fact whose certainty factor is computed to be .2 or less is judged unknown and the cenainty factor is reset to 0.

Figure 3-5: 0PS3: Schematic of Operating System

```
RULE:  IF premises  THEN  action
             or
      IF  p        THEN   a
```



4. Example: Preliminary Design of Bridges

In the preliminary design of bridges the first step is the definition of a need, eg. a roadway between two points. The preliminary design can be separated into two parts: first, the horizontal and vertical alignment; and second, the selection of an alternative structure or structures. For this example, we assume that the alignment is determined before the designing engineer is involved. Some of the constraints on the alignment are the cost of property, the earthwork involved, and who will be affected.

The second part, the selection of alternatives, will be discussed in terms of artificial intelligence techniques. The selection of alternative structural types, such as simply supported steel, prestressed concrete, tied arch, or truss, depends on span lengths and their ratios; i.e., the comparison of the lengths of adjacent spans. The selection of component types (e.g., deck vs. through truss, plate girder vs. box beam, etc.) depends on span lengths as well as available vertical clearance. Finally, material type (eg. steel vs. prestressed concrete beams) depends largely on relative costs. The span lengths are estimated in preliminary design by the application of alignment and clearance constraints, and cost analysis. It is these constraints that will generate the rules to be executed in a knowledge based system.

Applying the and/or tree with certainty factors, the roots of the trees may be alternative bridge structures. The leaves of the tree may be input parameters such as those defining horizontal and vertical alignment, information about the site, clearance restrictions, and current pricing information (see figure 4-1).

The use of OPS3 in the selection of alternatives would eliminate the need of developing a hierarchical decision tree. If necessary, the certainty factors of the and/or tree could be implemented by the rules. The following rules are a sample of some of the entries in the production memory, written in a fictitious "language".

```
The given facts stored in working memory may be:

  river,highway,rai1 way of boolean type (indicating whether
                                          present or not)
  equations of horizontal and vertical alignment;
    x' = f(x,y)
    z' * f(x')
    x' is centerline of bridge in xy plane
    z' is vertical alignment along centerline of roadway
  elevation of river.highway,rai1 way
  location of river.highway,or railway as intersection with x'
  endpoints of bridge along x', e.g. x'(O) = 0
                                     x'(N) = total length
```

(Assume one horizontal alignment per analysis.)

Initial clearances and constraints:

```
   IF river
    THEN      no pier/abutment between xrmin and xrmax
         AND min vertical clearance zrmin (Army Corp, Navy, EPA)
   IF highway
    THEN      no pier/abutment between xhmin and xhmax
         AND min vertical clearance zhmin (DOT)
   IF railroad
    THEN      no pier/abutment between xrrmin and xrrmax
         AND min vertical clearance zrrmin (RR)
```

```
note: 1) xrmin and xrmax measured along line normal to
         center of waterway
      2) xhmin,xhmax,xrrmin, and xrmax measured along
         line normal to center of road/railway
```

```
   IF xmins AND xmaxs computed above
    THEN controlling locations x'(i)
         along horizontal alignment
   IF x'(i)
    THEN calculate span lengths
         span(i) = x'(i+1) - x'(i)
```

Initial component types:

```
   IF (max span > 500 ft )
    THEN span type is truss or arch
   IF span(i-1) = span(i) = span(i+1)
    THEN  span types are simply supported
   IF 0.60 span(i) <= span(i-1) = span(i+1)  <= 0.80 span(i)
    THEN span type is continuous
   IF (z'(i) - zmin) > span(i)/20
    THEN component type is deck truss
    ELSE component type is through truss or arch
   IF zmin < (min(z') - depth of beam)
    THEN box girder beam
```

Initial material types:

```
   IF (cost index of steel < cost index of concrete)
    THEN use steel
   IF steel bridge cost > $5 million
    THEN segmental concrete bridge cost
```

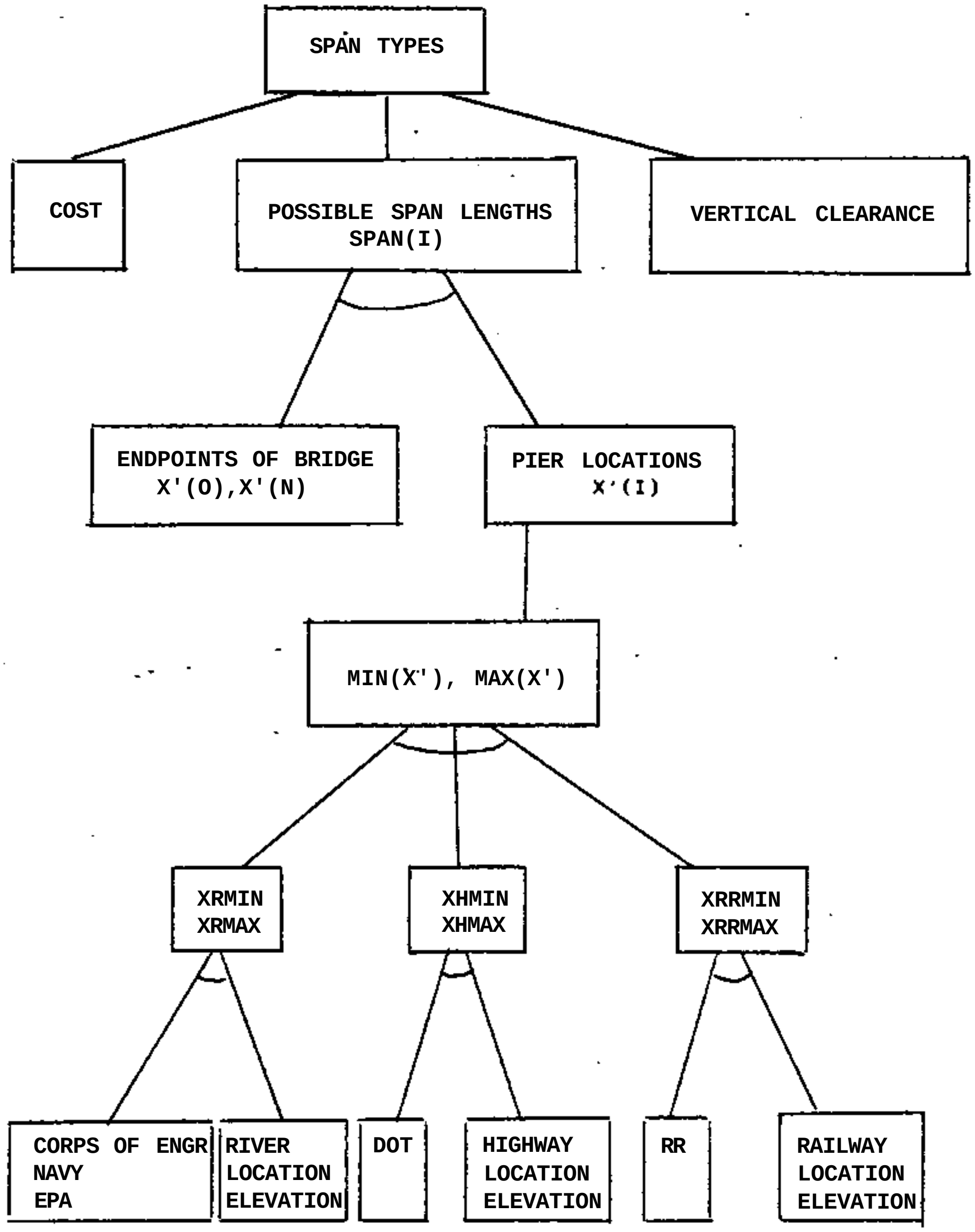
Optimization rules:

```
   IF (span(i) + span(i+1)) < span(i-1)
    THEN eliminate pier at x'(i+1)
     AND span(i) = span(i) + span(i-1)
   IF (span(i) > span(i-1) + span(i+1))
     AND clearance ok
    THEN add pier at x'(i) + span(i)/2
     AND recompute spans
```

The resulting facts, i.e., span lengths and types, and component types, material and preliminary specifications, could be processed and stored into frames. The frame representation may be viewed as a network data base, where a frame containing a level of information is linked to adjacent levels. The highest level frame would contain general information common to all alternatives. As a particular alternative is developed, lower levels of frames are instantiated with data. It may be possible to develop more than one alternative within a frame structure by duplicating frames and changing certain data within these frames.

The process of representing the knowledge of experts involves collecting information for rules and data structure through structured interviews. This is followed by the addition and revision of rules as sample bridge designs are run through the system. The development and execution of the rules depends on the system to be used. The advantage of OPS3 is the option of stating the rules in any order. However, decision trees provide a visual representation of the process involved for design. The system to use eventually will depend largely on local availability.

figure 4-1: Example of And/or Tree



5. Conclusion

The preliminary design process relies heavily on the expert's ability to identify and analyze situations, and to evaluate alternatives. This ability is developed through personal experience and the passed on experience of other experts. Since it is impossible for an expert to pass on all the knowledge he has gained from experience, the departure of an expert (from an office or the field of engineering) means the loss of some of that experience. The development of knowledge based systems will permit not only the retention of expertise, but also its logical extension, as well as access to the expertise by other engineers.

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