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SESSION 3

APPLICATION TO DESIGN AND CONSTRUCTION

Expert System Applied in State Engineering Offices

Système expert mis en application dans les services techniques nationaux

Expertensystem im Einsatz bei staatlichen Planungsabteilungen

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SUMMARY
This system is able to simulate the complicated thinking processes that railway experts make out all kinds of technical reconstruction measures. It drafts the feasible technical innovation schemes by adopting mulitple knowledge-representation methods and the technology of optimizing knowledge base and using forward-backward and two-stage combined type of inference and the imprecise-reasoning model which is based on the interval representation and determines the recommended plans according to the fuzzy-overall-level concept by applying the similarity-preference-ratio theory on fuzzy mathematics. And then it evaluates economy of the recommended plans and completes the decision. Now this system is being applied in the governmental engineering consultive services.

RÉSUMÉ
Le système expert présenté dans cet article est en mesure de simuler les processus de raisonnement que doivent effectuer les concepteurs des chemins de fer, pour tous les genres de mesures techniques à prendre dans les travaux de construction. Le développement de solutions innovatrices réalisables se fait à partir d'innombrables méthodes de représentation de la connaissance et de techniques d'induction à plusieurs niveaux. Le système expert détermine les recommandations de planification d'après un concept flou généralisé, en y appliquant la théorie du rapport des préférences aux similitudes tirée du problème mathématique des incertitudes. La décision finale découle d'une étude comparative de rentabilité. A l'heure actuelle, ce système expert est mis à l'essai dans les services techniques nationaux.

ZUSAMMENFASSUNG
Das vorgestellte System simuliert die komplizierten Denkprozesse von Eisenbahnplanern bei allen Arten technischer Baumassnahmen. Mögliche innovative Lösungen werden aus mehrfachen Methoden zur Wissensdarstellung und mehrstufigen Induktionstechniken gewonnen. Das System bestimmt die Planungsempfehlungen nach einem übergreifenden Fuzzy-Konzept, indem die Theorie des Verhältnisses von Aehnlichkeit zu Präferenz aus der unscharfen Mathematik angewendet wird. Die endgültige Entscheidung wird nach einem Wirtschaftlichkeitsvergleich gefällt. Zur Zeit steht dieses System bei staatlichen Projektierungsstellen in Erprobung.

1. FOREWORD

In China,the railway passenger-and-freight volume is about 2/3 of the total volum of transportation. However, the total length of the railway network is short, the technical facilities are backward and tension is felt both in freight and passenger transportation. Besides building a lot of necessary new tracks in the future, it is important to increase the capacity of the existing railways, especially that of the 40 thousand single tracks which accounts for more than 3/5 of the total lenght of the network. This is a very important measure since it demands smaller amount of investiment but benifits more and more quickly. Then,to build an enlarging- capacity reconstruction and artifitial decision- assistant surporting system to make decision scientific is of great significance.

In the recent 40 years, China has undertaken technical reconstruction of the railways, such as Beijing-Guangzhou, Beijing-Shanghai, Beijing—Harerbin and those in the southwestern mountain areas and has got good results. During this process the railway experts have accumulated plentiful experience. So we built An Expert System for Reconstruction Schemes of Single-Track Railway (ESORR). Since it has rational structure, rich knowledge and dear man-machine interface, and the enlarging-capacity plans it gives are feasible in economy, the system is emphasized by authoritive engineering consultive service. It has formally applied to assist to make decisions in railways engineering consultation with good results.

The system is composed of the scheme drafting,scheme evaluating and selecting, scheme economy evaluating,and decision file compilation sub-systems. Its structure is shown in fig.1.

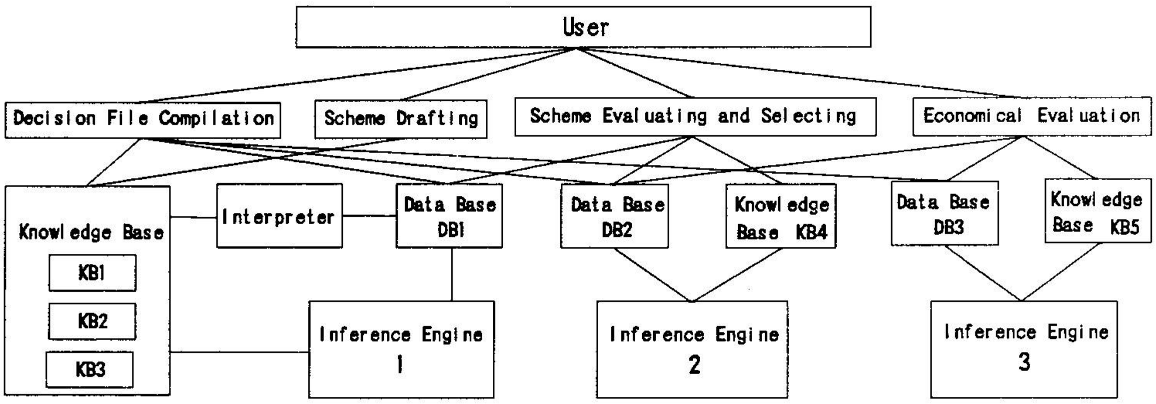

Fig.1 Structure of ESORR system

2. THE SCHEME DRAFTING FOR RAILWAYS TECHNICAL RESTRUCTION

The drafting of reconstruction schemes is an important procedure which is most capable of reflecting the plentiful experience of experts in deciding the technical reconstruction of single-track railways.

2.1 Structure Analysis of Subject Knowledge-Base

2.1.1 Resolutionability

The objective concept of reconstruction measure in the knowledge of subject of the existing lines technical reconstruction has the structure shown in fig. 2. K_i represents the scheme i.

2.1.2 Multi-objectives

Any above reconstruction measure K_i also comprise a number of specific transforming plans. Figure 3 shows it.

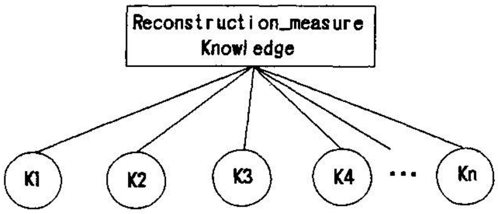

Fig.2 State Knowledge (1)

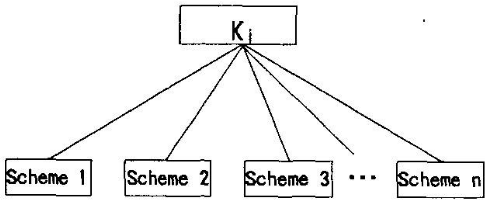

Fig.3 State Knowledge (2)

Scheme i is an arbitrary non-decomposability sub-objective, namely the implementing scheme. It can be processed as an independent knowledge cell. The pre-conditions binded it decides whether the scheme is right or not. The specific plan is discribed with one or multiple production-rules. Therefore, the knowledge in this subject should have the following structure type, as demonstrated in figure 4.

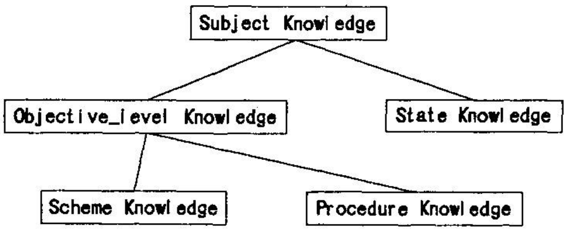

Fig.4 The Structure of Subject Knowledge

The statement knowledge is that to decompose an objective concept into the sub-objective ones. The object-level knowledge means the knowledge which directly relates with the solution finding of problems. In object level, the scheme knowledge is a kind of empirical and enlightening knowledge, it gives the effect and cause relationship of establishing the programme. The procedure knowledge provides the necessary data for the establishment of the schemes it is composed of some computing models.

2.2 Knowledge Representation

The traditional methods of knowledge representation are not suitable to the field of decision for the technical reconstruction of the existing lines since in this subject the decision of a problem does not totally rely upon the judgement of pure logic inference, it also needs organical data calculation, and analyses, evaluates, compares and decides all kinds of possible rusults as in order to produce feasible plans which could be chosen. For this reason, the research group adapts a type of comprehensive knowledge-representation method and uses multiple kinds of methods to optimize the knowledge base while setting it up on the basis of researching the structure characteristics of the subject knowledge.

2.2.1 Fact Expression

This sub-system expresses facts by predicate (logical method) . There are one- element predicate and multiple-elements ones, such as:

$$Q(a),\ Ix(b,c)$$

Q, Ix , the names of predicate, indicate the attribute of a or the relationship between b and c.

2.2.2 Representation of Expert Experiences Knowledge

It is very appropriate to represent the experience knowledge of specific experts in the aspect of technical reconstruction of the existing lines with the production rules. In this system, The rules are placed in the knowledge bases KB1 and KB2.

Example: in KB2, there is a rule:

IF the ruling grade is Ii=6‰,

and the local topographic form belongs to Ⅱ class,

and the horizontal and vertical condition of the line permits the extension of station tracks,

and the effective length of the arrival and departure tracks can not meet the demands of future trains.

THEN the length of the tracks should be extended to 550m (CER-R=0.8).

Here "CER-R=0.8" means that the confidence degree of this rule is 80 percent.

2.2.3 Representation of The Procedure Knowledge

This system adapts sub-program and predicate to represent the procedure knowledge.

In this system, there are two major goals to apply procedure knowledge. One is to carry out all kinds of calculation which inference needs, to analyse the capacity of schemes, to get the value of capacity which could satisfy the needs of future transportation volume, and to take this as the basis of empirical inference. The other is to manage the system, such as to dynamically modify some rules in knowledge base etc.

2.2.4 Representation of State Knowledge

Generally speaking, the structure of the knowledge of this sub-system reflects the thought of "sorting-and-choosing". The system uses the methods of knowledge-representation which combine the object-orientated and production-rule.

For example a kind of reconstruction measure can be expressed as the following object:

object-name: to transfer traction power
super-level object: reconstruction measure
sub-level object: to change the types of locomotives
method 1: information model: input data, output result
method body: to call procedure, to compute data
(example: to calculate the capacity of the line)
method 2: information model: to display the basis situation of the result
method body: to call data base

There are 11 types of objects in the system. They makes up a object-type tree, in which every object has several sub-categories, and each object may have many methods to realize respective functions of the object.

2.3 Inference Machanism

The technical reconstruction decision for single-track railways involves many factors and its procedure is complicated. In order to be fitful to the pratical situation, the designing of inference machanism of this system satisfies the following four aspects of demands: to be able to simulate the process by which the human experts resolve practical problems; to be able to solve the problem which correlative evidences are not suitable for one-time inputting; to be able to analyse problems quantatively and qualtatively; to be able to deal with the problems with the nondeterminacy of origional data and rules.

2.3.1 Interence Strategy

The reasonning type of this system is called two-stage-combined—initiative inference, that is the type of reasonning which combines forward-backward mixed inference with the information which the customer provides.

The foreward inference makes the customers always focus on the most hopeful reconstruction measures. It makes the system be able to determine the feasible schemes according to the major data of existing lines even under the pre-conditions which the evidences have not been defined (since under most conditions the states of the existing lines are quite different, it is very difficult to input the relative materials and data one-time).

After the forward inference finishes, the output will come out if the system has found some kind of technical reconstruction measure existing; otherwise system enters the process of backward inference. The backward inference network is designed to furtherly test the feasibility of schemes.

In the backward inference,the system considers feasible technical reconstruction schemes with preference, then require customers for proofs which haven't input into data base according to the structure of knowledge base.

2.3.2 Application of Imprecise Inference

There are three major kinds of nondeterministic information which we possibly meet in the technical reconstruction of single-track railways:

The first kind is of "nature of probability",since the conditions are not enough and there aren't identified cause-and-effect relationships between conditions and incidents. Volume index, for example, can be produced indirectly in the way of comparing other traffic volumes which have some similarity if the customers can not define it.

The second kind of the nondeterminacy which is caused by fuzzy concepts belongs to "ambiguity", such as the set of topography conditions (class I. II, III, IV, V) . The classes are fuzzy concepts. This kind of nondeterminacy is expressed with subordinate function.

The third displays the degree which customers don't understand facts because of incomplete information.

To use the numbers of intervals to express nondeterministic information can integratedly indicate the above three. On the basis of the above thoughts a type of imprecise inference model expressed by the numbers of intervals is provided, and it has been used in the reasonning of the system.

2.4 Function of System Interpretation And Knowledge-aquirement

The system provides interpretation under the following two situations. One is that the system gives explanation when customers don't understand the questions which it asks them while in backward inference.The other is that the system will provide the procedure of inference after it produces schemes.The inference interpretation of the system uses the method of execution-track.

The knowledge aquirement of the system is established to further develop and improve knowledge base. The subject experts needn't know the inside expressing types of principles, and needn't input the whole principle word by word. The system will automaticly transform the information into a complete inside representation type of principle as long as the relevent data are input according to the system's reqirement.

3. COMPREHENSIVE EVALUATION OF TECHNICAL RESTRUCTION SCHEMES

The scheme-drafting sub-system will reccomend more than two feasible technical-reconstruction plans in most cases. Therefore,the reccomended schemes must be evaluated in order to select the best alternative on the whole. For this aim the comprehensive evaluation sub- system for technical reconstruction scheme is designed.

3.1 Evaluation Indexes Setup

Generally, an evaluated matter are influenced by many factors. The degrees of importance of each factor in the matter are very different from expert to expert and from condition to condition. These factors are called evaluated indexes. This sub-system adapts nine evaluated indexes of engineering investment, repaying period, project time, environment protection and net cash-value rate, inner profit rate, transportation capacity reserve rate, capacity coordinating degree, construction interference degree etc..

In most cases the weights of the evaluated indexes are different with different lines. Therefore,to the special line which will be remaked the primary task to evaluate several feasible technical-reconstruction schemes is to identify the weights of indexes. In this sub-system, the weights of indexes are identified with man-machine interaction according to the experiences of experts and subjective conditions.

3.2 Estimation of Engineering Cost

Among indexes, there is a very important one, engineering investment. Because there are many factors affecting investment, and even most of them cann't be totally forecasted, the estimation of investment is a complicated procedure to an engineering project, especially a railway technical-reconstruction program.

There are two major methods for the estimation of engineering investment. One is rough-estimate, the other is meticulous-caculation.This system uses the former since it is applied in the feasibility research stage of technical-reconstruction of railway. The investment-estimation principle is that under the pre-condition that the objective conditions of the line of reccommended schemes are equal, the major engineering investment of each reconstruction scheme is calculated with "price system" method.

3.3 Method of Comprehensive Evaluation-and-selection

There are a lot of comprehensive evaluation-selection methods.What the system uses is the method to comprehensively evaluate the indexes of every scheme and select the best one with similarity-priority-ratio theory of fuzzy mathimatics and the concept of set- overall- level provided on this base. This method is rigorous,simple and reliable since it is realized through a set of algorithms. The detailed is in document[5].

The basic procedure of the Comprehensive-evaluation-selection is firstly to constitute an ideal specimen-scheme. Every feasible plans then are compared with the specimen- schemen in each index. The plan which has the most closeness to the specimen on the whole is the best one The process of the evaluation-and-selection of the schemes is as the follows:

(1) To choose the best values of the indexes from the given reccomended plans builds a specen as the rule of evaluation-and-selection if it doesn't exist; (2) The closeness- distance between the values of indexes of each plan with those of the specimen- scheme is calculated with Haiming length; (3) To produce the overall level of each plan in order to comprehensively evaluate and select the closeness-distance of any alternative to the specimen-scheme; (4) To express each plan's degree of closeness to the specimen-scheme with quantative methods; (5) In order to really reflect each reccomended plan's closeness to the specimen-scheme, the system regulates the closeness-degree from the importance of each index, and brings forth the reccomended scheme which is closest to the specimen.

The result of evaluation-and-selection is to get an alternative which the overall- level of all indexes is the highest in the reccommended schemes. while the best scheme comes out, the computing values of the many economical indexes of the scheme,such as the data of repaying period of investment, the annual investment distribution in project time ect., will be stored in data base in order to be used by the sub-system of economical evaluation.

4. TEST AND APPLICATION OF ESORR SYSTEM

After it had been tested and improved during the process of research, the system has been used by the authoritive organization-China International Engineering Consulting Company, in the technical-reconstruction decision-assisting for several trunk lines: Chengdu-Kunming, Baotou-Lanzhou and Lanzhou-Xinjiang of the grand Asia-Europe bridge, and comparatively satisfactory results are achieved.At the same time the acquired information have further improved the system. The Designing Institute of Beijing Railway Bureau also successfully used it to carry out the decision-assisting to the technical- reconstruction of Beijing- Chengde railway. The brief introduction of the technical-reconstruction decision- assisting of the several above lines are the following.

4.1 Technical reconstruction of Chengdu—Kunming Railway

The railway from Chengdu to Kunming,total length of 1100 kilometers, passing the industrial, mineral, hydro-electric bases in Leshan,Xichan, Panzhihua and Kunyang ect. , with abundant resources of iron, coal, phosphorus, woods and hydro-power along it , is an important trunk line to develop the economical construction of the southwestern China.

The Chengdu—Kunming line was open on July 1, 1970, and formerly began to operate in 1971. At the present time, the existing line is not fitful for the demand of the increasement of transportation. The occupying rates of the passing capacity of each segment of the 559 kilometers section from Chengdu to Xichang were over 85 percent in 1985 and over 100 in 1987. The volume has been overflow and the line is operating over its load.The total length of the Chengdu—Yangang section is 157 kilometers. With 13 segments it is one of the busist sections of Chengdu-Kunming line.In 1989, the Second Designing Institute of Railway Ministry conducted the feasibility reserach about the technical-reconstruction of electrification to this section, and its results are consistant with what the ESORR system achieved on the whole. See table 1.

Table 1

	Content of Scheme	Long Term Traffic Capacity	Engineering Cost
The second Design Institute of Railway Ministry in ChengDu	1. To adopt SS1 electric locomotive traction; 2. To extend the effective length of arrival & departure tracks to 850 meters; 3. To add a dividing intermediate station between GongXing - PuXing section.	18.8 million tons per year	184.21 million yuan (in 1979 price)
ESORR	1. To adopt SS1 electric locomotive traction; 2. To extend the effective length of arrival & departure tracks to 850 meters; 3. To set up two dividing intermediate stations one between GongXing-PuXing section,another between PuXing-Qing LongChang section.	20.6 million tons per year	207.32 million yuan (in present price)

4.2 Technical reconstruction Decision-assisting of Lanzhou-Xinjiang Railway

Lanzhou-Xinjiang Railways has a total length of 1904 kilometers.It is the only grand trunk of China accessing the northwestern border areas.In order to cooperate with the opening of the Asia-Europe Grand Land Bridge, and much more importantly to exploit the plentiful mineral resources in Xinjiang and to develop the economy in the minority nationality regions, the country has decided to invest to carry out technical reconstruction in the Eighth Five- Year Plan to this single-track railway, which has got a very tense capacity already. The First Designing Institute of Railway Ministry Had provided a feasibility research report at the end of 1990. And the China International Engineering Consulting Company Carried out a decision assisting with ESORR system.

To the most difficult controlling section, from Jiayuguan to Harmi, the system puts forward all possible reconstruction schemes, and outputs their investment,designing capacity and the concerned technical-economical indexes, and compares their advantages and disadvantages in accordance with the different transportation volumes of the near and far future Therefore,the objective and dispartial suggestion are quickly, completely provided to the decision- making organization. According to the decision-assisting report the expert group made their minds up and gave the finnal decision suggestion. China International Engineering Consulting Company is very satisfied with the results of ESORR system.

4.3 Technical reconstruction Decision-assisting of Baotou-Lanzhou Railway

The large amount of freight transported by the southern part of Baotou-Lanzhou railway is mainly coal. The line's transportation capacity has already been saturated. During the research of technical-reconstruction, the designing institute provided the reconstruction plan of electrification only But the experts were diffcult to decide whether the double-line needed or not. After the consulting company meticulously calculated and optimatically selected all feasible schemes with ESORR system, the double-line plan was abandoned. This Decision-assisting saved more than one million Yuan of survying cost, and half a year of the earlier stage of the project was shortened. And it was highly praised by the concerned institutions.

REFERENCE:

1.Donald A. Waterman, A Guide to Expert System, Addison Wesley Publishin Company, Inc., 1986.

2.P.Chatalic, D.Pubols, and H. Prade, An Approach to Approximate Reasoning Based on the Dempster Rule of Combination, International Journal of Expert Systems Research and Applications,1987/1988, volume 1, Number 1.

3.J.R. Quinlan, Consistency and Plausible Reasoning, Proc, 8th International Joint Conference on A.I., Karlsruhe, FKG, 1983.

4.He Zhongxiong, Fuzzy Mathimatics and Application, Tianjin Science & Technology Publishing House. 1985.

5.Northern Jiaotong University, Research Report on An Expert System for Reform Schemes of Single track Railway. 1991.

6.The National Planning Committee, Economical Evaluation Methods and Parameters of Building Projects China Planning Publishing House.

7.Xu Zhufeng, Evaluation Rules of Projects, China Translating Publishing House.

Expert System in Underground Excavations

Système expert pour travaux souterrains

Expertensystem im Untertagebau

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SUMMARY
The presense of karst is a potential danger in tunneling if not foreseen. An expert system, based on experiences in karstic and in underground engineering has been developped for prediction of karst debacles when a tunnel is excavated through a carbonate rock area. This system has been demonstrated and confirmend by experts.

RÉSUMÉ
Le forage dans les zones karstiques peut entraîner des conséquences désastreuses dans la construction de tunnels. Basé sur la connaissance de la science karstique et des travaux souterrains, une banque de données a été développée, afin de diagnostiquer les dangers karstiques en cours de forage dans la roche calcaire. Ce système expert a pu être testé avec succès et confirmé par des experts.

ZUSAMMENFASSUNG
Unvorhergesehenes Anfahren von Karststrukturen beim Tunnelvortrieb kann katastrophale Auswirkungen haben. Mit dem Wissen chinesischer Experten in Karstkunde und Untertagebau wurde eine Datenbank zur Vorhersage von Karstgefahren beim Vortrieb in Kalkgestein aufgebaut. Das Expertensystem wurde erprobt und von Wissenschaftlern validiert.

1. INTRODUCTION

The problems which we meet very often are karst when tunnels or other underground structures are excavated through a carbonate rock area, such as caves filled with sand and crushed rocks, sinkholes, subterranean rivers etc. In many cases, karst may become a very serious disaster in tunneling if no any prediction. The prediction of karst disasters until now relies, besides lots of data from geological exploration, on a unified analysis of these data and on a proper assessment, both of which involve expertise. AI-expert system which simulates the processes of decision making of an expert by computer has been put into practices in recent year[1][2][3]. Therefore, by our point of view,an expert system can be a way to consult about karst disaster for engineers.Under such a consideration we developed an expert system for prediction of karst disasters in tunneling engineering or other underground engineering.

To build an expert system has two ways, one is building by a shell or tools, another is developing proper program according to the characteristics of this problem solving. In this system, the latter way was adopted.

2. KNOWLEDGE BASE

For building this knowledge base, we elicited knowledge from text books, handbooks, research reports, case studies and especially from experts of karst sciences in China by knowledge acquisition [4] .It is known that the development of karst needs a certain environment in which the factors are: soluble and unsolvable rocks (fabric) , water and recent/ancient meteorology, geological structure conditions, topography and conditions of hydrogeology (karst hydrodynamic unit), karst geomorphology,tectonic movements,deep karst and palaeokarst. The general flow chart of this system is showed in Fig.1.

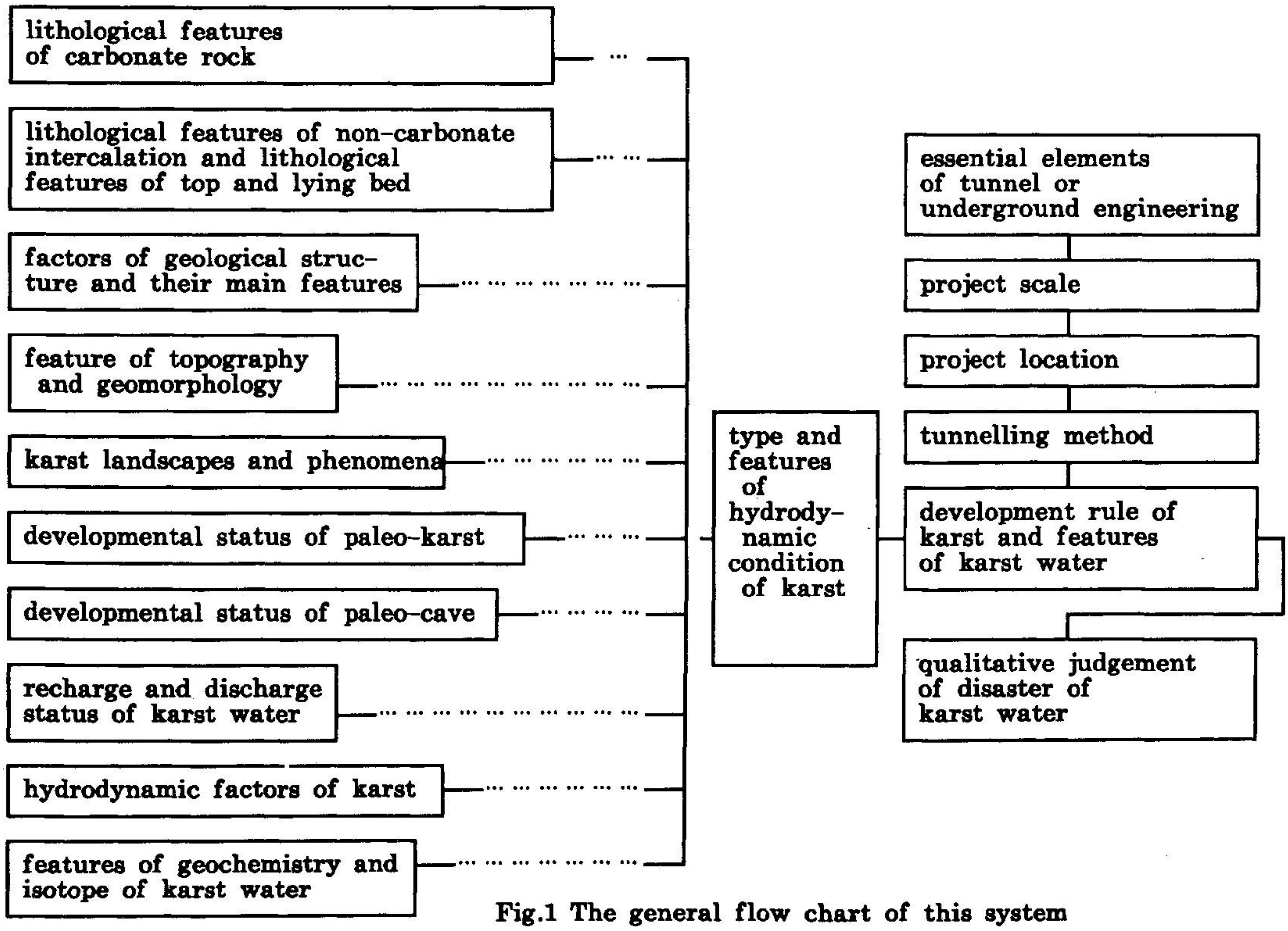


Fig.1 The general flow chart of this system

Of course,it is seen that the development of karst is controlled by ten factors in first order,such as lithological features,which are affected by those factors in second order, and other lower order factors are reasoned by analogy.Obviously,it can be expressed as a reasoning tree. As an example, the factors relationship for the features of paleokarst is showed in Fig.2.

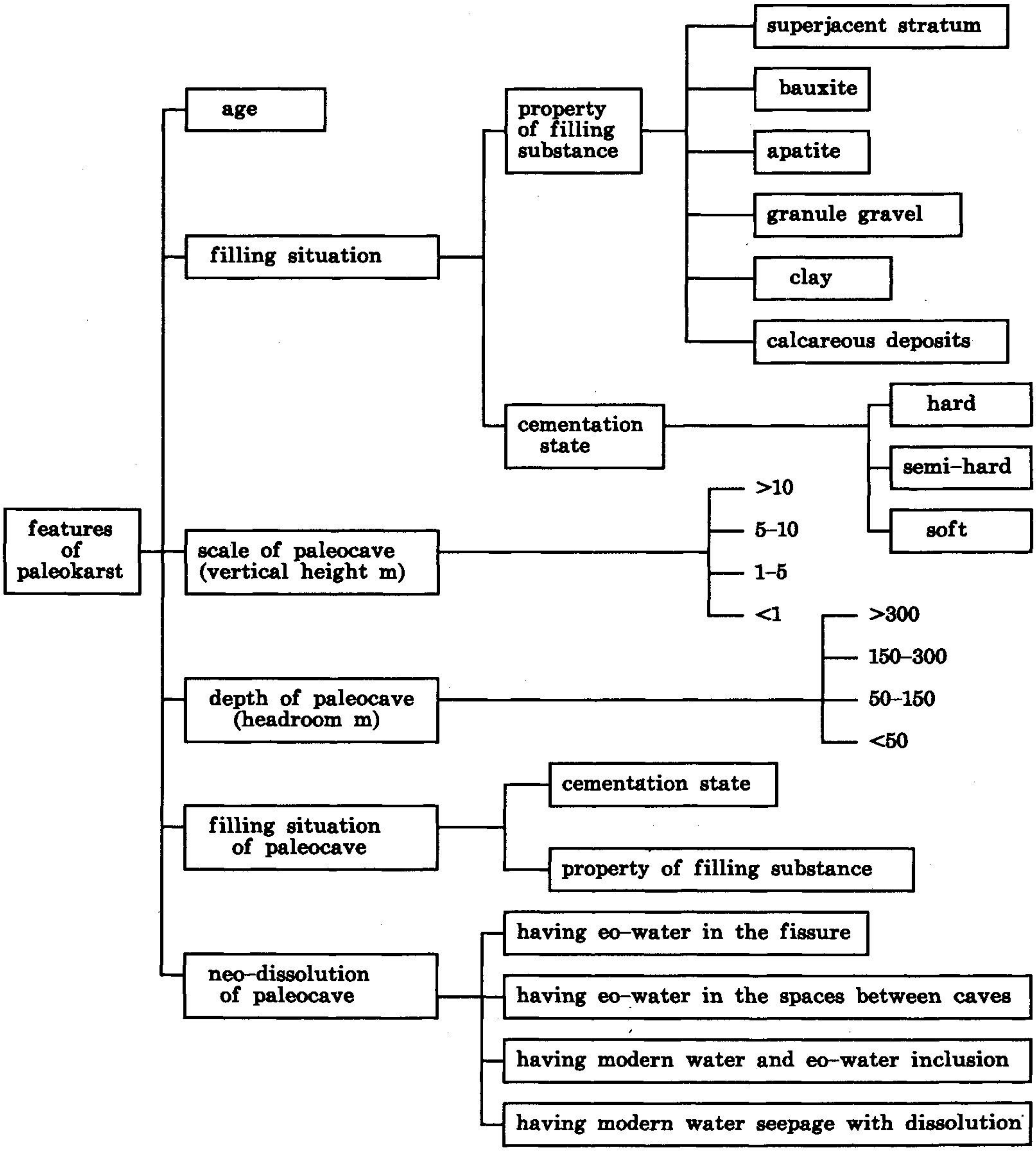


Fig.2 The factors relationship for the features of paleokarst

On this reasoning tree, some of the factors of lowest order are omitted in this paper for simplification. The lowest order factors are the system inputs which should be supplied by user through man-machine communications. Then,the system may infer from the lowest layer, step by step up to the top, to gain the final conclusion.It stands to reason that the above factors should be considered at first from a region of integrated hydrogeological unit including recharge and discharge, and then from a region nearby the underground structure.

3. KNOWLEDGE REPRESENTATIONS

Knowledge representation is a process to symbolize and to formalize these knowledge[5].Both rules and frames are combinably used in this system, that means the knowledge base is composed by parameter file and rule file.

3.1 Parameter file

Parameter file is composed by frames. Any concepts or events,which are called parameters here, appeared in rules should be defined with frames. A frame is a collection of semantic net nodes and slots that together describe a stereotyped object, act, or event. The components of a frame are showed as the following:

Prmti (i=1,2,...n)
- name :
- type :
- ask :
- show :
- range :
- score :

In this system the classification of parameters may be divided into: yes/no, single value, multi-value and fuzzy. such as:

Prmt2
- name : lithologic character and texture of carbonate rock
- type : m-value
- ask : "lithologic character and texture of carbonate rock"
- range: crystalline texture, fragmental texture, skeleton texture, pel-micrite structure

Prmt3
- name : single layer thickness
- type : fuzzy
- ask : "single layer thickness of carbonate rock"
- range: >2, 2-0.5, 0.5-0.1, 0.1-0.05, <0.05
- score: $\tau 0$ $\tau 1$ $\tau 2$ $\tau 3$ $\tau 4$

where the content in the slot of "ask" is the words appeared on the screen, which need to answer by the user as the input, and "score" expresses the degree of confidence(d. c. see the next section, "Approximate Reasoning" in detail).

3.2 Rule file

Rule file is composed with rules. A rule consist of an "if" part and a "then" part. To work forward with such rules, moving from condition-specifying "if" part to action- specifying "then" part,which are called condition-action rules or production rules. Its formal type may be defined as:

```
rulei (i=1,2,...n)
    if   antecedent1 (d.c.1)
         antecedent2 (d.c.2)
             :
    then consequent  (d.c.i)
```

where the (d.c.i) is the degree of confidence of this antecedent and this rule.

for example:

```
rule70
    if   time is D or C or P or T                            (1)
    and  texture is crystalline or skeleton                  (1)
    and  single layer thickness is (2–0.5m)                  (1)
    and  lithological features is pure carbonate rock        (1)
    then a–conclude is fit for strong karst development      (1)
```

4. APPROXIMATE REASONING

Domain experts very often do some reasoning based on their own knowledge according to personal experiences, more or less subjective judgement, more or less precise and/or certain evaluation and appreciation. Consequently the inference is faced to lots of uncertainties. Approximate reasoning is a way to deal with this kind of problems, and is a very active research topic in artificial intelligence.There are many approaches in this area, some are based on Probability, some on Fuzzy Set Theory, or are called non-numerical method [6]. In this system fuzzy set theory approach was used by two steps, first the d. c. of antecedent was determined and then the d.c. of conclusion was concluded.

4.1 The Degree of Confidence of Antecedent

The d.c. of antecedent is defined by frame score slot in which for single values d.c. is 1; d.c. with the preferred are 1 or are distributed through weight in m-value, and the fuzzy one is dealt with by the following way.

for example:

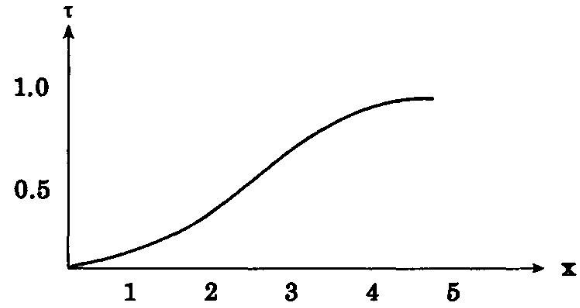
```
prmt3
    name  : single layer thickness
    type  : s-fuzzy
    ask   : "single layer thickness of carbonate rock(m)".
    range : >20, 20-5, 5-1, 1-0.5, <0.5
    score : 1.00, 0.64, 0.00, 0.00, 0.00
```

If the user's answer to the "ask" about the layer thickness is >20m.This input is a precise value but an approximate one, which means somewhere may be equal to 20m or somewhere are less than 20m. To reflect this situation and to fulfil the requirement of fuzzy reasoning later, the following means was used.

When the thickness input is >20m, then the d.c. of >20m is 1, but other indexes thickness also have their d.c., τ i(range/d.c.) as:

>20m/1.00, 20–5m/0.64, 5–1m/0.16 1–0.5m/0.00 <0.5m/0.00

This calculation was adopted out of consideration for that the membership function was normal distribution and could be enumerated by the formula in Fig.3. Where kj and tj are the parameters of membership function, kj=n(the general number of factors) , tj may be determined according to Zadeh's method, that is τ =0.5 at its crossover point[7].



$$\tau_i=\exp[-(\frac{k_j-x_j}{t_j})^2]$$

Fig.3 Membership function

4.2 The Degree of Confidence of the Conclusion

4.2.1 If the rule has only one antecedent, such as:

if A(τ 1) then B(τ 2)

where A is antecedent with d.c.= τ which may be determined by the frame or by the lower inference, and B is conclusion with rule's d.c.= τ which is provided by domain expert. Then the d.c. of conclusion B is

$$\tau = \tau 1 * \tau 2$$

4.2.2 If the rule has multiple antecedents, such as:

if A1(τ)&A2(τ)&.....An(τ) then B(R)

where R is the d.c. of this rule, τ is the d.c. of antecedent.Two cases may be occurred: if A1, A2, ... An play the same role ,that is to say these antecedents are equal weight, otherwise their weights W1, W2, ...Wn should be defined by domain expert respectively. Then the d.c. of conclusion from this rule is:

$$\tau = \{ \sum_{i=1}^{n} (\tau i * Wi) \} R$$

for example:

rule 32

if the height of groundwater divide is >300m (τ 1)
and groundwater hydraulic gradient is 0.27 (τ 2)
and speed of karst water is >10 (τ 3)
and hydraulic—relation among carbonate rock is very weak (τ 4)
and leakage relation is very weak (τ 5)
then the characteristic of hydrodynamic is weak karst water(R32) τ =0.7

That means the d.c. of the conclusion inferred from this rule is 0.7

5. FUZZY PATTERN CLASSIFICATION

The conclusions of prediction disasters are divided into four categories:

(1) The disaster with serious active karst water

From one or multiple vasculars of active karst water will flow in suddenly with large specific yield also in company with debrises and sands. If the flow will continue in a long period more vasculars will be induced and collapese on ground surface will be occurred.

(2) The disaster with action karst water

From one or more than one vasculars active karst water flows in with not large specific yield which will be increased after certain time ,and then more vasculars will be induced. Karst water is in company with debrises and sands. If the flow keeps in a long period, collapese on the surface also can be found.

(3) The disaster with close-active karst water

From only one vasculars of active karst water flows in. But there are karst water inclusions dispersed permeation from which the karst water may also be sent out with lots of debrises and sands.If the closed karst water flows in, the volume of them will be decreased with time, but the active water volume will be increased. The collapese will be occurred on surface partly if long period karst water flows in.

(4) The disaster with karst water inclusion

Only the closed karst water will flow in with debrises and sands.During this karst water is diminished, attention must be pay to other induced karst water.

It is not possible that the conditions of hydro- geology and engineering geology of a concrete position of a structure are fulfilled the antecedent's requirements for karst development of one of the above categories. For example, maybe some antecedents coincide with the second category, but some of them coincide with the third one. For this reason a technique called nearest neighborhood was adopted[8].The patterns recognized are supposed to be fuzzy subsets A1, A2, ... An of the universe of discourse U. A certain pattern B also is a fuzzy subset in U. The principle of nearest neighborhood is:

$$(B, Ai) = \max_{1<i<n} (B, Ai)$$

where Ai is the d.c. inferred from the real engineering set, which means that the degrees satisfied those antecedents of the four categories respectively. B is one that implies a fulfillment one of antecedents of the four categories.

6. OPERATION of THIS SYSTEM

This system runs on IBM-PC and its program was programmed with C. The operation is proceeded through man-machine communication. Once the conclusion is reached then the reasoning line could be given from the explanation facilities of this system. The validity of this system has been demonstrated and affirmed by domain experts.

7. CONCLUSION

Until now some of the technologies in engineering sciences are dealt with by expertise of domain experts, prediction of karst hazards is one example of them. The expert system appeared in recent years has provided us a means to handle this kind of problems. In this system lots of experiences in karst development were collected from Chinese experts in karst sciences. It is believed that this kind of accumulations is very beneficial to engineers. This system can be used in tunneling engineering or other underground engineering with great potential for cost saving.

8. ACKNOWLEDGEMENT

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9. REFERENCES

[1]. B.G.Buchanan and E.H.Shortliffe: Rule-Based Expert Systems, Addison- Wesley Publishing Company(1984).

[2]. R.O.Duda et al.: Development of the PROSPECTOR Consultant System for Mineral Exploration. Final report for SRI projects 5821 & 6415,Artificial Intelligence, SRI International, 1978.

[3]. Q.Zhang et al.:An Expert System for Classification of Rock Masses. Proc. of the 29th U.S.Symp.on Rock Mechanics.1988

[4]. Q.Zhang: Knowledge Acquisition in Expert System. Computer Science, No.5, 1987, (in Chinese).

[5]. Jiwen.Guan: About Knowledge Representation. Computer Science, No.1, 1987,(in Chinese).

[6]. L.N.Kanal & J.F.Lemmer: Uncertainty in Artificial Intelligence, 1-4, 1986, 1988,1989, 1990.

[7]. L.A.Zadeh. 1981. PRUF a Meaning Representation Language for Natural Language. In Fuzzy Reasoning & its Application, Mamdani & Gaines ed. Academic Press.

[8]. Peizhuang.Wang & et al. Applied Fuzzy Mathematics 1989 (in Chinese)

Expert System for Seismic Assessment of RC Buildings
Système expert pour l'aptitude sismique de bâtiments en béton
Expertensystem für die Erdbebentauglichkeit von Gebäuden

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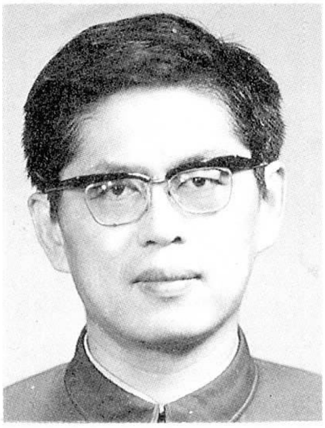

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SUMMARY
The expert system presented has been practically used for seismic resistance evaluation of existing single story reinforced concrete industrial buildings. The paper discusses its knowledge acquisition, representation, architecture, handling of deep knowledge, integration of knowledge base, graphic software and computing programmes.

RÉSUMÉ
Un système expert a pu servir à déterminer l'aptitude sismique des bâtiments industriels existants, en béton armé et à un étage. Les auteurs exposent l'acquisition des connaissances, la représentation, l'architecture, l'accès aux connaissances particulières, ainsi que l'intégration de la banque de données, avec logiciel graphique et programmes de calcul.

ZUSAMMENFASSUNG
An vorhandenen einstöckigen Industriebauten aus Stahlbeton wurde ein Expertensystem zur Ermittlung der Erdbebentauglichkeit eingesetzt. Der Beitrag behandelt die Erhebung der Wissensbasis, die Darstellung, den Aufbau, den Zugriff auf tiefliegende Erkenntnisse, sowie die Integration der Datenbank mit Graphiksoftware und Berechnungsprogrammen.

1. PRELIMINARY REMARKS

The need for diagnosis, evaluation, rehabilitation and retrofit of existing buildings is quickly growing up in many countries in the world. Diagnosis and strengthening of existing buildings are more difficult than design of new buildings, and skillful engineers in the field are lacking. Experience and expertise involving concepts, judgment and inference play important role in the field. Development of the expert system for evaluating seismic resistance of single story RC industrial buildings, SASIBR, is based on symbolic inference capacity of the expert system technology.

Developing expert systems in the field of structural engineering started in the late 70's [1], 15 years later than that in many other fields. This is perhaps because of the following executive characteristics of the knowledge in structural engineering [2, 3], that make building expert systems of structural engineering more difficult than in other fields:

-A deal of important knowledge on structural engineering are in various codes and standards,

-complicated numerical computation is often inevitable in the field of structural engineering,

-A great amount of data is often involved in the field,

-Uncertainty involved with many parameters in the field is more suitable to be described by the probability theory,

-A variety of knowledge in the field leads to the necessity of development of integrated systems.

SASIBR has been developed based on the following principals of practicability that make expert systems vital:

-Integrity of knowledge: Expert systems have to keep complete knowledge necessary for their work. The knowledge on evaluating seismic resistance of existing buildings consists of two parts. The first one is on construction requirements that guarantee these buildings to have reasonable load transferring paths, and on requirements of detailed design regulations that guarantee structural components of buildings to exert their assigned load bearing ability. The second one is on analysis of effects of different loads and check of strength of structural components of different materials. Integration of knowledge makes expert systems able to carry out throughout indoor evaluating work. SASIBR has the both parts of complete knowledge on evaluating seismic resistance of single story RC industrial buildings.

-Authority of knowledge: Knowledge stored in expert systems has to be authoritative in concerning fields, and can be generally accepted by engineers in concerning profession. SASIBR has complete knowledge of concerning provisions of two Chinese nation codes revised recently, i.e. The Evaluation and Strengthening Design Code on Seismic Resistance of Buildings [4] and the Design Code of Seismic Resistance of Buildings GBJ11-89 [5], and their commentaries, as well as explanation on concerning provisions by responsible members of the revising committee.

-Ability to work on the most popular computers and operating systems. SASIBR has been designed to work on IBM PC/AT or compatible computers and under DOS operating system.

-Convenience to be used: SASIBR interacts with users in Chinese. It can display graphically on screen structural models of evaluated buildings, loads, and computed forces, deformations, and safety margin. Its specially designed input unit can minimize user's input effort by five ways. Its execution is suitable to practical evaluation work that different data are input at different stages of evaluation. Junior engineers can use it after a few days training.

-Ability to quickly obtain conclusions: Engineers from a design institute finished by SASIBR evaluation work of a two span buildings and obtained a reliable report of evaluation in one day, tree days less than that needed without it.

After 5 year research and development, and after being tested by first users and improved , SASIBR has been practically applied now. It checks buildings unit by unit and span by span. Its knowledge base can fire external programs and get data from them. When each of its execution ended, SASIBR produces a final report that gives evaluation conclusion with a list of components and connections that should be strengthened. SASIBR includes 400 facts and 600 rules. Its source file consists of 18,000 lines. SASIBR is offered in 5 pieces of 5" diskettes of double density, together with a manual of 77,000 Chinese characters[8].

2. ACQUISITION AND REPRESENTATION OF KNOWLEDGE

2.1 Effects of Earthquakes on buildings

SASIBR holds the data of design seismic intensities of 195 cities and countries in China, with normalized design response spectra from the Code [5]. In addition, it can accept results from special seismic risk analyses.

2.2 Knowledge of Seismic Resistance of Single Story RC Industrial Buildings

This block of knowledge consists of 2 parts. The first part describes the following effects on seismic damage of the whole structure of being evaluated buildings:

-The importance of buildings and potential secondary disaster.

-Harmful situation of site geology, soil characteristics and natural or artificial foundations.

-Vertical and plan irregulation of building configuration. In transverse direction it involves existence of single brick end wall at two ends of a building unit, existence of brick partitions higher than 3 meters transversely filled in bents, existence of unequally spaced columns along column lines in a building unit, and existence of operating platforms rigidly connected to columns. In longitudinal direction it involves existence of side walls of different materials in a building unit, existence of brick walls higher than 3 meters longitudinally filled in column lines, and so on.

The second part of knowledge is main contents of knowledge in SASIBR, that involves the complete knowledge evaluating seismic resistance of components, members and connections of single story RC industrial buildings. Based on different functions this part of knowledge is filled in five sub-bases of knowledge:

-Skylight systems: The most serious damage to single story RC industrial buildings is caused by collapse of RC skylight frames in the longitudinal direction of building unit. This sub-base keeps knowledge on top chords and vertical struts of skylight frames, on vertical bracings of skylight frames, on window frames and concrete panels on skylight frames, and on connections between these members, and between skylight frames and roof trusses, and so on.

-Roof systems: This sub-base keeps complete knowledge on requirements on all members and connections of both of purlinless roof system (with precast RC double tees supported directly on roof trusses) and purlin roof system (with corrugated cement sheets or steel formed deck units supported on purlins). See Fig. 2.

-Walls: Solid brick walls in single story industrial buildings usually do not bear any load from other components, even then improperly designed or located brick walls have made serious damage to the buildings during past earthquakes. Badly located brick walls damaged RC columns, falling down blocks of brick walls smashed lower components and equipments, and near-by buildings, and caused secondary disaster. This group of knowledge includes knowledge on both solid brick walls and precast concrete panels, and also includes knowledge on end walls, side walls, blocking walls and filled partitions. Its structure is showed in Fig. 3.

-Column bracings: Column bracings designed for resisting effects of wind and overhead cranes usually have the ability to bear effects of earthquakes up to intensity 7. In addition of column bracings, brick side walls and columns can also bear effects of earthquakes in the longitudinal direction of building units. Seismic damage of single story RC industrial buildings due to improperly designed column bracings in the longitudinal direction during past earthquakes, therefore, was not very serious. This group of knowledge involves only check of construction characteristics, and does not need dynamic analysis, according to ideas of experts in the field.

-RC columns: This group of knowledge includes RC columns connected to bracings, upper parts of columns supporting roof trusses of the spans of their two sides at unequal heights, and column brackets supporting the lower trusses or crane girders. In many cases, dynamic analysis and strength checking are necessary, and should be kept in SASIBR, and link to the sub-base of knowledge.

-General assessment of seismic damage of spans, units, and buildings: This group of knowledge gives marks on each span, each unit and each building based on the evaluation of the sub-bases of knowledge.

2.3 External programs

Based on the requirements of evaluation of seismic resistance of single story RC industrial buildings, the following 5 external programs are included in SASIBR:

-Data reading program PR: It reads the data necessary for dynamic analysis and strength checking, but not needed by knowledge base.

-Data reading and pre-processing program of bents PG: It makes analytical models of buildings having up to 6 spans after reading data, numbers nodes and elements, condenses masses of blocks of walls, columns or crane girders on proper nodes, calculates loads on column brackets from crane wheels and crane girders, deals with built-up RC columns or columns that have big opens in their webs, and assigns 12 different combinations of dead loads, live loads, snow loads, loads from cranes, and seismic effects, according to the related Code.

-Static and dynamic analysis program of 2 dimension finite element PS.

-Strength checking program of RC and steel components PSA: It is totally based on the recently revised Codes [6,7].

-Graphic display program PP: It displays structural models of finite elements of the bents of being evaluated buildings, loads at the nodes, free vibration mode shapes, computed moments, axial and shear forces on all members of the bents, deformation of the bents, and safety margins of all members of the bents. A menu in PP can help users to do many things.

2.4 Representation of knowledge and Inference

The production rules are used for representing knowledge in SASIBR. Forward chaining and depth first search are used for SASIBR.

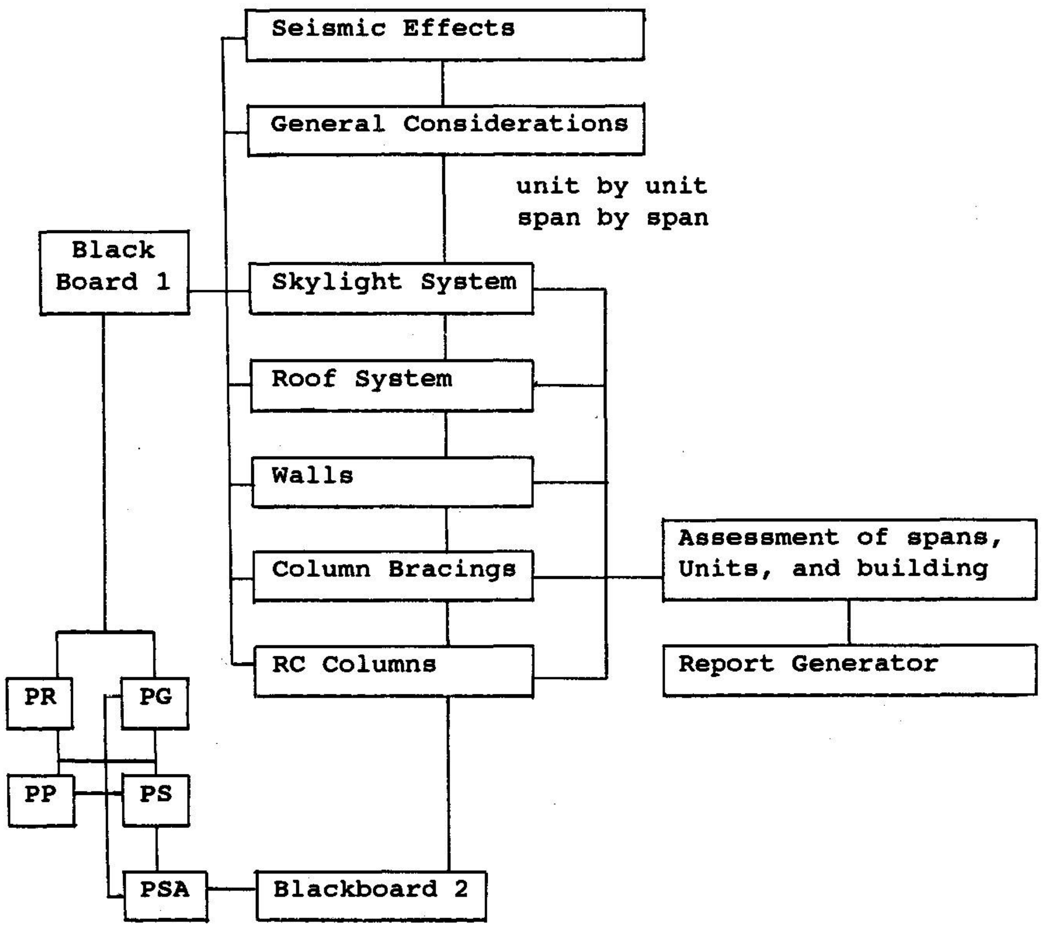

Fig. 1 Architecture of SASIBR

3. ARCHITECTURE OF SASIBR AND ITS KNOWLEDGE BASE

3.1 Architecture of SASIBR

SASIBR has blackboard structure, its knowledge base is divided into 8 sub-bases (Fig. 1). Transferring information between the sub-bases or between the sub-bases and the external programs is carried on by the blackboards.
The knowledge base has hierarchical structure, at the top level is the general considerations, next to the top level are the 5 sub-bases. All of the 5 sub-bases have plenty of knowledge, for instance see Fig. 2 for the sub-base 'Roof

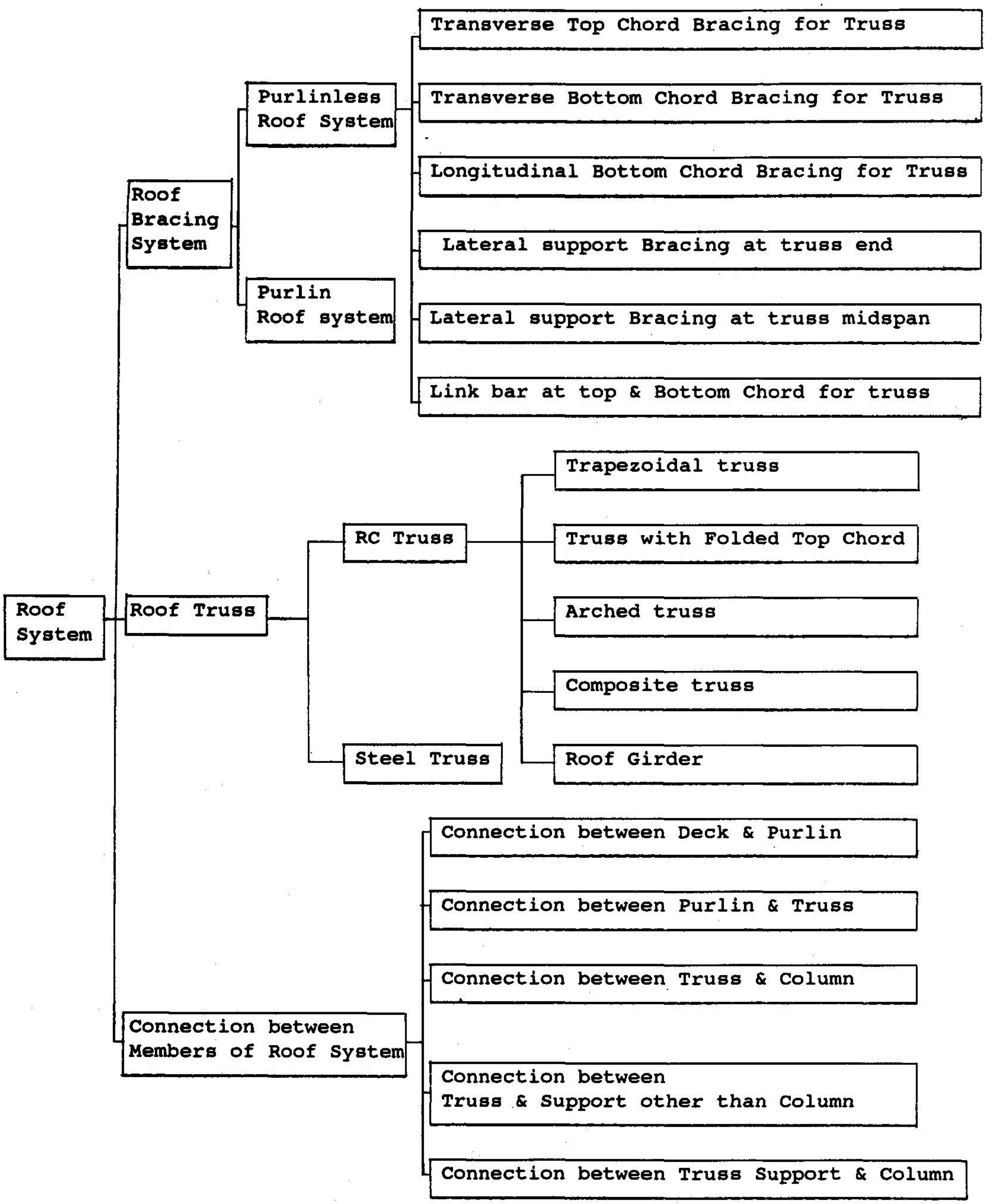

Fig. 2 The sub-base 'Roof system'

System', and Fig. 3 for the sub-base 'Walls', the knowledge in the sub-bases also have hierarchical structure. For instance, the hierarchical structure of the lower sub-bases 'Top Chord Bracing for Trusses' in the sub-base 'Roof System' is showed in Fig. 4.

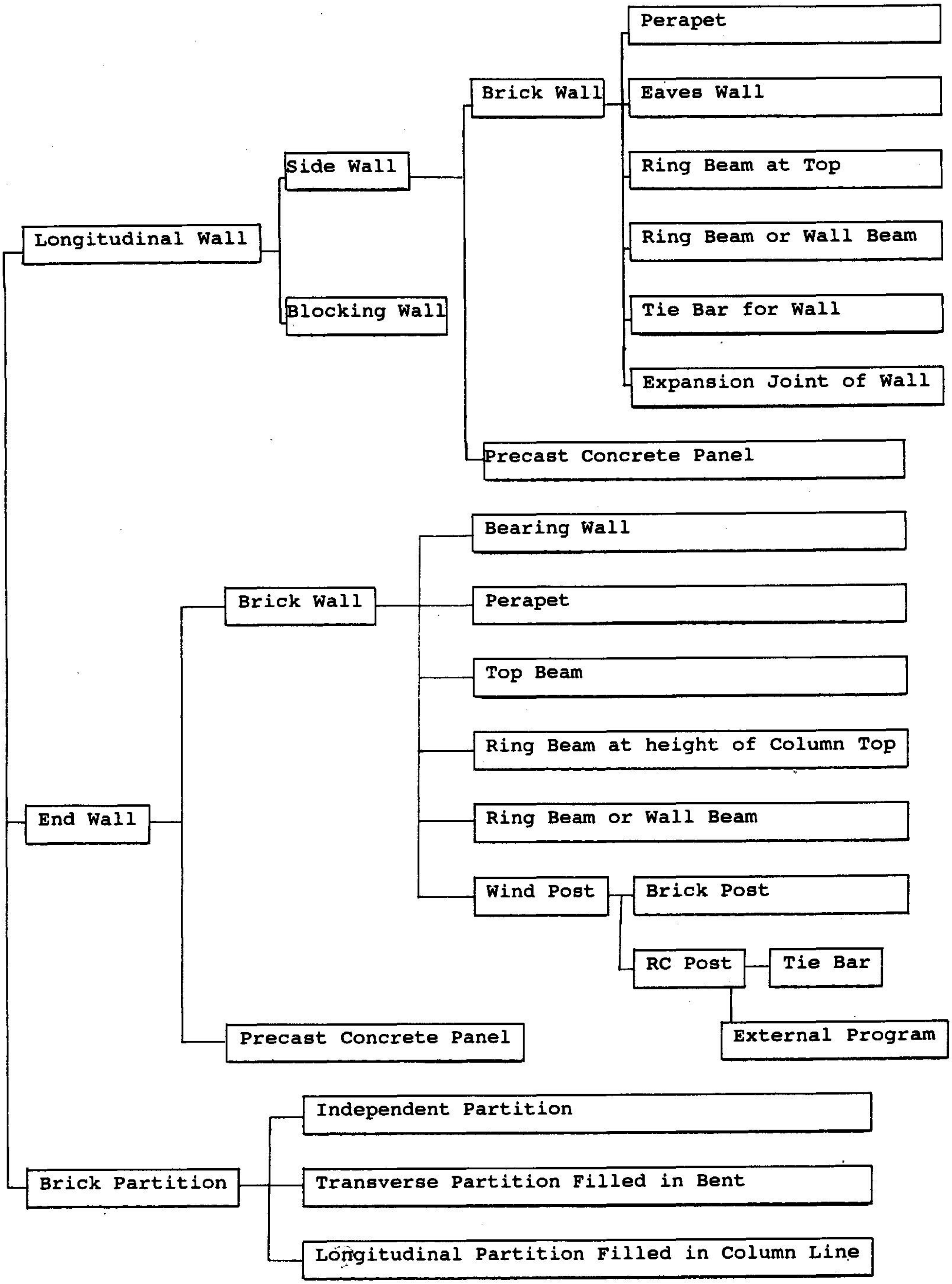

Fig. 3 The sub-base 'Walls'

The context of SASIBR holds all of initial and inferred data and facts such as
'A line of Top bracings for truss exists in each end bay',
'Type of roof truss is Trapezoidal',
and so on.

Every sub-base of knowledge holds knowledge of special area, that is represented by a number of rules. For example, one of such rules,

RULE#
IF Roof system has Purlin,
AND Type of roof truss is Trapezoidal,
OR Type of roof truss is Arched_top_chord,
OR Type of roof truss is Polygonal_top_chord,
AND Intensity is 9,
THEN a line of Top bracings should be set in each end bay.

is in the block 'Layout of bracing' in Fig. 4.

3.2 Implement of SASIBR

The languages of Assemble and FORTRAN are used for developing SASIBR. Designing the blackboards for transferring numerous data is a difficult job. Some available expert system shells, such as INSIGHT2+ is not suitable for transferring such big amount of data. A specially designed manager of data base in SASIBR supervises the blackboards for transferring information.

The following 5 ways are used in SASIBR for inputting data:

-The data base manager generates a list to guide input of data after a few information on general considerations are input. Users can input data according to the list, and avoid spending much time on judging which data should be input and on inputting great amount of useless data.

-Any piece of data can be input by either filling the data list or by answering the screen. Great amount of data is better input by filling the list. During execution, SASIBR will ask users to add some data when needed.

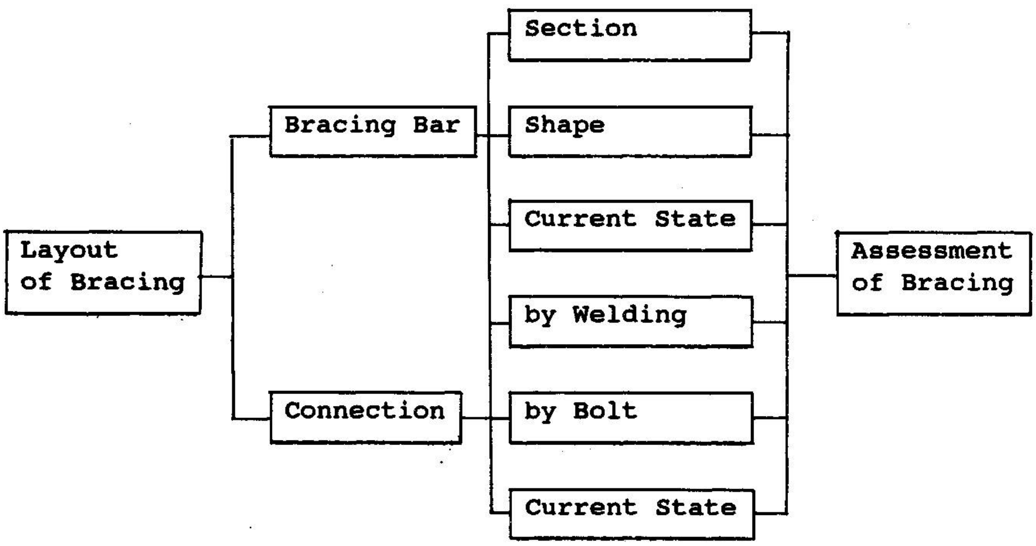

Fig. 4 The sub-base 'Transverse Top Chord Bracing for Truss'

-The data list includes default values of many data. The default values are standard or most common values of data.

-Many mistakes made by users during input are immediately found and shown on screen.

-Data needed by practically evaluating works are from different sources such as documents, drawings, and field testing. And the data input during the earlier stages of evaluation decide what data will be needed for the later stages when practical evaluation works are being carried on. Based on these situation, SASIBR is designed in such a way that its execution can be broken at any step , and then continued after some new data are input or some old data are corrected without loss of any data whether by input or inferred before.

Similarly to practical evaluation, SASIBR evaluates consecutively each span and each unit of buildings one by one. For each span of buildings, SASIBR use the five sub-bases to obtain conclusions. All informations about the conclusions are stored in the context, that will be used for general assessment and the final report.

The data in the knowledge base of SASIBR will be automatically transferred to the external programs when needed. Dynamic analysis and strength checking, however, require more data than that needed by the knowledge base. The programs PG and PR will read that part of data. The instruction how to input those data is in the book 'SASIBR Reference Manual'[8].

REFERENCES

1. WATERMAN D. A., A Guide to Expert Systems. Technology Inc., 1986.

2. FENVES S. J.., expert Systems: Expectation versus Reliability. Proceedings of IABSE Colloquium. Bergamo, Italy, 1989.

3. LUI X. L., and QIN Q., Expert System Technology in Structural Engineering. Jiaotong Press, to be published.

4. Aseismic Evaluation and Strengthening Design Code of Buildings. to be published.

5. Aseismic Design Code of Buildings (GBJ11-89). Jiangong Press, 1989.

6. Design Code of Concrete Structures (GBJ10-89). Jiangong Press, 1989.

7. Design Code of Steel Structures (GBJ17-88). Jihua Press, 1988.

8. CHEN S. R., and QIN Q., SASIBR REFERENCE MANUAL. CRIBC, 1991.

Expert System for Estimating Bill of Quantities

Système expert de détermination des métrés

Expertensystem für die Mengenkostenermittlung

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SUMMARY

This paper presents an expert system for estimating civil engineering works and its autoadaptive databases. The representation of a portion of knowledge possessed by experienced estimators, the inference mechanism, autoadaptation of the databases to the changes in knowledge base and other components are discussed in sufficient detail. The proposed system has adequate explanatory facilities and hence can help novice estimators or students in the determination of the bill of quantities on an international scale.

RÉSUMÉ

Le système expert développé par les auteurs est destiné à la détermination des métrés en génie civil et à l'auto-adaptation de la banque de données correspondante. Il expose en détail l'apport de connaissances d'éminents experts en estimation des coûts, le mécanisme de déduction, l'adaptation automatique de la banque de données en fonction des modifications intervenant dans la base de connaissances, ainsi que d'autres composantes du système expert. Ce dernier peut, grâce à l'incorporation de moyens auxiliaires explicatifs, apporter une aide appréciable à des techniciens inexpérimentés dans la détermination des métrés pour des maîtres d'ouvrage à l'échelle internationale.

ZUSAMMENFASSUNG

Der Beitrag präsentiert ein von den Autoren entwickeltes Expertensystem für die Kostenermittlung von Tiefbauvorhaben und dessen sich selbsttätig erweiternde Datenbank. Die Darstellung des Teilwissens erfahrener Kostenschätzer, die Uebertragungsregeln, die Anpassung der Datenbank an Aenderungen in der Wissensbasis und andere Programmkomponenten werden angesprochen. Dank eingebauter Hilfestellungen kann das Programm Neulingen oder Studenten bei der Mengenkostenermittlung für internationale Auftraggeber behilflich sein.

1. INTRODUCTION

Chinese contractors are becoming more and more involved in overseas operations and they need computer softwares to aid them in pricing bill of quantities provided by international employers.

There are several foreign estimating softwares available on the international market. But they are not quite suitable for Chinese contractors because of their being expensive and written in English.

When the authors conceived an estimating software for the Chinese contractors three years ago, they had two options to choose, a conventional algorithmic program package and an expert system.

As a matter of fact, in China there are several dozens of computer packages in use by construction companies to estimate domestic construction projects. The estimating packages are based on the State or regional authorities stipulated norms for detailed estimates of the normal amount of labour, material, or construction equipment required per unit measure of various building or civil engineering works elements. All of the packages are custom built for local regions and difficult to adapt to other parts of China, let alone of the world, Their inflexibility is due to the steps in which human estimators estimate a construction projects having been coded into them and their users being unable to modify the steps as the case may require.

Expert systems have several advantages over the algorithmic packages because of being able to handle structured symbolic data, complete or incomplete, certain or uncertain, which represents a model of the relationships between data elements and the uses to be made of them, and to communicate with their users in natural Chinese language.

In order to make the conceived estimating system to hold appeal to Chinese contractors, the authors decided to try an expert system even though it would be risky to make such a try. The expert system built by the authors is termed ESBOP and its architecture is given in Fig.1.

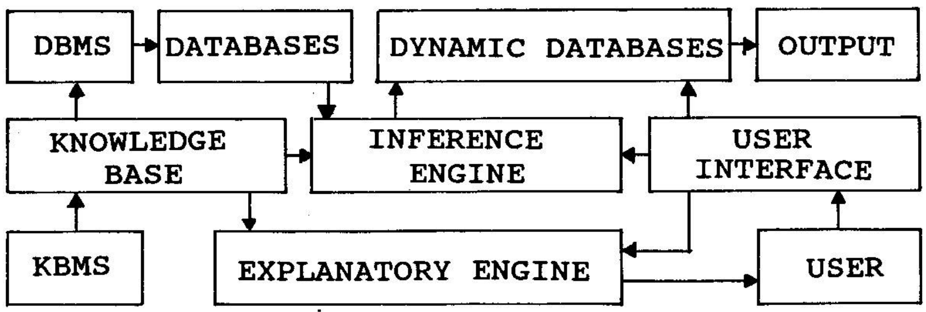


Fig.1 Architecture of ESBOP

2. KNOWLEDGE REPRESENTATION

As well known, a prerequisite for applying the expert system technology to the domain of estimating or pricing bill of quantities is the existence of human experts in estimating. An expert estimator combines his common sense, awareness of fluctuations of resources suppliers' quotations and other potential risks which will influence and affect his tender price, knowledge of the correctness and sufficiency of his tender and the rates and prices entered by him into the bill of quantities and skills of defining and manipulating formulas when estimating a works and prices bill of quantities provided by the employers.

Again as well known, it is very difficult to elicit all the estimating specific knowledge out of the experienced estimators and represent them in a form that lends itself to implementation on a computer.

However, it is equally true that a portion of the estimating knowledge body can be adequately captured by several sets of production rules.

The rules can be otherwise coded into conventional programs, which will sacrifice the flexibility achieved and deprive the user of control over the system as below described.

2.1 Estimating Formulas Used By Chinese Contractors

The example formulas the Chinese contractors use to calculate the unit rates and prices of the work items in the bill of quantities are as follows.

1. Unit rate = Labour and material cost + Overheads + Profit, or
   Unit rate = Direct cost + Indirect cost
2. Price of a work item = Unit rate x Quantity
3. Overheads = Labour and material cost x Overhead rate, or
   Overheads = Direct cost x Overhead rate, or
   Overheads = Annual overhead expenses
4. Profit = Labour and material cost x Profit rate, or
   Profit = Direct cost x Profit rate
5. Overhead rate = Annual overhead expenses
   / Annual output of a construction company

and etc.

Obviously, the formulas constitute a vital part of the knowledge body of an experienced estimator.

2.2 Representation of Formulas in Production Rules

It is a key step to represent the estimating knowledge as above mentioned in a way appropriate to implement on computer. A close look at the formulas and careful consideration of the relationships in the given portion of the knowledge body will convince the reader that they can be represented in rule form as follows:

```
Rule 1: IF Labour and material cost AND Overheads AND Profit KNOWN
        THEN Unit rate CAN BE OBTAINED
        OPERATORS wnn+n+=
        CONDITIONS used for Method 1

Rule 2: IF Direct cost AND Indirect cost KNOWN
        THEN Unit rate CAN BE OBTAINED
        OPERATORS wnn+=
        CONDITIONS used for Method 2

Rule 3: IF Unit rate AND Quantity KNOWN
        THEN Price of a work item CAN BE OBTAINED
        OPERATORS wnnx=
        CONDITIONS unconditional
```

Rule 4: IF Labour and material cost AND Overhead rate KNOWN
THEN Overheads CAN BE OBTAINED
OPERATORS wnnx=
CONDITIONS unconditional

and etc.

The OPERATORS in a rule indicates to the ESBOP inference engine what operations it should make on the known antecedent variables to derive the value of the consequent variable, while the CONDITIONS indicates under what conditions the rule shall be fired. The rules may be coded into knowledge base in an arbitrary order, not necessarily in a logical sequence.

The full set of production rules will be chained into inference network, as shown in Fig.2(a) when the inference engine reasons.

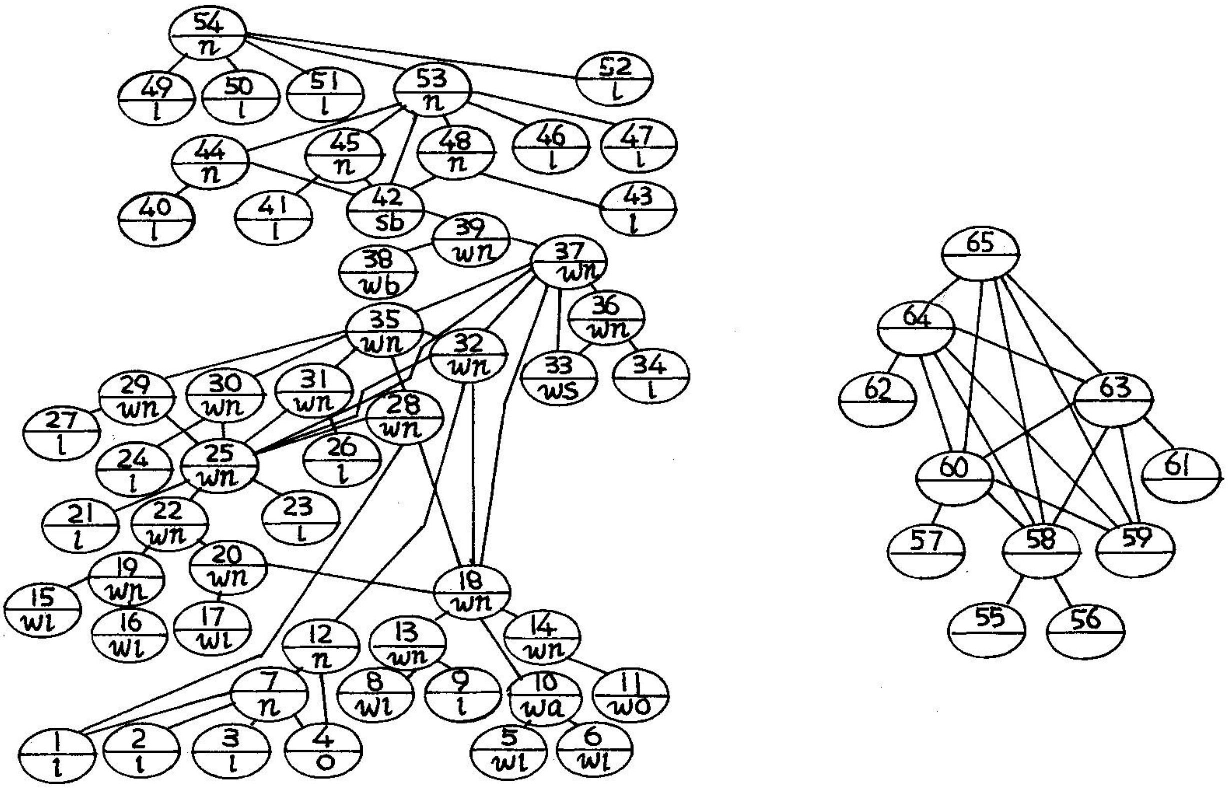
The representation of the formulas in a set of production rules rather than coding them into sequential algorithmic steps of a conventional programme makes it possible for the users, instead of the system developer, to change the estimating formulas as the case may require. For example, if the user wants to add freightage, leakage loss and purchase and storage costs to building material supplier's quotations to produce his estimates of building material costs, he can give this task to ESBOP. One thing ESBOP needs in order to perform the task is the estimating formulas. It is easy for the user to put them into the knowledge base. The formulas are represented in a set of production rules which are chained into the inference network as shown in Fig.2(b).

The inference network in Fig.2(a) represent the model of pricing bill of quantities by an experienced estimator. It is a hierarchical structure of cost or data items, linked through rule and logical arcs, as depicted in the figure. The oval circled cost or data items which can be identified in the pricing process are referred to as nodes. The lines or arcs represent the dependency of one cost item upon the other cost or data items.

Any node in the network together with the nodes, if any, linked to it through arcs from below represent a rule. This node in question represents the consequent of the rule and the nodes linked to it from below represent the antecedents of the rule. For example, the node 12, node 4 and node 7 represent the rule for calculating "Overhead rate". In this case, "Overhead rate" plays the role of the consequent, while "Annual overhead expenses" and "Annual output of a construction company" play the role of antecedents, because the value of "Overhead rate" can not be derived until those of "Annual overhead expenses" and "Annual output of a construction company" are evaluated.

It can be seen from Fig.2(a) that the nodes can be classified into three categories. The top level node in the inference network represents the Tender Price and therefore is the model's goal node, which terminates but does not originate arcs. The terminal or "leaf" nodes correspond to the data asked of the user or retrieved from the databases and therefore are referred to as data nodes which only originate arcs. The intermediate nodes are linked to each other through arcs from both above and below. They represent well-defined cost items forming the Tender Price and therefore are referred to as subgoal nodes.

The rules as shown in Fig.2 are used by the Chinese contractors to estimate building construction works. If there is a need of estimating installation work or other civil engineering works such as roads, bridges and tunnels the user is provided with a facility for coding their formulas applicable to the same into the knowledge base and then ESBOP will manipulate them as intelligently as a human estimator.



(a) (b)

1. Profit rate
2. Employee productivity
3. Number of employees
4. Annual overhead expenses
5. Supplier's quotations of materials
6. Material consumption per unit of elementary work
7. Annual output of a construction company
8. Workhours per unit of elementary work
9. Worker daily payment
10. Material cost
11. Minor material percent
12. Overhead rate
13. Labour cost
14. Minor material cost
18. Labour & material cost
32. Overheads
54. Tender Price
55. Hauling distance
56. Freight rate
57. Leakage loss percent
59. Supplier's quotations of materials
61. Storage waste percent
62. Purchasing cost percent
65. Estimate of material cost

(some items omitted)

(a) Pricing Bill of Quantities
(b) Adding freightage, leakage loss and etc. to supplier's quotations

<u>Fig.2</u> Inference Networks

3. INFERENCE

The ESBOP employs two forms of inference in its reasoning, that is, backward and mixed chaining. There is a user interface in ESBOP for switching the inference between the two forms of chaining in response to the user's request or to the current status of the system.

3.1 Backward Chaining (Goal driven reasoning)

Backward chaining proceeds in two stages, the first stage chains rules together to form an inference network or subnetwork. The second evaluates the antecedents and then the consequent, rule by rule.

ESBOP begins backward chaining by offering to the user menu options which are actually the nodes in the inference network depicted in Fig.2. The user chooses an option, or sets a subgoal or goal. In response to the users option, the inference engine searches the knowledge base and chains all the rules needed to reach the subgoal or goal. In this stage, all the activated rules are examined to ensure that none of them makes more than one appearance in the set of active rules. The activated rules form a complete subset of the knowledge base, which means that the inference subnetwork or network formed of the chained rules is not broken. It can be verified that in this stage the backward chaining uses the depth-first search strategy.

Backward chaining enters the second stage thereupon to evaluate the nodes in the inference subnetwork. This is a bottom to top process, or in a forward fashion because the antecedent nodes are evaluated before the consequent node. The data nodes are assigned the values retrieved from the databases or asked of the user. The values are put into a dynamically allocated memory area referred to as dynamic database for subsequent evaluation of the intermediate or subgoal nodes. When evaluating an intermediate node, the inference engine searches the dynamic database for the values of the antecedents of the rule of which the intermediate node is the consequent. The evaluating process continues until the user chosen node is evaluated. Once the goal or subgoal set by the user is reached, the inference engine comes back to the interfacing menu and returns the control to the user.

The backward chaining as above explained can be illustrated using the case of "Overhead rate". If the user chooses "Overhead rate" at the interfacing menu, the backward chaining will proceed in the two stages as shown in Fig.3. The arrows and the circled arabic numbers indicates the directions and the sequential order of chaining the rules and evaluating the nodes. The chaining and evaluating indicated by the dashed arrow will be avoided by the inference engine.

In this case, Rule 12,7,1,2,3 and 4 are chained in that order. Then the inference engine reverses the order as follows.

Rule 1: IF database1 KNOWN THEN Profit rate CAN BE OBTAINED OPERATORS 1 CONDITIONS unconditional

Rule 2: IF database1 KNOWN THEN Employee productivity CAN BE OBTAINED OPERATORS 1 CONDITIONS unconditional

Rule 3: IF database1 KNOWN THEN Number of employees CAN BE OBTAINED OPERATORS 1 CONDITIONS unconditional

Rule 4: IF database2 KNOWN THEN Annual overhead expenses CAN BE OBTAINED OPERATORS o CONDITIONS unconditional

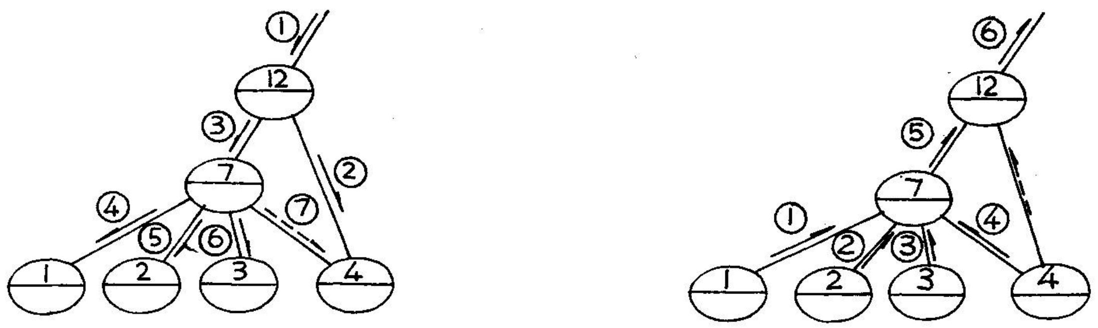
Rule 7: IF Employee productivity AND Number of employees AND Profit rate AND Annual overhead expenses KNOWN THEN Annual output of a construction company CAN BE OBTAINED
OPERATORS nn*n1+/n-= CONDITIONS unconditional

Rule 12: IF Annual overhead expenses AND Annual output of a construction company KNOWN THEN Overhead rate CAN BE OBTAINED
OPERATORS nn/= CONDITIONS unconditional

Having activated the rules, following the '1' in the OPERATORS, the inference engine searches database1 for the values of the consequents of Rule 1 - 3 and retrieves, for example, 0.15, $24,000 and 750 persons, while for that of Rule 4's consequent, it , summing all the overhead expenses in database2 according to the 'o' in the OPERATORS, finds $2,119,230. When it is Rule 7's turn, the engine, making the math as the 'nn*n1+/n-=' indicates, evaluates the consequent as 24,000 x 750/(1+0.15) - 2,119,023 = $13,533,150.91. "Overhead rate", the consequent of Rule 12, is then evaluated to be 2,119,023/13,533,150.91=0.1566 as the 'nn/=' tells.

3.2 Mixed Chaining (Data driven chaining)

When the user regains hold of control at the interfacing menu, he can choose to set another subgoal or goal. If the inference network or subnetwork to be formed by the inference engine in order to reach the newly set subgoal or goal does not contain the nodes which have been evaluated and the values of which have been put into the dynamic database, then another backward chaining will take place. However, if the inference network or subnetwork does contain the evaluated nodes, then the inference will be in a mixed fashion, or a combination of forward and backward chaining. In order to reach the user's new subgoal or goal, the inference engine will search the dynamic database for the last entered item and then pick out of the knowledge base the rule the antecedents of which contain the last item in the dynamic database. Then the inference engine attempts to evaluate the consequent node. If the last item is the only antecedent of the activated rule, then the attempt will succeed. Otherwise, the antecedent(s) of the rule other than the last item in the dynamic database will act as trigger(s) making the inference engine to do backward chaining(s) so that they are evaluated and the attempt to evaluate the consequent node can succeed. When the consequent node has been evaluated, its value will be added to the dynamic database and become the new last item in the same.



(a) Activating rules (b) Evaluating nodes

Fig.3 Backward Chaining

The reason for the inference engine to combine forward and backward chaining instead of using simply the backward chaining to reach the new subgoal or goal is to save reevaluating the previously evaluated nodes, and hence economize the use of the dynamic database.

If the consequent node happens to be the new subgoal or goal, then the mixed chaining will be ended. Otherwise, the evaluated node will trigger a new round mixed chaining in a way similar to the aforesaid until the new subgoal or goal is reached.

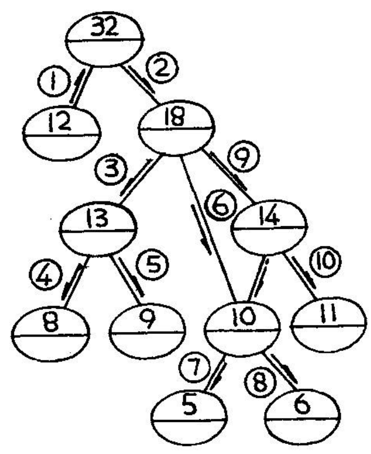


Fig.4 Mixed Chaining

Fig.4 gives an example of the mixed chaining. In this example, the user, after "Overhead rate" has been evaluated, chooses "Overheads" option at the interfacing menu as his new subgoal.

4. EXPLANATORY FACILITIES

ESBOP is provided with two explanatory features. It answers "How" questions from the user. When the user asks "How is "Overhead rate" evaluated?", the system answers by displaying all the rules needed to evaluate "Overhead rate" in a backward chain on the monitor's screen and thus the user will be satisfied by tracing the sequence of rules. "Why" questions are interpreted as "Why is a cost or data item needed to evaluate the subgoal or goal?" The answer is given by displaying the rule chain in a forward fashion which is originated by the node representing the cost or data item in question and top ended by the subgoal or goal node.

The explanatory facilities makes the system very friendly and transparent to the user and can help students in learning estimating and pricing.

5. ACTIVE RULES STACK AND DYNAMIC DATABASE

The rules activated in the first stage of backward chaining are sorted in such a manner as to enable the antecedents of every rule to be evaluated before the consequent and then the pointers to the sorted rules are pushed into a stack named "active". The evaluating begins from the stack top. The pointer to the stack moves down as the evaluating proceeds. When the pointer is down to the stack bottom, the user's subgoal or goal is reached.

All the data and values the inference engine has sought from the databases or derived during chaining are added to the dynamic database which is managed dynamically during the reasoning. The dynamic database does not come into existence until the inference is put into operation and grows in size as the inference goes on. At the same time it keeps track of the reasoning history. The last entered item represents the current status of the system indicating to the inference engine where it arrives when it runs along the inference subnetwork in a backward or forward fashion.

6. AUTOADAPTIVE DATABASES

ESBOP may be different from the expert systems for the domains other than estimating and pricing in that it manipulates much more numeric data than the other systems. The unique characteristic requires the provision of a powerful database management. The DBMS of ESBOP manages building materials, the norms for detailed estimating, bill of quantities and various charge rates.

The serious problem facing the DBMS is the variability of the data structure of the databases. As claimed above in the paper, the system can be adapted by the user to the tasks other than estimating building construction projects, out of which arises necessity of the DBMS's adapting itself to the specific task data structures.

Certainly, there are several approaches to this problem. The common method is to provide a feature (as with dBASE III or IV) by which the user defines the data structures for their particular tasks using CREATE or MODIFY STRUCTURE commands. However, the user will feel it an additional burden to do this. Having studied the inference networks given in Fig.2, the authors find a cue to propose an alternative approach to this problem.

6.1 Dependency of Data Structure of Databases on Data Nodes of Inference Networks

For convenience and clarity of exposition, let us consider the inference network as shown in Fig.2(b). The goal node is the estimate of building materials and the six data nodes represent the building material suppliers quotations, hauling distance, freight rate, leakage, storage waste and purchasing cost, respectively. On the other hand, each record in the building material database shall at least have six fields which are nothing else but the six data nodes in the inference network. It is this coincidence that reveals the dependency of data structure of databases on the rules coded into the knowledge base and leads the authors to a solution to making the databases respond automatically to the changes in the knowledge base.

6.2 A Dictionary Supplementing Knowledge Base

It is certainly true that the records in the building material database shall have another three fields for the purpose of identifying individual materials, namely, description, specification and measure unit. The three fields are the basic attributes of building materials, but do not appear in the inference network and the knowledge base. A dictionary added to the DBMS makes good the insufficiency of the knowledge base. The words and phrases representing the attributes of the data nodes in the inference network are elicited out of the user by the inference engine built in the DBMS and put into the dictionary.

The inference engine of the DBMS can adapt the data format of its database to the tasks implied in the knowledge base without need of the user making changes to them, which explains why the databases are referred to as "Autoadaptive Databases".

When it comes to a dictionary, there is always a fear that it may not be able to cover all possibilities. The sufficiency of the dictionary is guaranteed by the DBMS's capability of picking out the new words or phrases which appear in the new rules coded by the user but have never made appearance in the dictionary before. If the DBMS does make such a discovery, it will prompt the user to put all the synonyms and attributes of the new data nodes into the dictionary.

Having incorporated the dictionary and the inference engine, the DBMS has become intelligent and much more convenient to the user. The enhanced DBMS is shown in Fig.5.

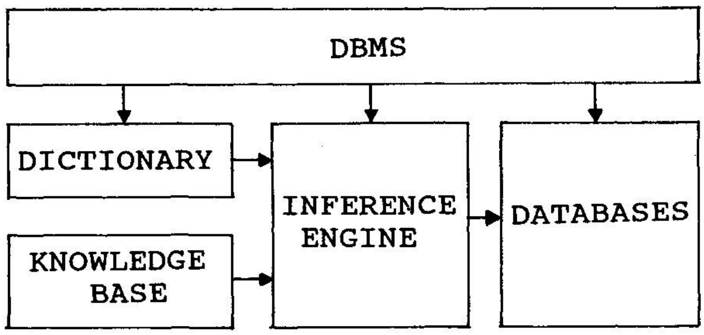


Fig.5 Enhanced Database Management System

7. IMPLEMENTATION DETAILS

ESBOP is coded in Microsoft C. C is both a symbol and a numeric processing language and best meets the need of building expert systems. Its recursive function makes it easier to code the inference engine than several other programming languages such as BASIC and FORTRAN. The good portability of C also makes it popular with the world wide programmers. ESBOP is run under DOS and on GW286, GW386 and other compatible microcomputers with Chinese character system.

REFERENCES

1. P.H. WINSTON, Artificial Intelligence, 2nd Edition. Addison-Wesley Publishing Company, 1984.

2. L. JOHNSON, E.T. KERAVNOV, Expert Systems Technology - A Guide. Abacus Press, 1985.

3. Y.J. LU, S.Q. WANG, Q. LU, Expert System ESBOP for Bidding of Overseas Construction Projects. Proceedings of 1989 Annual Conference on Intelligent Decision Support Systems for Civil Engineering Works sponsored by the National Natural Science Foundation of China, Electronic Industry Press, Beijing, 1990.

4. Y.J. LU, L.M. SUN, Q. LU, Generation of Database Management Systems by Using Production Rules. Journal of Tsinghua University, Vol.31, No.5, 1991.

Intelligent Controller Based on Neural Network
Réseau neuronal en tant que système de contrôle intelligent
Neuronales Netzwerk als intelligentes Prüfsystem

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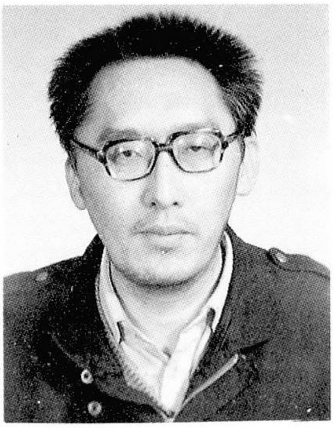

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SUMMARY
In the present paper, a new version of the knowledge-based system for structural preliminary design, which is based on neural networks, is introduced. Some intelligent control problems, such as the decisive influence of domain knowledge and the necessities of using controller are discussed. The measurability and controlability of the neural network controller are proved, and an intelligent controller based on Back-Propagation algorithm is developed. Finally, an application example is presented.

RÉSUMÉ
L'article présente une nouvelle version d'un système expert pour le prédimensionnement des structures, basé sur les réseaux neuronaux. Il décrit les problèmes relatifs à la surveillance intelligente, comme l'influence déterminante de la connaissance de base et la nécessité d'avoir recours à une fonction de contrôle. Un système de contrôle intelligent, dont la mesurabilité et la manoeuvrabilité ont été prouvées, a été développé en se basant sur l'algorithme de rétropropagation. Pour terminer, son utilisation est illustrée à l'aide d'un exemple.

ZUSAMMENFASSUNG
Der Beitrag präsentiert eine neue Version eines Expertensystems für die Vorbemessung von Tragwerken, basierend auf neuronalen Netzwerken. Dabei werden Probleme der intelligenten Ueberwachung, wie der entscheidende Einfluss der Wissensbasis und die Notwendigkeit einer Controller-Funktion erörtert. Ein intelligenter Controller mit nachgewiesener Mess- und Steuerbarkeit wurde auf der Basis des Back-Propagation-Algorithmus entwickelt. Die Anwendung wird an einem Beispiel gezeigt.

1. INTRODUCTION

The structural design is divided into three stages: the conceptual design, the preliminary design, and the construction design. Computer has been used widely in the construction design. For the time being, however, the application of computer in the preliminary design is still in its infancy. Obviously, the reason is that the construction design can be more easily performed by computer for its simplicity and systemic nature. In the preliminary design, however, both thinking in images and thinking in logic can not be avoided. One or more structural configurations that may provide the intended structural function must be generated. It is often to provide feedback on structural configurations or originally assumed key parameters to satisfy the architectural decisions. In fact, this stage is considered as the most creative phase of structural design. Obviously, it is hard computerised.

Artificial neural networks, as a new knowledge representation paradigm, is receiving a lot of attention and represents advancements. Neural networks are ideally suited for solving certain types of engineering problems that require a mapping from a large distributed set of input features to a large distributed set of output features, such as pattern association, etc. Thus, neural networks may be treated as a new representation mode of knowledge, especially related to thinking in terms of images. The first expert system for the preliminary design of high-rise buildings (HIDE-1), which is based on neural networks, was developed at Tsinghua University in 1989[1]. A new version (HIDE-2), which is based on a combination of neural networks with a rule base , was developed in 1990[2]. In 1991, a prototype for the preliminary design of space grid structures was developed[3]. In this system, each neural network is treated as a block which can be used not only as various knowledge representation modules but also as a simulation module, instead of the finite element calculation and an optimization module. However, it should be mentioned that SPRED-1 essentially relies upon a related data bank, which includes a number of previously designed similar projects. The data bank is used for learning of neural networks, it is so-called example-based reasoning.

In the present paper, a new version SPRED-2 is introduced, which can be used to consider special grid structures without enough previous examples or with very strong constraints. In the latter case, an intelligent controller based on neural networks is used. The emphasis of the present paper is put on how to use the controller to control the system to satisfy the designer's special requirements which is so-called constraints. Then, the controllability and the measurability of the intelligent controller are proved. Finally, a typical example for preliminary design of a spatial grid deck is given.

2. RETHINKING ABOUT DOMAIN KNOWLEDGE AND THE DESIGN PROCESS

In preliminary design, the thinking mode of design is a combination of both image thinking and logic thinking, which may have several scheme choices for a same project and usually the thinking path is not unique either. For this reason, it is rather difficult to formulate a mature model or algorithm for the thinking mode. The preliminary design, however, is a key stage during the whole design process, the choice of both structural schemes and some important parameters gives an essential effect on the structural design quality. Although the development of artificial intelligence brings us a promising light in the recent years, there are a few systems that can be used in practical engineering design. The reasons may be summarized as follows.(1) Many investigators, who are engaged in the research of knowledge-based systems, are experts only in artificial intelligent technique. Some of them want to accomplish a knowledge-based system only by the conversation with domain experts for several times. In fact, some subjects are concerned with deep knowledge, and most of domain knowledge can not be formalized by a artificial intelligent expert who has only a little talk with domain experts. The reasoning mode of an knowledge-based system depends, to a great extent, on domain knowledge. So domain experience plays an important role in formalization of a knowledge-based system. (2) During development of knowledge-based systems people often note the symbol process systems that is based on the logic thinking, but rarely pay more attention to the association mode, which is based on the image thinking. Therefore, the deeper reasoning ability is a conspicuous lack in the system, i.e., many systems are very sensitive to the object change and the knowledge acquisition becomes a "bottle neck". In the preliminary design process, the thinking mode of domain experts may have following characters. (1) The objective functions are related with one another, with structural schemes, design parameters and so on. The relations usually form a very strong network. In many cases, it can not be substituted by a hierarchical relation. (2) During the whole process, the objective functions and constraint conditions may be changed. (3) Designers hopes to obtain a most satisfactory solution among all the feasible solutions, but for different designers, the final decisions are very different. It seems very important to consider the three mentioned characters in the new system.

In the present paper, only spatial grid structures are considered, which can be shown in Fig. 1.

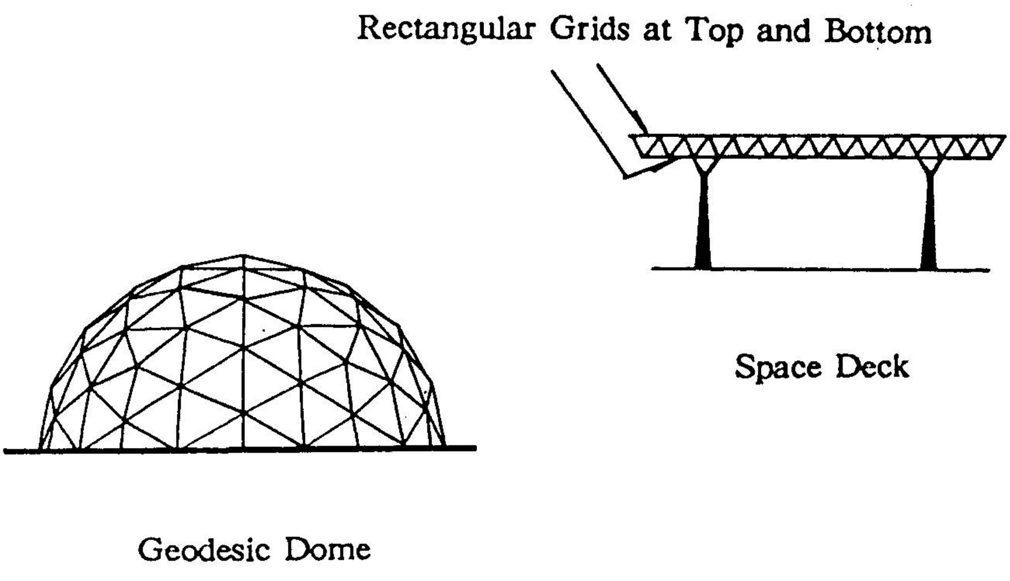

Fig.1 Typical spatial grid structures

3. THE PRESENT SYSTEM SPRED-2

The present system, SPRED-2, consists of three subsystems, each of them is designed for three following cases, respectively.

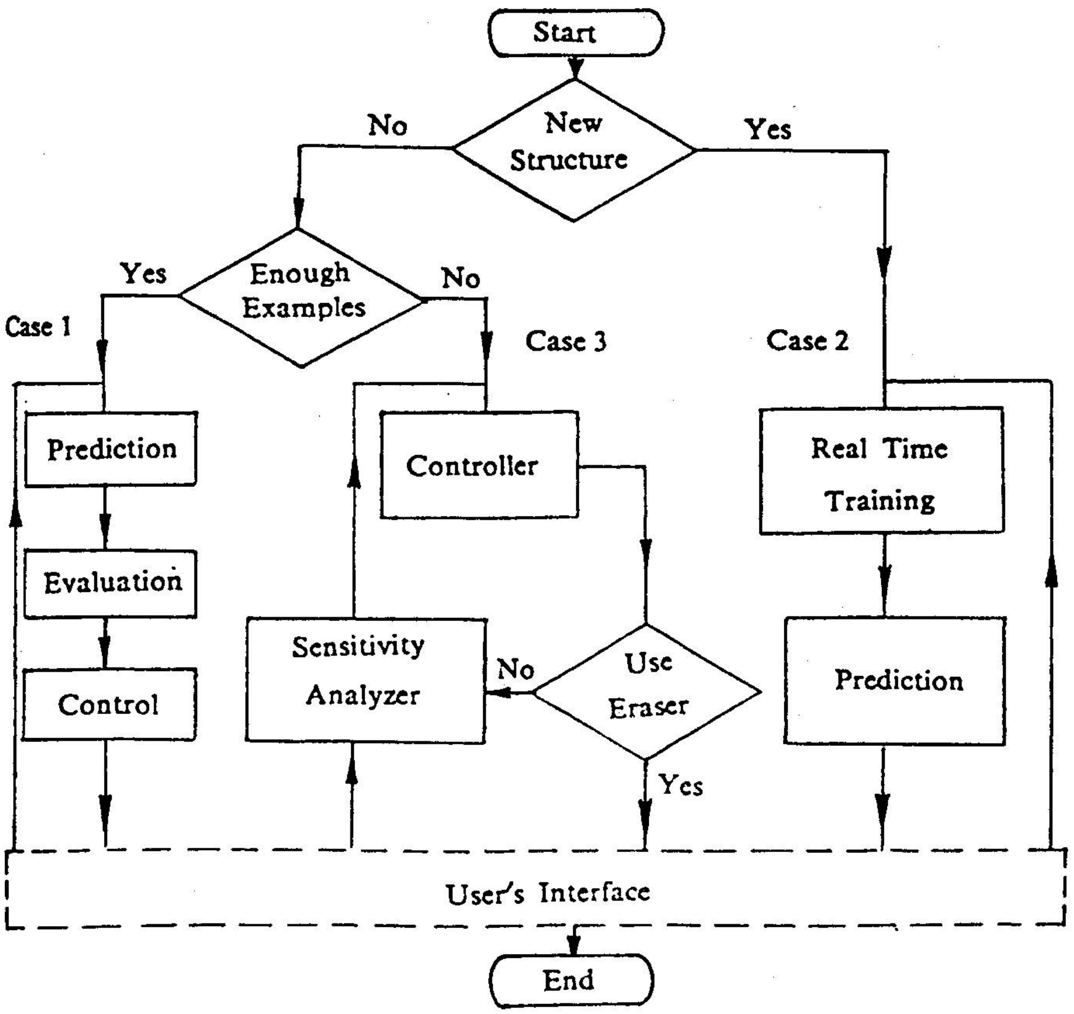

Fig.2 System architecture of SPRED-2

(1) **Case 1: To design common spatial grid structures with enough previous designed examples.** Since there are many samples used for reference, the structural configuration can be easily determined. The outputs obtained by the present subsystem usually have a little error to compare with the results from the finite element method (FEM). For this kind of structures, using both the rules given by knowledge base and the structural behaviour parameters from neural networks, the obtained optimal scheme can save 20%-30% total amount of steel. The original system, SPRED-1, becomes a subsystem of SPRED-2 and it is designed just for Case 1 only (Fig. 2). In this subsystem, many neural network moduli are used to simulate, evaluate and control the design process. In the prediction stage, a set of feasible schemes are created by a knowledge base and a data bank. Afterwards, each feasible scheme is evaluated by the evaluation part. Finally, the qualified feasible schemes should be optimized in the control part. If necessary, the optimal scheme can be checked or corrected by information fedback from the user's interface.

(2) **Case 2: To design special spatial grid structures without enough previous designed examples.** Since designers have no enough knowledge on this kind of structural behaviour, designers prefer to have a conservative scheme, and the amount of steel often increases. In the present subsystem, however, the real time training is used (Fig. 2). During this training process, first, the FEM is used to calculate a number of assumed structural samples similar to the new designed project. The assumed structural parameters here are selected by orthogonal tables. After calculation these assumed samples and their behaviours are learnt by a neural network modulus. All weight values in the modulus are also stored into a dynamic data base. Using dynamic data base with some rules from a knowledge base, the parameters for the new project, such as structural dimension, design load etc., can be given by a prediction modulus. Although these predicted structural parameters are approximate results compared with those determined by FEM, they can cut down 30-100% of the amount of steel obtained by designer's experience only. Usually the predicted accuracies are very satisfactory for the preliminary design. In addition, since the Davidom-Fletcher-Powell Method (DFP) is used to accelerate the convergency process[3], the inference time, even for B-P algorithm, is very limited. Therefore, the real time training for a new design project becomes possible.

(3) **Case 3: To design common spatial grid structures with some strong constraints or requirements.** In this case, the structure to be designed has almost common configuration, but some of its design parameters are constrained. For example, due to the space limitation, the grid depth is limited. Probably, due to the aesthetics requirement, the structural grid size or the maximum diameter of joints is limited. In these cases, therefore, structural engineers have to selects some parameters which are different from the most satisfactory points. It is very common that, in practice, structural engineers have to select some parameters which are not so satisfactory but very realistic within a feasible domain. On the other side, since the uncertainty of the aesthetics viewpoint, the constraint softening is also possible. In fact, during this design process, the revised information is often fedback to the original input nodes of the system to obtain a better scheme. It is so-called "the recursive process"[4]. The present subsystem Case 3 consists of three parts, i.e., a controller, a scheme eraser, and a sensitively analyser (Fig. 2), which can be explained as follows.

First of all, a neural networks with three layer perception is set in the intelligent controller, which has five input nodes (such as the structural plan dimension, the structural depth,grid lines, the number of the different member types, support conditions, and applied loads), and five output nodes (such as the total amount of steel, maximum internal forces, the maximum deflection, maximum reaction, and the maximum size of the joint). The link weights of the three-layer perception are from the prediction data bank of subsystem Case 1. When the original scheme with some strong constraints is given, a control algorithm can be used to give a most satisfactory feasible scheme. The basic idea is to adjust the values at hidden nodes of the three-layer perception, which will be introduced later. Afterwards, the scheme eraser works to check the obtained scheme by a knowledge base. Some unreasonable data may be deleted. In this case, the sensitivity analyser is driven to help designers or users to modify the input or output data. Then a new recursive process starts.

4. THE CONTROL ALGORITHM

First, an expected solution is defined as

$$\Phi = \{Z_1^*, Z_2^*, \cdots, X_1^*, X_2^*, \cdots\}^T \tag{1}$$

where $Z_1^*, Z_2^*, \cdots$ are expected output values from users, and $X_1^*, X_2^*, \cdots$ are expected input values. Then, an energy function can be assumed as

$$E = U + V \tag{2}$$

in which

$$U = \frac{1}{2}\left[(Z_1^* - Z_1)^2 + (Z_2^* - Z_2)^2 + \cdots\right] \tag{3}$$

where $Z_1, Z_2 \cdots$ are output values from the three-layer perceptron, and

$$V = \frac{1}{2}\left[(X_1^* - X_1)^2 + (X_2^* - X_2)^2 + \cdots\right] \tag{4}$$

where $X_1, X_2, \cdots$ are input values from the same perceptron. Now, the objective is to find the values $\{Y\}$ at hidden nodes of the perceptron, which can be treated as a conditional function, to make the energy function E minimum. It means that the obtained parameters $\{X\}$ and $\{Z\}$ represent the most satisfactory scheme. Before to perform the control algorithm, the controllability and the measurability should be proved first. Their definitions can be given as follows.

Controllability: For any given arbitrary value of $\{Y\}$, the initial conditional function $\{Y_0\}$ can change to $\{Y\}$ by finite modifications of $\{X\}$.

Measurability: For obtained output values $\{Z\}$, the conditional function $\{Y\}$ can be certainly determined.

Since the B-P algorithm is used in the present controller, each term of $\{Z\}$ and $\{Y\}$ can be given by following equations respectively.

$$Z_n = [1 + \exp(-\Sigma W_{nm} Y_m)]^{-1} \tag{5}$$

$$Y_m = [1 + \exp(-\Sigma W_{ml} X_l)]^{-1} \tag{6}$$

where l,m,n are subscripts of node values $\{X\}$,$\{Y\}$, and $\{Z\}$, respectively. W.. are connect weights. From Eq.(6), we have

$$\bar{Y}_m = \ln\frac{Y_m}{1 - Y_m} = \Sigma W_{ml} X_l \tag{7}$$

Symbolically, it is

$$[W]\{X\} = \{\bar{Y}\} \tag{8}$$

where $[W]$ is the weight coefficient matrix, $\{\bar{Y}\}$ is another expression of the conditional function $\{Y\}$.

If the rank of $[W]$ is the same as the number of hidden nodes m, then Eq.(8) must have unique solution, which means that the system is controllable. If the rank of $[W]$ is less than m, then no solution exists. Since in the present three-layer perceptron the number of hidden nodes usually are less than that of input nodes, this case hardly happens. If the rank of $[W]$ is larger than m, then multi-solution exists for Eq.(8). In this case, some input values can be assumed as constants to make the system controllable.

Similarly, from Eq.(5), we have

$$\bar{Z}_n = \ln\frac{Z_n}{1-Z_n} = \Sigma W_{nm} Y_m \tag{9}$$

Symbolically, it is

$$[\bar{W}]\{Y\} = \{\bar{Z}\} \tag{10}$$

where $\{\bar{Z}\}$ is another expression of $\{Z\}$. If the rank of $[\bar{W}]$ is the same as the number of output nodes n,then Eq.(10) must have unique solution, which means that the system is measurable. If the rank of $[\bar{W}]$ is less or larger then n, there is no solution or multi-solution, which should be avoided.

In conclusion, if m=l and m=n, then the controllability and the measurability can be certainly guaranteed.

Now the control problem is to find a conditional function $\{Y\}$ or $\{\bar{Y}\}$ to minimize the energy function E. Here, the gradient method can be used.

From Eq.(2), for each m

$$\frac{\partial E}{\partial Y_m} = \frac{\partial U}{\partial Y_m} + \frac{\partial V}{\partial Y_m} \tag{11}$$

where

$$\frac{\partial U}{\partial Y_m} = \frac{\partial U}{\partial Z_1}\frac{\partial Z_1}{\partial Y_m} + \frac{\partial U}{\partial Z_2}\frac{\partial Z_2}{\partial Y_m} + \cdots \tag{12}$$

Let

$$\frac{\partial U}{\partial Z_1} = Z_1^* - Z_1 \tag{13}$$

$$\frac{\partial U}{\partial U_2} = Z_2^* - Z_2 \tag{14}$$

and so on, thus

$$\frac{\partial U}{\partial Y_m} = \sum_n (Z_n^* - Z_n)\frac{(-1)\exp(-\Sigma W_{nm}Y_m)W_{nm}}{[1+\exp(-\Sigma W_{nm}Y_m)]^2} \tag{15}$$

Similarly,

$$\frac{\partial V}{\partial Y_m}=\frac{\partial V}{\partial X_1}\frac{\partial X_1}{\partial Y_m}+\frac{\partial V}{\partial X_2}\frac{\partial X_2}{\partial Y_m}+\cdots \tag{16}$$

Let

$$\frac{\partial V}{\partial X_1}=X_1^*-X_1 \tag{17}$$

$$\frac{\partial V}{\partial X_2}=X_2^*-X_2 \tag{18}$$

and so on, thus

$$\frac{\partial V}{\partial Y_m}=\sum_l (Z_l^*-Z_l)\frac{(-1)[1+\exp(-\Sigma_{ml}X_l)]^2}{\exp(-\Sigma W_{ml}X_l)W_{ml}} \tag{19}$$

Substituting Eq.(15) and Eq.(19) into Eq.(11) the $\partial E/\partial Y_m$ for each m can be obtained. Thus the (k+1)th modification of $\{Y\}$ can be expressed as

$$\{Y\}_{k+1}=\{Y\}_k-\eta\left\{\frac{\partial E}{\partial Y}\right\} \tag{20}$$

where η is a constant.

Using the newest $\{X\}$, $\{Y\}$, and {Z) can be done, which can be sent to the scheme eraser and be checked by a knowledge base.

5. THE APPLICATION EXAMPLE

Recently, a new design project, Zhong Guan Cun Shopping Center, has just been completed. The preliminary design of the project was done by SPRED-2. It is a double-layered space deck with 18x70m plan dimensions. At beginning, architects gave an original suggestion with very strong requirements on the structural depth and the maximum diameter of joints. According to the existing designed projects from the data bank, it seems that some requirements may be unreasonable. Using the Case 3 of SPRED-2, the final results can be done and shown in Table 1. It is the best compromising scheme between the original requirements and the collected domain knowledge. It can be seen that if the constraint on the structural depth from architects can be released, other parameters will be improved significantly.

	Original Scheme from Architects	Final Scheme Given by SPRED-2
Total amount of steel (kN)	891.8	646.8
Structural depth (m)	1.0	1.4
Max. internal force (kN)	196.0	137.2
Max. displacement (mm)	210	78
Max. size of joints (mm)	300	250

Table 1 The Structural Schemes of Zhong Guan Cun Shopping Center

6. REMARKS

(1) In the present, some characteristics of knowledge based systems in design are discussed. In order to imitate the thinking procedure of human being, the combination of both logic thinking mode and image thinking mode is needed and the domain knowledge is very important.

(2) The preliminary design of spatial structure is divided into three cases. The third case, which is used very widely in the preliminary design of spatial grid structures, is explained in detail in present paper.

(3) An intelligent controller is developed for obtaining the design parameters , which most close to the requirements given by the architects. Its controllability and measurability are proved. By adjusting the values of hidden nodes, the controller can be used to control the design variables and the structural parameters to obtain a most satisfactory scheme.

REFERENCE

1. J.ZHANG and X.L.LIU, "A PRELIMINARY STRUCTURAL DESIGN EXPERT SYSTEM FOR HIGH-RISE R.C. BUILDINGS BASED ON NEURAL NETWORK (HIDE-1)", Research of the Application of AI Aided Decision-making Systems in Civil Engineering, Ed. by X.L.Liu, etc., Electronic Industry Publish House, Beijing, 1990, pp.166-178 (in Chinese).

2. J.M.LI and X.L.LIU, "AN EXPERT SYSTEM FOR THE PRELIMINARY DESIGN OF HIGH-RISE BUILDINGS BASED ON A COUPLING OF A NEURAL NETWORK AND A RULE BASE (HIDE-2)", Technical Report CE-ESS-90-01, Dept. of Civil Eng., Tsinghua Univ., Beijing, 1990 (in Chinese).

3. X.L.LIU and M.GAN, "A PPRELIMINARY STRUCTURAL DESIGN EXPERT SYSTEM (SPRED-1) BASED ON NEURAL NETWORK", Proceedings, Artificial Intelligence in Design, 91, Ed. by J.Gero, Butterworth Heinemann Ltd., 1991, pp785-799.

4. Y.ZENG and G.D.CHENG, "ON THE LOGIC OF DESIGN", Design Studies, Vol.12, No.3, Butterworth-Heinemann Ltd., 1990, pp.137-144.

Expert System for Construction Site Layouts
Système expert pour l'aménagement de chantiers de construction
Expertensystem zur Planung von Baustellen

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SUMMARY
ESBE is the hybrid object-oriented expert system for the optimization of construction site layout. It combines a hybrid system, consisting of an expert system and mathematical facility layout algorithms, the construction site database, the CAD component and the user-interface/3D-visualization component. Several aspects of the integration and realization of the latter in ESBE are discussed.

RÉSUMÉ
ESBE est un système expert hybride à orientation objet, destiné à l'aménagement de chantiers de construction. Il comporte un système hybride constitué d'un système expert et d'algorithmes mathématiques de planification d'installation, d'une banque de données de chantier, d'une composante de conception assistée par ordinateur (CAO), ainsi que d'une interface d'utilisateur / composante de visualisation tridimensionnelle. Les auteurs exposent différents aspects de l'intégration et de la réalisation de cette dernière composante pour ESBE.

ZUSAMMENFASSUNG
ESBE ist ein hybrides, objektorientiertes Expertensystem zur Planung von optimalen Baustellenlayouts. Es enthält ein hybrides System, bestehend aus Expertensystem und mathematischen Facility-Layout-Algorithmen, Baustellendatenbank, CAD-Komponente sowie als Benützerschnittstelle / 3D-Visualisierungskomponente. Es werden einige Aspekte der Integration und der Realisierung dieser letzteren Komponente in ESBE diskutiert.

1. INTRODUCTION

Despite the fact that the turnover of a large-scale construction site is that of a medium sized factory and "construction" means "transportation", only a few mathematical methods or other advanced information technologies treat the problem of finding an optimal realisation of the site plant. In contrast to this, other industries are using these modern methods to minimize cost, workload and time.

At the first glance, many reasons can be named why these modern methods have not yet been considered for the construction site. In this settings we must deal with a very complex dynamic process, which differs extremely from the process in a factory.

Because of these problems a hybrid object-oriented expert system called ESBE is being developed. The objective is the interactive generation of an optimized construction site lay-out. The task is the dimensioning and the arrangement of the individual construction site facilities. ESBE consists of three major parts: an object-oriented construction site database which contains general and company specific data of the construction site facilities and the building data; a hybrid system with mathematical optimization algorithms and an expert system (knowledge based system) as well as a well-tailored user-interface with a 3D visualization component.

The aggregation of the uncertain knowledge is realized using a combination of fuzzy and probability functions. Outputs of this expert system are the recommended type and amount of the different construction site facilities and a ranking of the appropriate areas (rectangles) to place the facilities. These areas serve as input to the mathematical algorithms, computing the optimal positions of the facilities inside these restricted areas. Both parts are realized using the object oriented language EIFFEL.

The user interface / 3D-visualization are the part of ESBE, that interacts with the user. They decide whether ESBE will be accepted by the user on the construction site which means how successful the system will be in practice. The paper describes the interfaces to the other components of ESBE and how it has been realized.

2. WHY TO TAKE THE EFFORT TO REALIZE A WELL TAILORED USER-INTERFACE / 3D-VISUALIZATION COMPONENT ?

In our opinion, the human factor is still playing the major part in almost every design step for an user-interface. There are many reasons to take big efforts especially in developing a 3D-visualization component, some of which are:

- user acceptance
  A three-dimensional image can be interpreted easier by the user than two-dimensional solutions used so far, because three dimensions correspond better to reality. Another problem is the loss of information of a three-to-two projection.

- trace of the building process
  Another feature is that the building process on the construction site can be traced on the screen in time-discrete steps. A two-dimensional top view cannot show the changing of

the height of an object, so the three-dimensional issue becomes attractive. It shows, for example, that the crane has to have a specific height at one discrete time period, because the front wall is higher than the rest of the building.

lack of information / data obtained by the user
The hybrid components of ESBE, i.e. the expert system and the mathematical optimization algorithms, cannot consider specific aspects of the construction site. Therefore the user, e.g. the construction site manager, is needed. Using the 3D-visualization component, he can introduce facts like the topology of the construction site, which is hardly possible using two-dimensional images.

3. HOW TO FEED THE USER-INTERFACE / 3D-VISUALIZATION COMPONENT

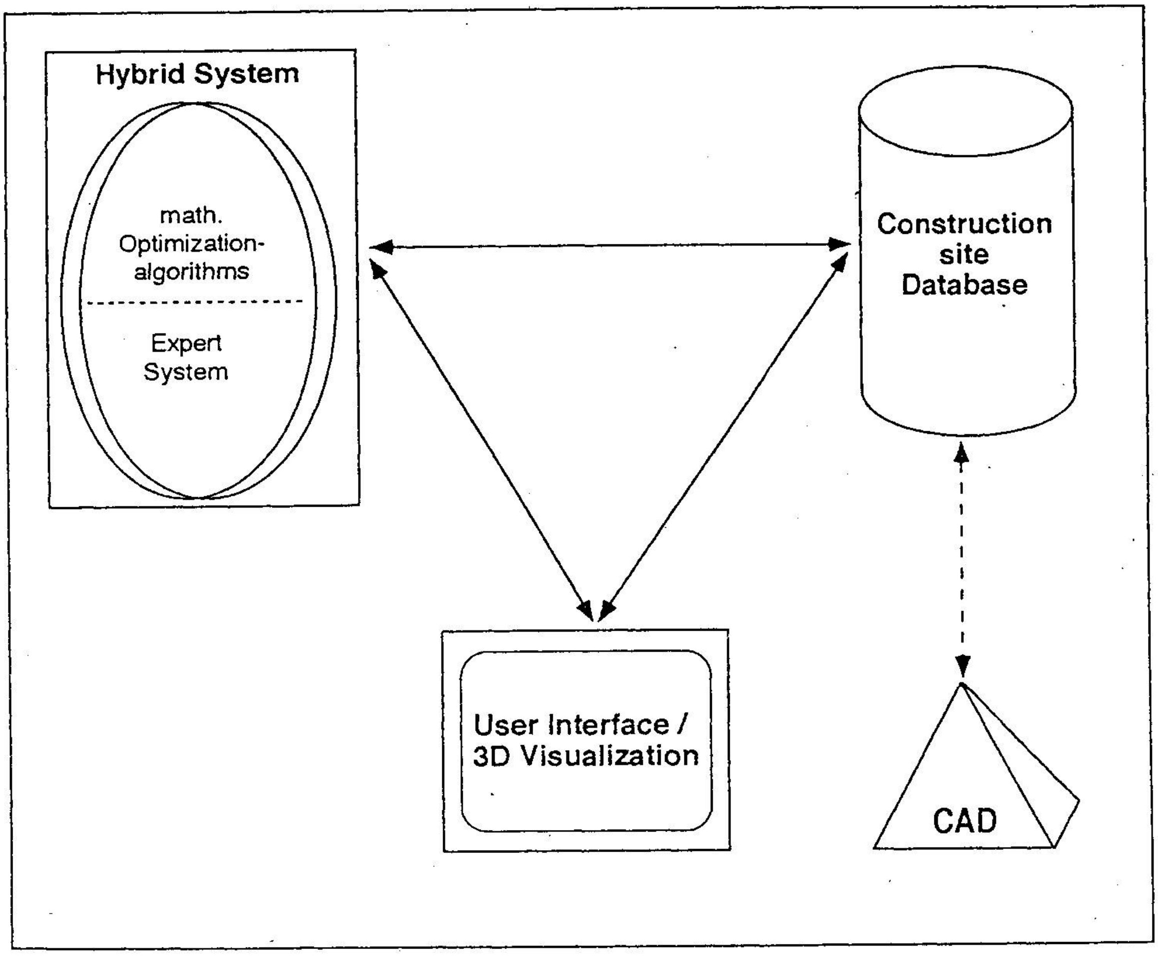

Fig. 1 Concept of ESBE

Fig. 1 shows, that the user-interface / 3D-visualization component has internal interfaces to the construction site database and to the hybrid system, which consists of the expert system and the mathematical optimization algorithms. The database contains building data fed by the CAD component. Asynchronous inter process communication (IPC) is implemented between the different components to ensure a fast data exchange.

3.1 The construction site database

So far, we have realized the database using the relational DBMS INGRES. To make the objects of the hybrid system persistent, they must be cracked down to entities in order to integrate them in the rDBMS. The next step will be to replace the rDBMS INGRES with an object-oriented database.

The project data can be separated into three major data blocs:

- main project data
  It contains general information about the project, e.g. address of the construction site etc.

- execution independent data
  It can be divided up into construction site data, e.g. site area, and the building divided up into construction units (cubes), coming from the CAD system.

- execution dependent data
  It is determined by the marker, like the project scheduling etc.

As a result, we get the individual jobs which are necessary to build the execution units and to optimize the construction layout: place, time and quantity.

The calculated and optimized layout at discrete time periods with all construction site facilities and the building can be retrieved from the database by the 3D-visualization component. The user-interface gives access to the whole database, e.g. the data sheet of a used crane.

3.1.1. The CAD component

The CAD component provides building data with its geometric, material and spatial aspects. Realizing this we used the so-called *element-method*. For this, the building has to be divided up into construction units (cubes), which are stored in a construction unit catalogue. The needed materials and their quantity are assigned to the construction units. The building itself will be reduced into execution units, which are assigned to the corresponding construction units and their local places in the building. Thus the geometrical and material aspects of the building is given. This information is fed into the highly integrated database.

3.2 The hybrid system

The hybrid system consists of the mathematical optimization algorithms and the expert system. The user-interface / 3D-visualization have the following fast communication over IPC with the hybrid system:

- compute layout for a specific time period

- layout computed; layout can be accessed in the database

- questions from the expert system to the user

- changing the position of a construction site element by the user
- etc.

The hybrid system will process a new construction layout, update the database and send the updated data back to the user-interface / 3D-visualization component.

4. HOW TO REALIZE THE USER-INTERFACE / 3D-VISUALIZATION COMPONENT

We used object-oriented analysis and modelling techniques to design ESBE. To realize the different components we chose the object-oriented programming language EIFFEL. The different components, the database, the hybrid system, the user-interface / 3D-visualization are separate processes. The are running on a RISC-workstation under the operating system UNIX.

We wanted to realize the user-interface / 3D-visualization component by using standardized tools to ensure portability.

Therefore OSF/Motif had been chosen for the user-interface. It supports network transparency, the optimized use of the workstation-network etc.

The visualization component is developed with PHIGS (the Programmer's Hierarchical Interactive Graphics System). It is a high level graphical library used to display and interact with three-dimensional (3D) images. As a standard approved by the International Organisation for Standardization (ISO), it offers portability to many different computers using different operating systems and window systems. We are using PHIGS PLUS, which is an enhancement of PHIGS, and already part of the standard. With the advent of the PEX protocol, developed by the M.I.T. X Consortium, PHIGS can be used to drive graphics display over the network.

The three-dimensional construction site is displayed in a variable PHIGS-Window under the graphical interface OSF/Motif.

5. HOW TO WORK WITH THE USER-INTERFACE / 3D-VISUALIZATION COMPONENT

A suitable user-interface with a 3D-visualization component has been developed. It gives the user the possibility to take a realistic view at the optimized construction site. The items in the following sub-chapters have been realized to help the user work with the 3D-visualization component. Some of these items are shown in the enclosed Fig. 2, 3 and 4. The ESBE main menu is always displayed in the top right corner. It contains the following options:

- determine project number
- optimize construction site

- activate ESBE database menu
- modify construction site facility
- select explanation component
- end of session

Below the ESBE main menu Fig. 2 shows the activated ESBE database menu. Fig. 3 shows a crane data sheet retrieved from the database. Technical and economical information, like the weight and the abbreviation of the chosen crane, are given. Even the working-load of the chosen crane is displayed under the PHIGS-window. All these information can be called by the user and their are required by the hybrid system to optimize the construction site. The user can select a discrete time to look at the construction site by using the time bar, which is displayed at the bottom of Fig. 2 and 4. In this case he chooses the 51th week. He can change between day, week and month.

The following sub-chapters demonstrate, what the user can do with the 3D-visualization component. Fig. 2, 3 and 4 show a PHIGS-window under OSF/Motif displaying a small construction site to demonstrate some of the given items.

5.1. Looking at the construction site from different viewpoints

PHIGS gives the opportunity to look at the construction site from different viewpoints. The following items have been realized so far:

- zooming
  The user can extend or reduce the picture of the construction site by simply moving the mouse. Fig. 4 shows for example a reduced construction site.
- moving
  The user can move the construction site to any direction by simply moving the mouse.
- rotate
  The construction site can be rotated around the centre of the world coordinate system by simply moving the mouse. Fig. 3 shows a side view and Fig. 4 a slant of the construction site.
- helicopter flight
  The user can simulate a helicopter flight over the construction site using the mouse. Fig. 2 shows this view.

5.2. Tracking the construction process

By changing the time on the time bar you can watch the progress of the construction and the needed machinery according to it. This is a big advantage because now you can plan your work by doing (simulating) it. Problems that normally appear only while construction is running can be discovered earlier and you can react to the problematic situation immediately by changing the schedule or other factors.

5.3 Animation of facility elements

Animation of the particular construction site facility elements, especially the cranes. This helps to see, if machines interfere with each other or with the building when they are working.

5.4 Changing the position of facility elements

To automate everything is a big hazard and not very useful, the user should take the final decision where to place the particular elements. Thus he can change the position of an element by simply activating the element with a mouse click. Now he points to the location and the element will turn to its new position. At that stage the user can activate a new optimization with the fixed location of the element.

5.5 Activation of the construction process

By giving a start and end time and a discrete time interval it is possible to track the progress of completing step by step. Thus the user can watch a "movie" of the construction progress.

5.6 Simulating a realistic walk over and through the construction site

The user can define his height and by using cursors he can walk in any direction over and through the construction site. Also he can change his view by using the mouse.

6. CONCLUSION

First tests using ESBE to optimize small construction sites show that we are on the right track, but still a lot of research has to be done on the different components, especially on the hybrid system. Nevertheless we have developed the user-interface / 3D-visualization component in parallel, because it has in our opinion a big impact on the entire system. We do not want to develop a fully automated system generating not changeable layouts. We want and need the interaction with the user giving hints, answering questions, playing on the computer, simulating etc., and all this in a demanding, attractive, almost with the greatest of ease to involve the user in the whole system.

7. REFERENCES

1. BERLAGE, T.: OSF/Motif und das X-Window System, Addison-Wesley, 1991

2. BOCK T.A., GEBHART F.S., LENNERTS K.H.: Object-Oriented Concept for Computer Integrated Construction, Faim Proceedings, 1992

4. GASKINS, T.: PHIGS Programming Manual, O'Reilly & Associates, Inc., 1991

5. MEYER B., Object-Oriented Software Construction, Prentice Hall International (UK) Ltd., 1990

6. KHOSHAFIAN S., ABNOUS R.,: Object Orientation - Concepts, Languages, Databases, User Interfaces, Wiley, New York, 1990

7. RUMBAUGH J., BLAHA M., PREMERLANI W., EDDY F., LORENSEN W.: Object-Oriented Modeling and Design, Prentice-Hall, New Jersey, 1991

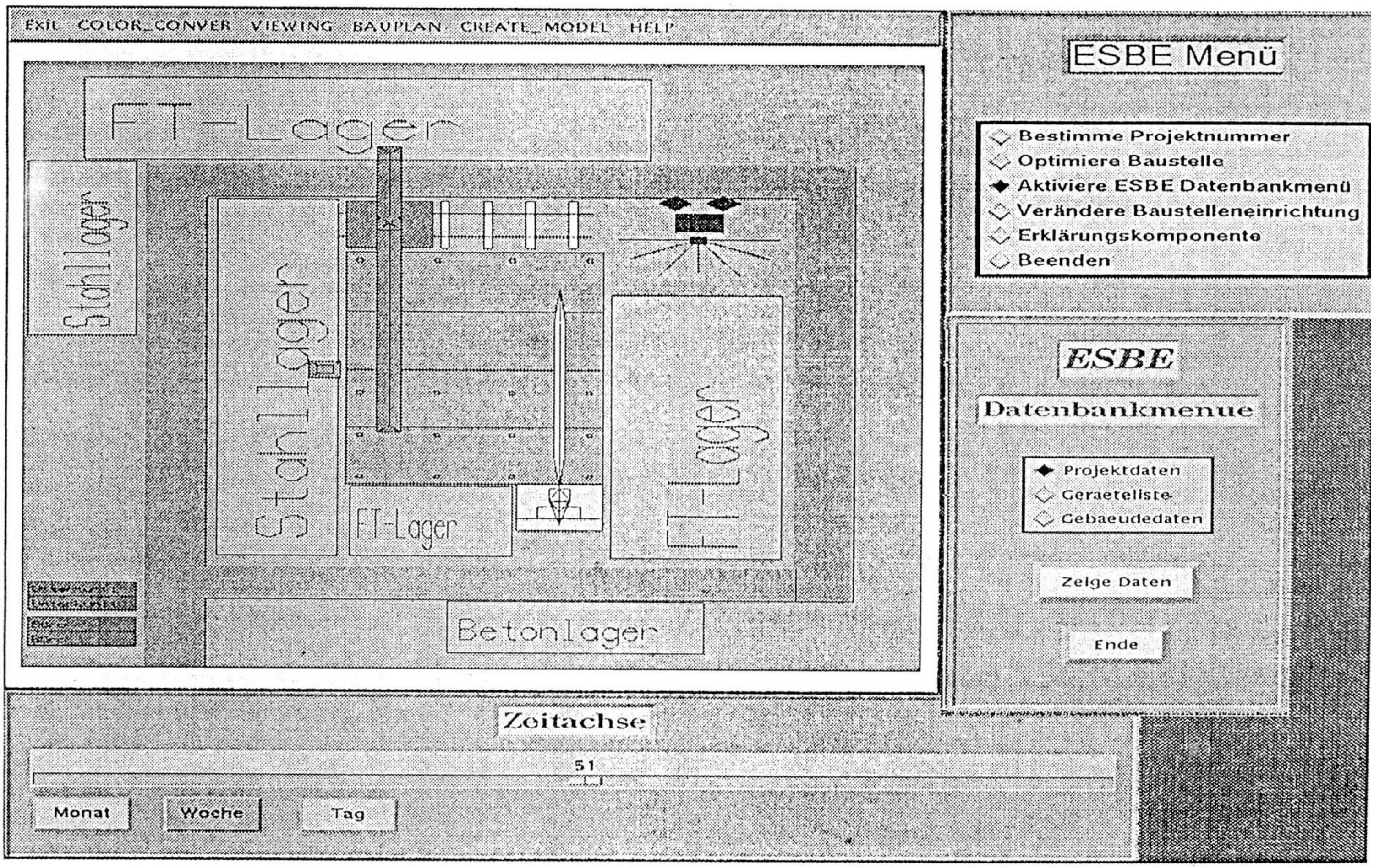

Fig. 2 Screen mask of ESBE

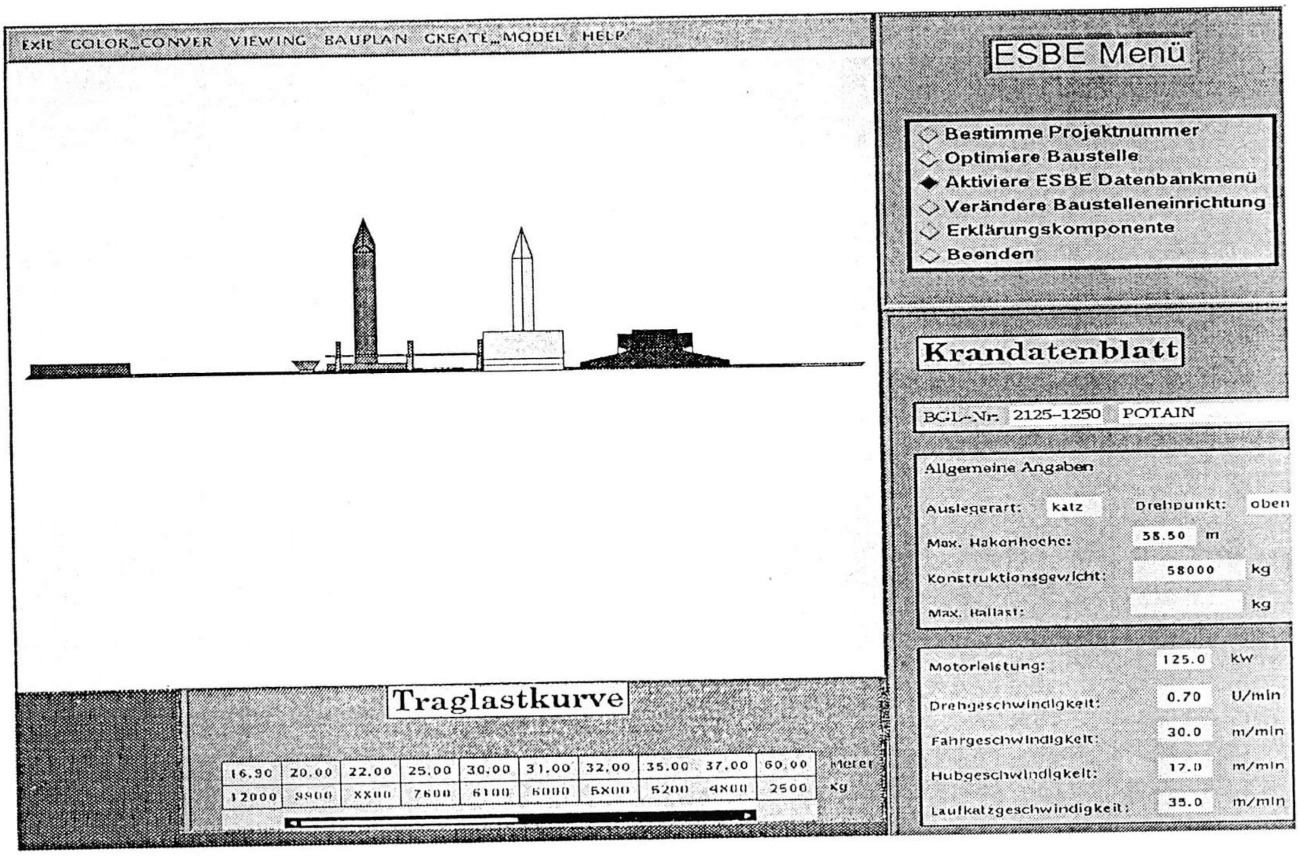

Fig. 3 Screen mask of ESBE

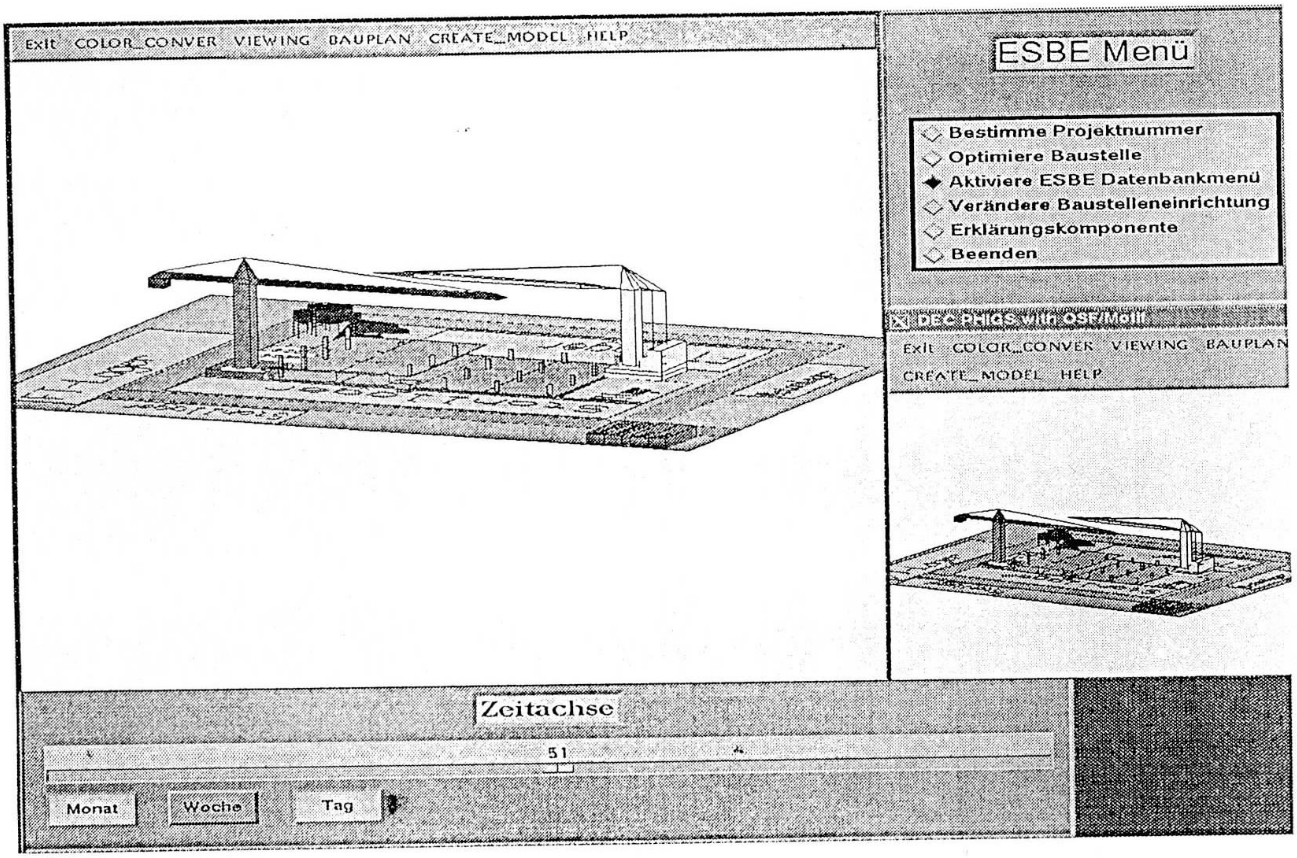

Fig. 4 Screen mask of ESBE

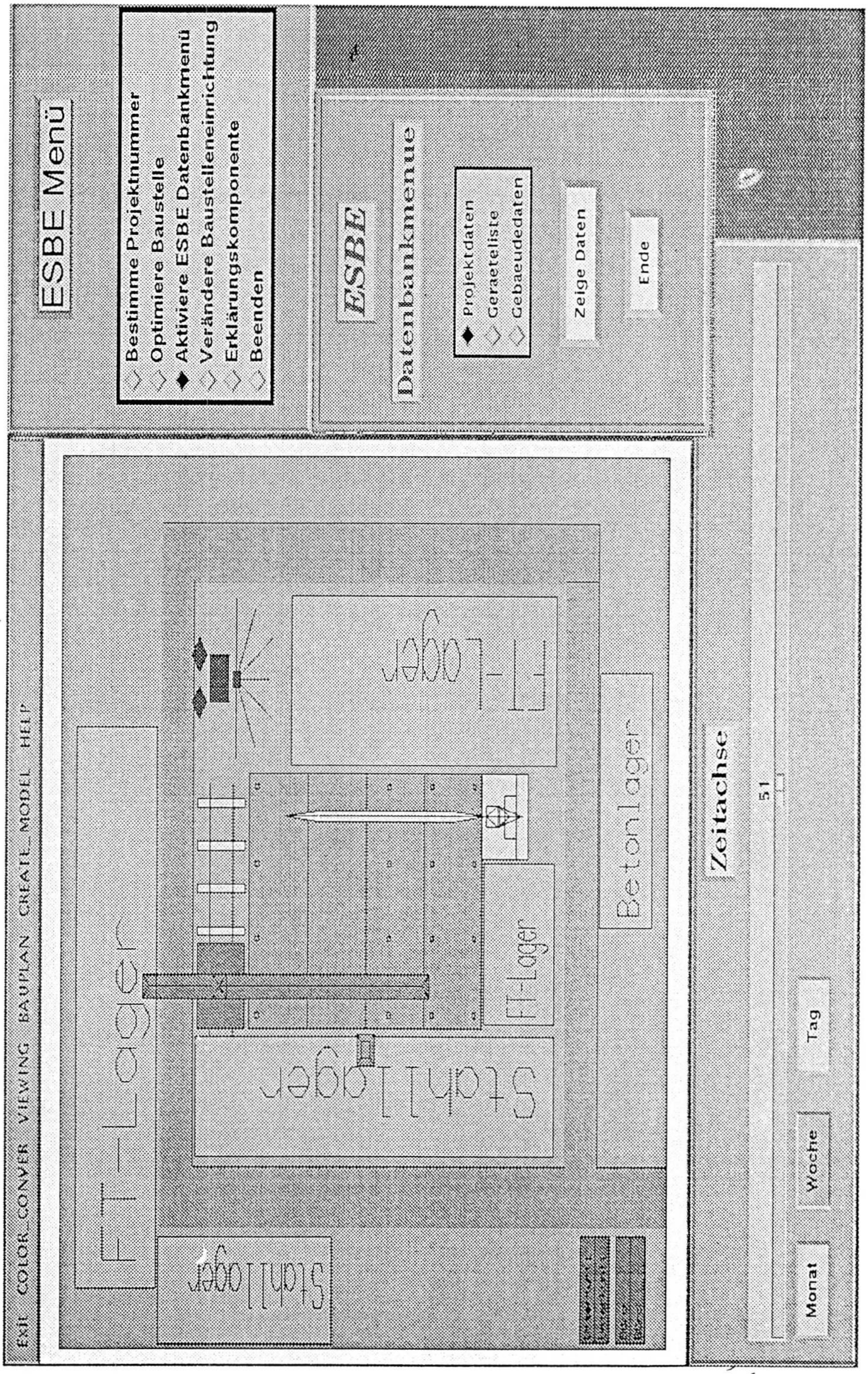

Fig. 2 Screen mask of ESBE

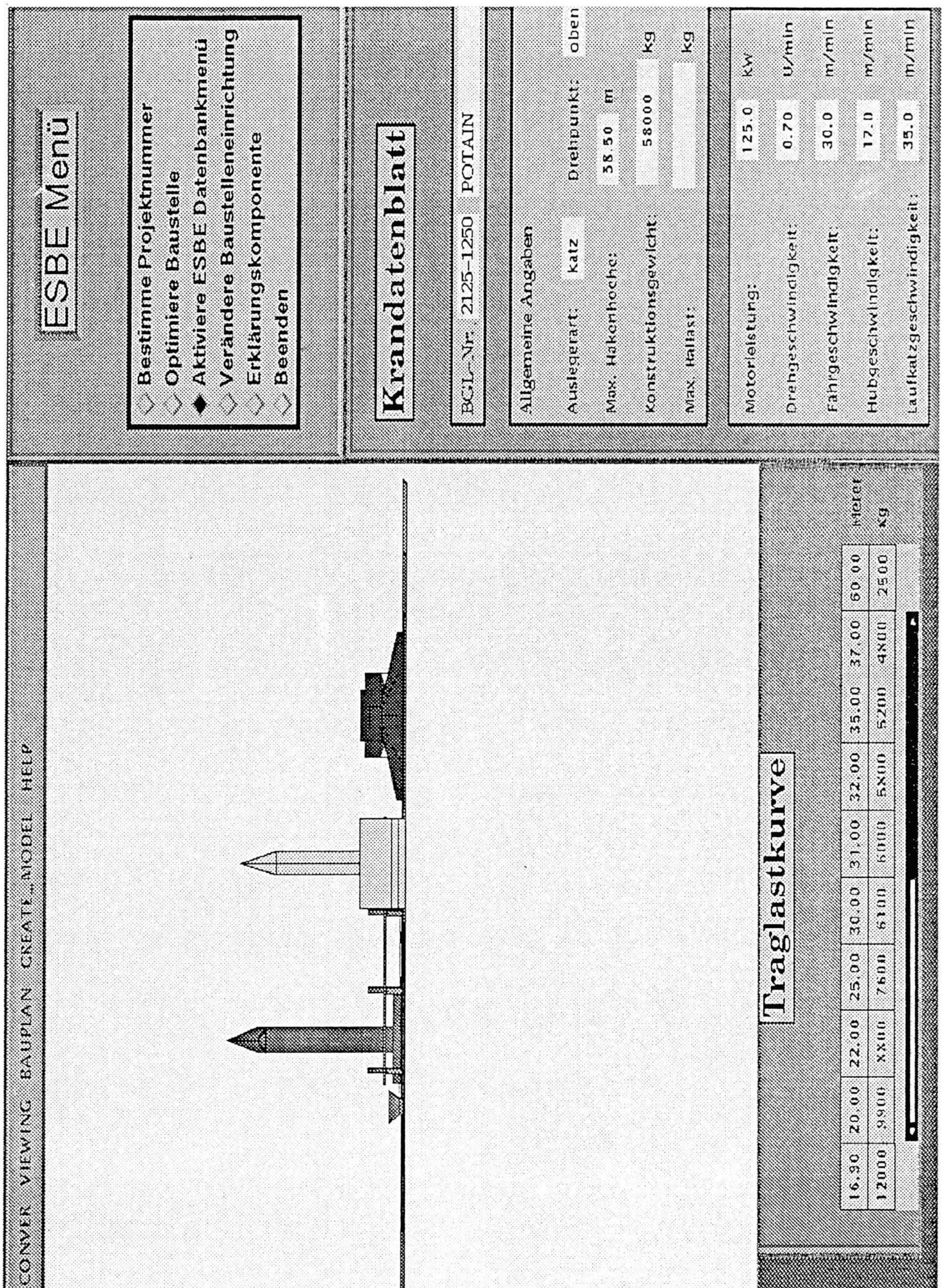

Fig. 3 Screen mask of ESBE

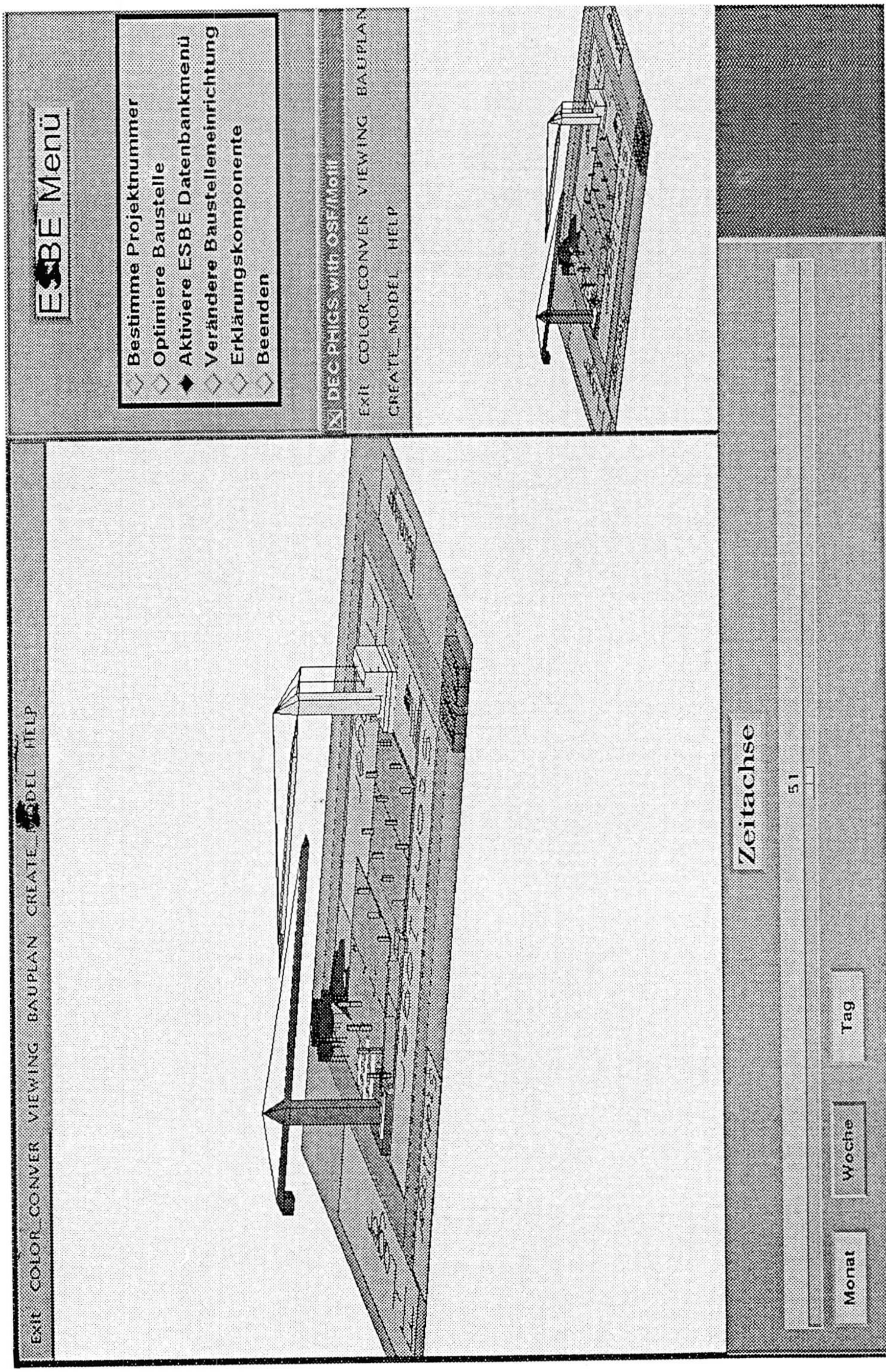

Fig. 4 Screen mask of ESBE

Knowledge-Based System Using Graphics and Image Processing

Système expert avec traitement de graphiques et d'images

Expertensystem mit Bildverarbeitung

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SUMMARY

Conventional knowledge bases are limited to symbolic representation of the knowledge using frames and rules. This paper presents a knowledge-based system for pedestrian bridge design which includes graphics and images. The object-oriented approach is applied to model the design objects graphically and to manipulate the constraints attached to them. It is shown how a graphics system can be used as the core element in an interactive, integrated preliminary design system that supports stress and vibration checking, cost estimation and three-dimensional landscape simulation.

RÉSUMÉ

Les banques de données traditionnelles se limitent à la représentation symbolique de la connaissance sous forme de masques et de règles. L'article présente un système expert pour le dimensionnement de passerelles piétonnières; ce système est en mesure de traiter des graphiques et des images. Les objets à étudier sont modélisés graphiquement, puis les conditions particulières à ces objets sont traitées de façon adéquate. Il est possible d'utiliser un système graphique en tant qu'élément central d'un système d'avant-projet intégral et interactif, qui sert de support à la vérification des contraintes et des caractéristiques vibratoires, à l'estimation des coûts et à la simulation tridimensionnelle.

ZUSAMMENFASSUNG

Herkömmliche Expertendatenbanken beschränken sich auf die symbolische Darstellung des Wissens in Masken und Regeln. Im folgenden wird ein Expertensystem für den Entwurf von Fussgängerbrücken vorgestellt, das Graphiken und Bilder darstellen kann. Die Entwurfsobjekte werden graphisch modelliert und die zugehörigen Nebenbedingungen in objektorientierter Weise gehandhabt. Es wird gezeigt, wie ein Graphiksystem als Kernstück eines integralen, interaktiven Entwurfssystems eingesetzt wird, das die Ueberprüfung der Spannungen und Schwingungseigenschaften, die Kostenschätzung und die dreidimensionale Lagevisualisierung unterstützt.

1. INTRODUCTION

Bridge design has been continuously profiting from the rapid development in the CAD/CAM systems. Automatic design and drawing systems are gradually taking over the manual and half automated design and drawing methods. Some automatic design systems are available for the preliminary design stage. These systems automate the algorithmic calculations of the loads and the structural analysis. Many CAD applications are available to help designers in the *graphical* representation of their ideas. These systems can be classified into two major groups: general purpose CAD and geometric modelling systems and specific domain CAD systems. However, the vocabulary that the general purpose systems offer is too primitive for expressing bridge design concepts. Specific domain drawing systems, on the other hand, expect a complete design data as input and therefore, they can be used only after the design is completed. As a result, bridge designers are still using manual drawing extensively in the first stage of the preliminary design when conceptual decisions about the bridge type and the main dimensions of the bridge are made [4].

Realizing these facts, in 1963, Sutherland developed Sketchpad [11] which is a pioneering computer drawing system with support for constraint specification and solution. The scope of Sketchpad and other similar systems is limited to very simple theoretical problems. In the field of civil and architectural engineering, Martini [5] proposed the Monge model for representing geometrical constraints. However, this model has not been implemented because of its complexity in representing real structures.

Some expert systems have been also developed to help selecting a bridge type that is satisfactory from different points of view such as economy, maintenance, landscape, etc. [7, 8]. Such expert systems do not consider the interactive nature of the design process and neglect the importance of graphics as a basic engineering media for design although some of them are concerned with bridge landscape evaluation [7].

In order to make computers more helpful in the preliminary design stage, there is a need for a new approach. The approach suggested in this paper emphasizes the total design system concept. The total system is centralized around a specialized graphics sub-system that can assist effectively in the preliminary design. The user of the system selects and graphically edits the prototype of the profile and the cross section of the bridge while the system insures that none of the geometric constraints is violated. The graphics sub-system is considered as the core element in an interactive, integrated preliminary design system that supports stress and vibration checking, cost estimation and three dimensional landscape simulation. Pedestrian bridges are chosen as a first step of applying the new approach because of the relative freedom in their design and the simplicity of calculating the live loads acting on them.

2. DESCRIPTION OF THE PROTOTYPE SYSTEM

2.1 The Concept of the System

The system is designed to fulfill, among others, the following requirements:

i) A rich library of prototypes of the components used in the design: These prototypes not only help in the graphical representation of the components, but also have knowledge about the default values, dimensional and positional constraints, and other attributes not directly related to graphics such as the material of the component.

ii) The ability to manipulate the components interactively: While doing free-hand drawing, designers express and amend some concepts in many iterations. To make the computer a substitute for the free hand drawing, the graphics sub-system should allow for maximum flexibility in processing the graphical components. Processing includes: (1) editing functions such as copy, cut, and paste, (2) graphical manipulation functions such as translation, rotation, and scaling, (3) graphical attributes setting (patterns, colors, lines) and (4) other functions for file management (save, load, etc.).

iii) The ability to check the effect of the graphical editing commands: Before executing any editing command, it is necessary to confirm that they do not violate any of the design constraints imposed by the design specifications or common sense rules.

iv) The ability to use the data resulting from the 2D graphics for analysis, cost estimation and landscape evaluation: In the preliminary design of pedestrian bridges, it is difficult to find the design that satisfies all the design conditions from the first trial and thus iteration is necessary. In each design cycle, the stresses in the critical cross sections are checked as well as the vibration characteristics of the bridge. The output of the graphics sub-system can be used for creating the input of the stress and vibration analysis. In addition, the same graphical data can be used for the cost estimation and landscape estimation with 3D drawing.

This system is intended to be used by novice designers or people with little design background and experience such as bridge planners. In addition, this system can be further developed to serve as an educational tool.

2.2 System Environment

The system is implemented on a workstation (SUN SPARC Station). C++ [9] is used as the main language for the system development. The system uses a library called Unidraw[12] for the 2D graphics system. Unidraw is a library of C++ classes that facilitate the development of domain-specific graphics object editors. Unidraw includes basic graphical components such as lines and polygons, commands for manipulating components, tools for selecting, transforming, and otherwise modifying graphical components. C++ is selected as the main language for developing the system because of its particular suitability for structured graphics editing. The well established advantages of C++ such as inheritance, encapsulation, code reusability and rapid prototyping are used in deriving new classes from the Unidraw library to fit the requirements of the system.

The 3D graphics module is developed in C language while the stress and vibration analysis modules are written in FORTRAN. The 3D graphics module is written using PHIGS library [10]

3. STRUCTURE OF THE PROTOTYPE SYSTEM

A prototype system has been developed that emphasizes the use of graphics not only as a group of lines that represent the final design, but as a knowledge representation method that has the power of gradually refining the design while checking the geometrical constraints. The structure of the final system is shown in Fig. 1. The five modules of the system are numbered in the figure and are explained in the following paragraphs:

i) Bridge images database:

The main purpose of the bridge multimedia database is to assist the designer in the preliminary design stage by allowing him to browse through the pictures of available pedestrian bridges and retrieve the ones that may be used as a starting point for the new design. The prototype database has so far more than 100 pedestrian bridge images in Japan taken from different sources[1]. The main table in the image database has one record for each image. Each record has the following fields (1) bridge name, (2) span length, (3) superstructure type, (4) sub-structure type, (5) material, (6) type of the crossing (over a river, a road, etc.), (7) the environment of the bridge (city area, rural area, mountain area), (8) part of the bridge shown in the image, (9) camera location, (10) pointers to related images of the same bridge, and so on.

The data of the main bridge dimensions are included in the database. These data can be used to draw the bridge profile and bridge cross section. Figure 2 shows an example of retrieving the cable-stayed pedestrian bridges with total span length less than 110 m.

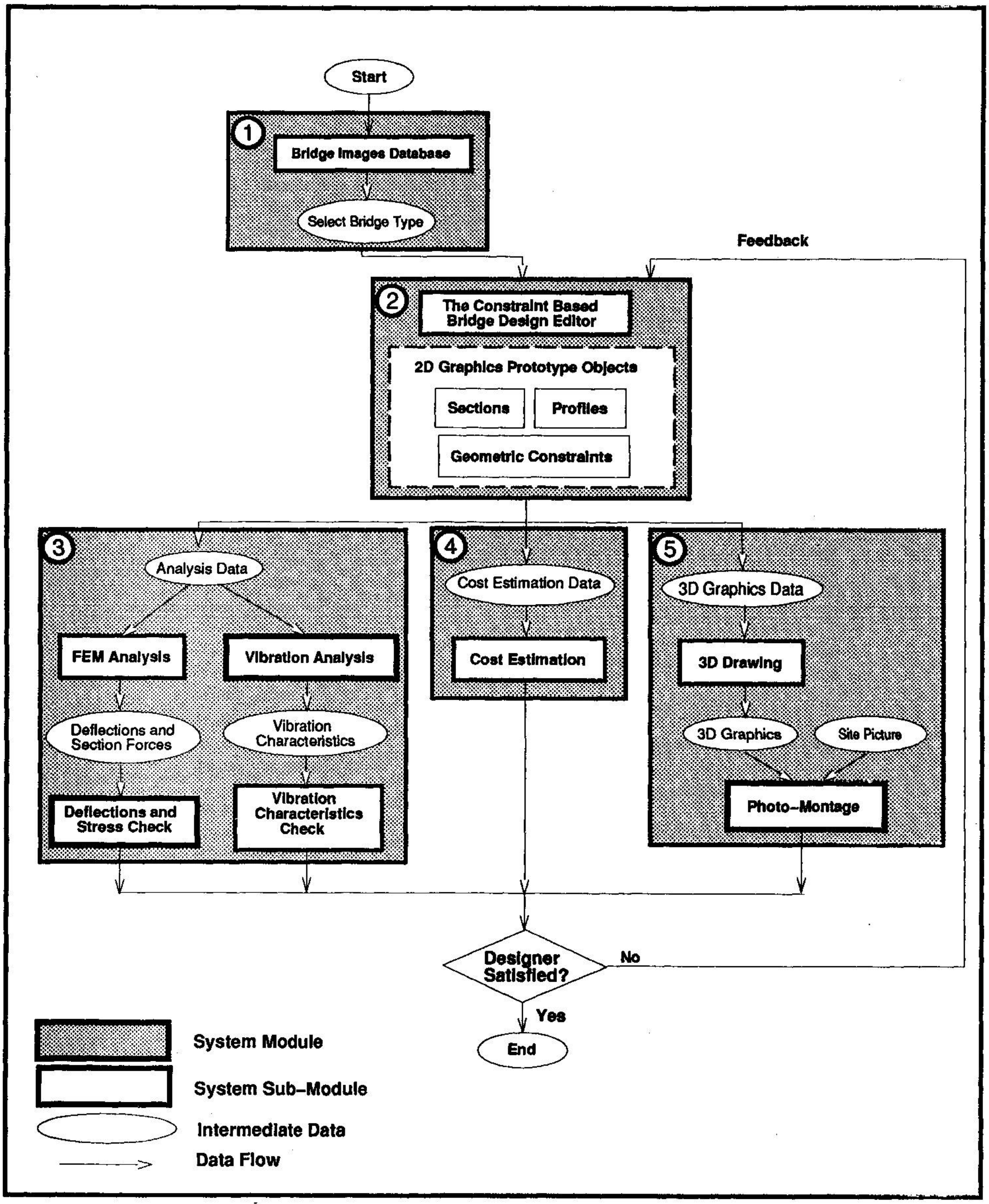


Fig. 1 System structure

ii) Constraint-based bridge graphics sub-system:

This module is the core module of the system. As this sub-system deals mainly with graphics, most of the constraints that are checked interactively are shape-related constraints, i.e. constraints on the dimensions of the members and on the connection between different members. The detailed description of bridge components hierarchy and the method of applying geometrical constraints during direct manipulation will be given in a separate section.

iii) Stress and vibration analysis modules:

In addition to the geometric constraints, other constraints used in design may require the structural analysis of the bridge and the calculation of stresses and displacements in several sections in order to check them against the allowable values. The system is equipped with structural analysis modules that can take the result of the initial design as input. In fact, one reason for choosing pedestrian bridges as the domain of this prototype system is the relative simplicity of calculating the load combinations used in the analysis.

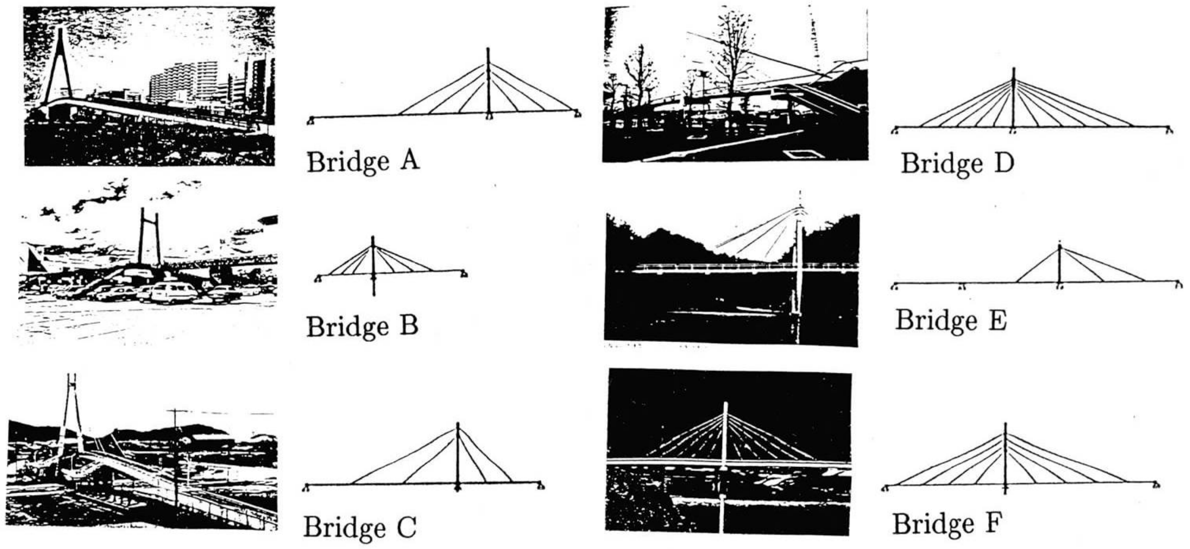


Fig. 2 Example of the images and graphics database retrieval

The natural frequency of pedestrian bridges is another important problem. The range of the frequencies of the steps of the pedestrians is from 1.5 Hz to 2.3 Hz. It is desirable to keep the values of the natural frequencies of the bridge outside this range in order to avoid resonance. In order to check these frequencies, the system is equipped with a vibration analysis module.

iv) Cost estimation module:

Cost is one of the major factors in deciding the type of the bridge to be built. The current trend in Japan is to estimate the cost of steel bridges considering only the steel weight. Although a new approach that considers the work needed in the bridge fabrication is appearing recently, the conventional method of using the steel weight only is acceptable in the initial design stage. This method can be applied directly by using the dimensions and material data resulting from the graphics editing. A special file containing the data necessary for the cost estimation is generated for each component and this data is used by the cost estimation module.

v) 3D drawing and photo-montage module:

Landscape evaluation is becoming more and more important. The photo-montage technique is well known and it has been used for the bridge landscape simulation. The method is based on synthesizing the image of the bridge site with the graphical presentation of the new bridge generated by computer graphics. However, because of the high cost of this method and the long time needed to prepare the data of the computer graphics, the current trend is to postpone the creation of the synthesized image until a later stage when the bridge type is already decided. In this system, the data needed for the 3D computer graphics is generated automatically from the 2D graphical representation resulting from editing the prototype objects. There are some limits on the 3D shapes that can be generated by the system because they are specified by combining the information in the 2D representations of the sections and profiles of the objects.

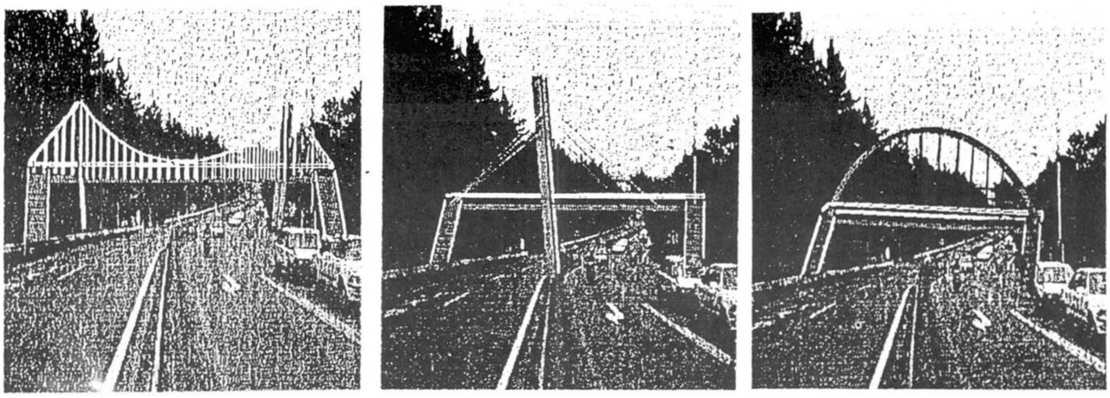


Fig. 3 Examples of the photo-montage

Figure 3 shows three examples of synthesizing the 3D graphics of different bridge types with the background image of a bridge site.

Table 1 Components of the bridge profiles and bridge sections

Bridge type	Components Used in the Profile
Plate Girder Bridge	Girder, Hand rail
Arch bridge	Girder, Hand Rail, Arch, Columns
Cable-Stayed Bridge	Girder, Hand Rail, Tower, Cables
Suspension Bridge	Girder, Hand Rail, Tower(s), Main Cable, Hangers
Cross Section Type	Components Used in the Cross Section
I-Plate Girder	Lower Flange, Web, Upper Flange Horizontal Stiffeners, Vertical Stiffeners
Box.Plate Girder	Lower Flange, Left Web, Right Web, Upper Flange, Horizontal Ribs, Vertical Ribs

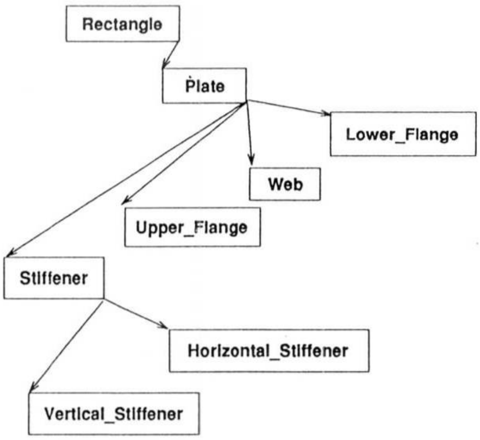


Fig. 4 Part of the components class hierarchy

4. THE SPECIALIZED GRAPHICS SUB-SYSTEM

4.1 Bridge Components Hierarchy

The elements used in the pedestrian bridge design are implemented by creating a graphical component for each of them. In order to facilitate the graphics editing, only two dimensional presentation is used. However, the internal data structure of each class has three dimensional representation. Each object is represented graphically by its cross section and its profile. An expandable library of graphical objects representing the bridge components is built using the object-oriented approach.

Figure 4 shows part of the object classes hierarchy representing the components of the cross section. The **Rectangle** class is used as the super class of the **Plate** class. The **Plate** class is the super-class of the **Upper_Flange**, **Web**, **Lower_Flange** and **Stiffener** classes. The sub-classes will inherit the attributes of their supper classes automatically. This property of the object-oriented approach means saving of time and effort in the system development and maintenance in addition to the possibility of deriving new classes from the available ones.

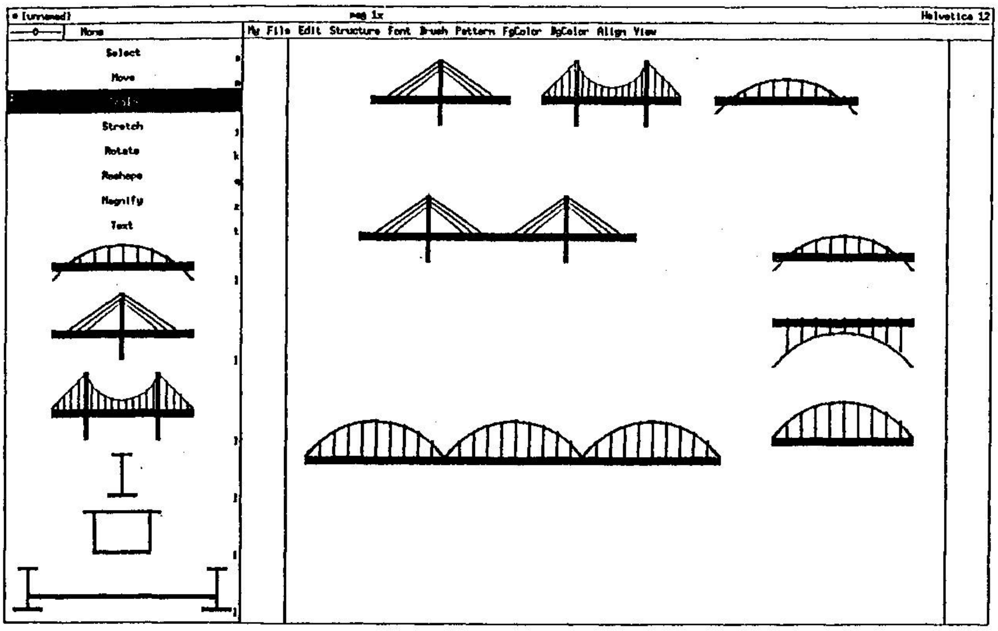


Fig. 5 Examples of the bridge profiles

The components implemented at the time being are shown in Table 1. Figure 5 shows some examples of the bridge profiles generated using the system. Most of the common bridge types such as plate girder bridge, arch bridge, cable-stayed bridge and suspension bridge have been implemented. The cross sections include the I-plate girder and the box girder with steel or concrete slabs.

Figure 6 shows example of some classes implementation. The class *Plate* includes a constructor and another class of type *Constrain**. The class *Flange* is a subclass of *Plate*. *Plate_Girder* is a composite object that has *upper_Flange*, *lower_Flange* and *web* members. The function *Connect* is used to connect the members of composite objects.

In addition to the dimensional parameters, other attributes are attached to the classes such as the color of the girder, the type of the material used and the support conditions. Furthermore, each class has a number of functions that calculate the properties of the object like the area of a cross section or the weight of a girder.

4.2 Constraints Representation and Processing

The constraints used in design can be normally classified into three types:

i) Structural constraints:

Design specifications [2, 3, 6] impose a large number of constraints on the dimensions of each element and the relations between the dimensions of different elements. These constraints are generally expressed by two inequalities in the form:

$$\text{Maximum value} > \text{Design variable} > \text{Minimum value}$$

The design variable in the previous inequalities can be a dimension of some element, the ratio between two dimensions or some more complex relation.

Another example of the structural constraints is the minimum thickness of web plate girder as given in Table 2 [3]. This example shows a variety of cases that can occur when the user changes, for instance, the distance between the flanges b, or the material of the web of an I-plate girder. Suppose that the user has selected the I-shaped cross section prototype with the dimensions and materials as shown in Fig. 7(a). If the user increases the height of the web from 110 cm to 120 cm while keeping the same web thickness and web material, the system will add one horizontal stiffener automatically as shown in Fig. 7(b) to satisfy the constraints of Table 2.

```
class Plate {
    Plate(width, thickness, length);
    class Constrain* constrain;
    // The constraints on the plate
    // dimensions.

         :
}

class Flange : public Plate {
    Flange(width, thickness, length);

         :
}

class Plate_Girder {
    PlateGirder();
    class Flange*     upper_Flange;
    class Flange*     lower_Flange;
    class Web*        web;
    web->Connect(upper_Flange);

         :
}
```

Fig. 6 Example of some classes implementation

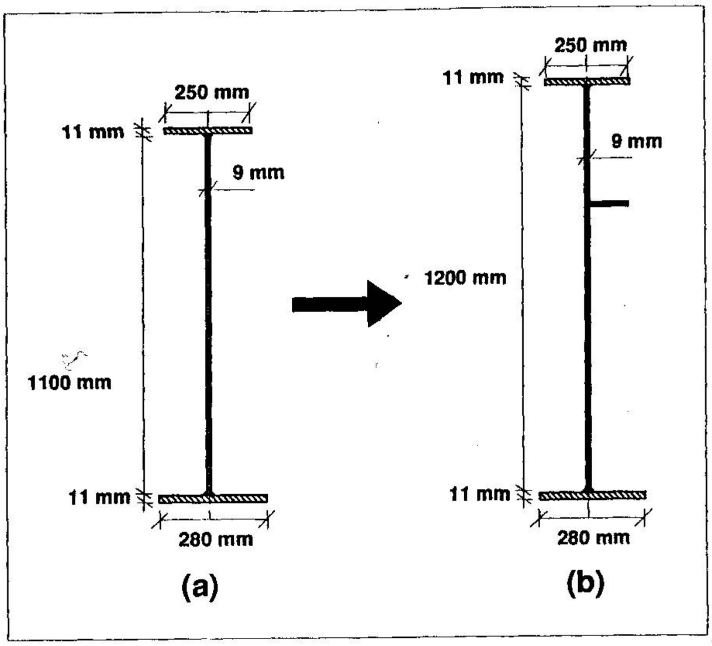


Fig. 7 Example of graphics editing of an I-shaped cross section prototype

ii) Architectural constraints:

Examples of the architectural constraints are the minimum width of the pedestrian bridge that allows two persons to walk side by side or the clearance condition under the bridge.

iii) Fabrication and construction constraints:

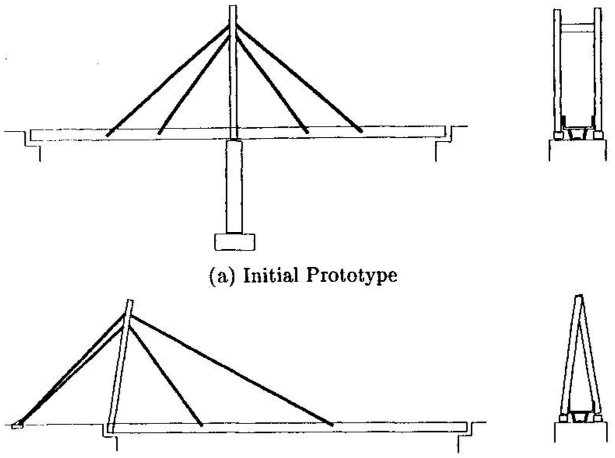
Fabrication imposes many constraints on the shape and dimensions of the bridge elements. An example of the fabrication constraints is that the thickness of the plates used in different members should follow the standard dimensions available in the market.

Design constraints of the previous types are usually forcible, i.e., they should be obeyed, and therefore they will be called here ***hard constraints.*** Not all design constraints are hard constraints. Other constraints are usually considered which are the result of experience or just the common engineering sense. These constraints will be called here ***soft constraints.*** The economical span range for each bridge type is an example of the soft constraints. This sub-system is designed to handle hard constraints as well as soft constraints. In the case the user attempts to take an action that violates a hard constraint, the sub-system will prevent this attempt and provide some explanation about the origin of the constraint. In the case of a soft constraint violation, the sub-system will only present a warning message about the constraint and the user should decide whether to execute the action or cancel it.

The constraints related to the dimensions and position of different components are implemented as check functions within the corresponding classes. The graphics editing transformation commands are interpreted by each object in a specific manner that guarantees that all the relevant constraints will be checked before the transformation is done. If the object is not a basic one, i.e., it has sub-components, the same process is repeated recursively to check all the sub-components.

4.3 The User-Interface and Processing Scenario

Figure 5 shows the user interface main screen of the system. On the left hand side are the manipulators such as Select, Move, Scale, Stretch and Rotate. The predefined prototypes of the bridge profiles and bridge cross sections and other components are shown under the manipulators. The prototypes are classified into two groups: cross sections and profiles. Above the viewing area is the menu bar which has several pull-down menus for file commands, editing commands, changing the material used in the section, changing the color, the pattern or the line thickness used, etc.



(a) Initial Prototype

(b) Prototype after Editing

Fig. 8 Cable-stayed bridge profiles

Table 2 Minimum thickness of web plates for plate girders

Steel grade	SS41 SM41 SMA41	SM50	SM50Y SM53 SMA50	SM58 SMA58
For girders without horizontal stiffeners	b/152	b/130	b/123	b/110
For girders with single horizontal stiffeners	b/256	b/220	b/209	b/188
For girders with double horizontal stiffeners	b/310	b/310	b/294	b/262

b : web height in cm

The cable-stayed bridge will be given here as an example to show the rich set of possible variations in the geometry of the bridge. Figure 8 shows two possible variations of the cable distribution and tower types. Figure 8(a) shows a conventional cable-stayed bridge with straight H-shaped tower and symmetric cables. Figure 8(b) shows a more innovative design with an A-shaped inclined tower on the extreme left end of the girder and the cables on the left hand side meeting at the anchorage. The user can change the bridge configuration by first selecting the prototype of the cable-stayed bridge and then manipulating it by applying operations like move, rotate, scale, etc. For instance, in order to change the prototypical cable-stayed bridge shown in Fig. 8(a) so that it becomes like the one in Fig. 8(b), the user needs to do the following manipulation: (1) Move the tower from the mid-point of the bridge to the left end. (2) Rotate the tower around its base for the desired angle. (3) Change the distances between the tower base and the anchorage point of the lowest cable on both sides of the tower. (4) Change the distances between the successive anchorage points of the cables.

Fig. 9 A new bridge type by adding an arc to a cable-stayed bridge

4.4 Combining Available Components for Innovative Design

The system has a number of pre-defined prototype objects representing a variety of common profiles and cross sections. If the designer wishes to design a new type that is not one of the pre-defined objects, then it is desirable that the system recognizes the new object. However, it is impossible to predict the infinite number of variations that can appear. Accordingly, the system has the ability to recognize only a finite number of patterns that are not implemented directly as prototypes. Suppose that the user likes to create a new bridge type, like the one shown in Fig. 9, by adding an arc to the cable-stayed bridge profile. The new profile can be created as follows: (1) create an instance of each of the cable-stayed bridge profile and the arc profile, (2) select both of the previous profiles and (3) group the two profiles in one new profile. The new profile can be edited further until it is satisfactory. In such cases, the checking ability of the system is limited to the constraints on the basic components only.

5. CONCLUSIONS AND DISCUSSION

i) A new approach for a total design system centralized around a constraint-based object-oriented graphics sub-system for pedestrian bridge design has been presented. The role of the graphics sub-system has been explained as a core for an integrated preliminary design system that offers, in addition to the functions of conventional CAD systems for bridge type selection, the ability to compare several potential designs visually and to produce a feasible and correct initial design.

ii) The scope of the prototype system was limited to pedestrian bridges because of the relative simplicity of their design and the freedom in adapting different bridges types. The system can handle the conventional bridge types such as plate girder bridges, arches, cable-stayed bridges and suspension bridges as well as innovative types that use combination of the same basic components. The successful results obtained from the prototype system encourage applying the same approach to other civil engineering structures.

iii) It was shown that the results of the two dimensional representation of the bridge section and bridge profile can be used effectively for different purposes in an integrated design system.

iv) It was shown how images of available pedestrian bridges can be integrated in a multimedia database and how this can assist in the selection of the bridge type.

REFERENCES

[1] *The Bridge Yearbook.* Japan Bridge Construction Society, 1980–1991 (in Japanese).

[2] Japan Road Association, Technical Standard for Pedestrian Bridges Construction. Technical report, 1979 (in Japanese).

[3] Japan Road Association, *Specifications for Highway Bridges – Superstructure*, 1980.

[4] Leonhardt F., *Bridges Aesthetics and Design.* Deutshe Verlags-Anstalt, 1982.

[5] Martini K., *Geometric Modelling for Structural Design.* PhD Dissertation, University of California, Berkeley, 1990.

[6] Ministry of Construction, Civil Structures Standard Design, Vol. 5, Construction of Three Dimensional Crossing Structures, All Japan Construction Technology Association, May 1985 (in Japanese).

[7] Nishido T. and Itoh Y., Developing of Advisory System for Evaluating Landscapes of Bridges. *Proceedings of the Third Pacific Structural Steel Conference*, Tokyo, 1992, pp. 985–992.

[8] Nishido T., Maeda K., and Nomura K., Practical System for Type Selection of Bridge Crossing River. *Expert Systems in Civil Engineering, IABSE colloquium*, Bergamo, 1989, pp. 311–319.

[9] Stroustrup B., *The C++ Programming Language, Second Edition.* Eddison-Wesley, 1991.

[10] Sun Microsystems, Inc., *SunPHIGS 2.0 Reference Manual*, 1991.

[11] Sutherland I.E., *Sketchpad: A Man-Machine Graphical Communication System.* PhD Dissertation, MIT, 1963.

[12] Vlissides J.M., Generalized Graphical Object Editing. Technical Report CSL-TR-90-427, Stanford University, June 1990.

Preliminary Design of Bridges Using Knowledge-Based Systems

Avant-projet de ponts à l'aide de systèmes experts

Vorentwurf von Brücken mit Hilfe von Expertensystemen

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SUMMARY

This paper concerns methods for the application of knowledge-based techniques to preliminary structural design. Different methods which can be used to improve software for computer aided design and engineering are discussed. A practical study of these methods is made by developing a prototype for preliminary design of highway bridges. In order to allow the design engineer to test different alternatives and to see the consequences of a certain design choice or design step a method which enables the user to make assumptions has been implemented. The use and the suitability of product models in computer aided structural design is also discussed.

RÉSUMÉ

L'exposé se réfère à l'application des techniques de systèmes experts dans l'avant-projet de structures porteuses. Il présente diverses méthodes en vue d'améliorer les logiciels de conception et de construction. Une étude pratique de ces procédés a permis de développer un progiciel utilisable dans le prédimensionnement des ponts routiers. En vue de fournir à l'ingénieur projeteur la possibilité d'examiner des alternatives, ainsi que les conséquences de choix effectués lors de l'avant-projet, ce progiciel comporte une méthode permettant d'entrer les hypothèses envisagées. L'article examine l'aptitude de produits modèles à être utilisés dans le projet assisté par ordinateur.

ZUSAMMENFASSUNG

Der Beitrag behandelt die Anwendung von Expertensystemtechniken auf den Vorentwurf von Tragwerken. Verschiedene Methoden zur Verbesserung von CAD/CAE- Software werden diskutiert. Ihre Anwendbarkeit konnte bei der Entwicklung eines Prototypprogramms für die Vorbemessung von Strassenbrücken erprobt werden. Um dem entwerfenden Ingenieur zu ermöglichen, verschiedene Alternativen und die Auswirkungen bestimmter Entwurfsentscheidungen zu studieren, enthält das Programm eine Methode zur Eingabe von hypothetischen Annahmen. Weiterhin wird die Verwendbarkeit von Produktmodellen in CAD für Tragwerke angesprochen.

1. INTRODUCTION

Common for all CAD/CAE–programs of today is that they are used at a relatively late stage of the design process, e.g. for the analysis and documentation of a "known" structure. Programs that support the early stages of design are rare and, if they exist, very specialized. Future generations of CAD/CAE–programs must be able to support the early stages of design. In order to accomplish such a support future CAD/CAE–programs must be able to describe knowledge such as codes, experience, heuristics etc. The use of expert system techniques is one way to deal with such knowledge.

Future generations of CAD/CAE–programs will also be working in a more complex environment than the CAD/CAE–systems of today and must be able to exchange data and information with external sources such as databases. In the future it is likely that for computer aided design there will be just one shared database for each project. Different computerized tools will use this shared database to retrieve and store information. One purpose of this approach using just one shared database is to avoid multiple storage of one and the same information. A database, that can be used during the entire design process, will be complex and must contain so much information that it should be able to cover all relevant aspects of the current problem field. An object description, which includes all types of information needed to describe the object during the entire design process, is often called a *product model*. This paper discusses the use of product models in computer aided structural design. It is also discussed how a knowledge based system can be devised by combining product models with production rules and/or procedures.

A practical study of these methods is made by developing a prototype (called PREBRI) for preliminary design of highway bridges. In order to allow the design engineer to test different alternatives, and to observe the consequences of a certain design choice or design step, a method which enables the user to make assumptions (hypotheses) has been implemented in PREBRI.

2. KNOWLEDGE REPRESENTATION IN DESIGN

2.1 Knowledge representation and databases

In structural design of today we use several different methods to represent knowledge. It can be visualized as *sketches, drawings, flow diagrams, results from analyses* etc. Different methods describe different aspects that designers have on the structure (figure 1). Each method gives a relevant description of the designed object used under different circumstances or by different actors in the design process. These methods have been developed under a long period of time and fulfil the needs that engineers, architects and contractors have in the process of building design. Different actors in the design process do not in general have difficulties in understanding these methods and to separate them from each other.

Computer programs for structural design purposes used today tend to reflect the above–mentioned methods to represent knowledge. There are programs for drafting, analysis, project planning etc. Computer programs used to solve a particular problem are usually effective tools and fulfil the task for which they were designed. Computer programs cannot (in contrast to humans) understand different methods to describe knowledge. This makes it difficult to exchange information between different kinds of programs. It is for example hard to use a drawing created in a CAD–program as input to a FEM–program and vice versa. A FEM–program cannot by itself extract those parts of a drawing that are necessary for the structural analysis. It can sometimes even be difficult to transfer information between different computer programs designed for the same task, for example to transfer a drawing from one CAD–program to another. In the latter case we often risk to lose information because the drawing has to be transferred using a standard, which just includes a minimum set of graphical information.

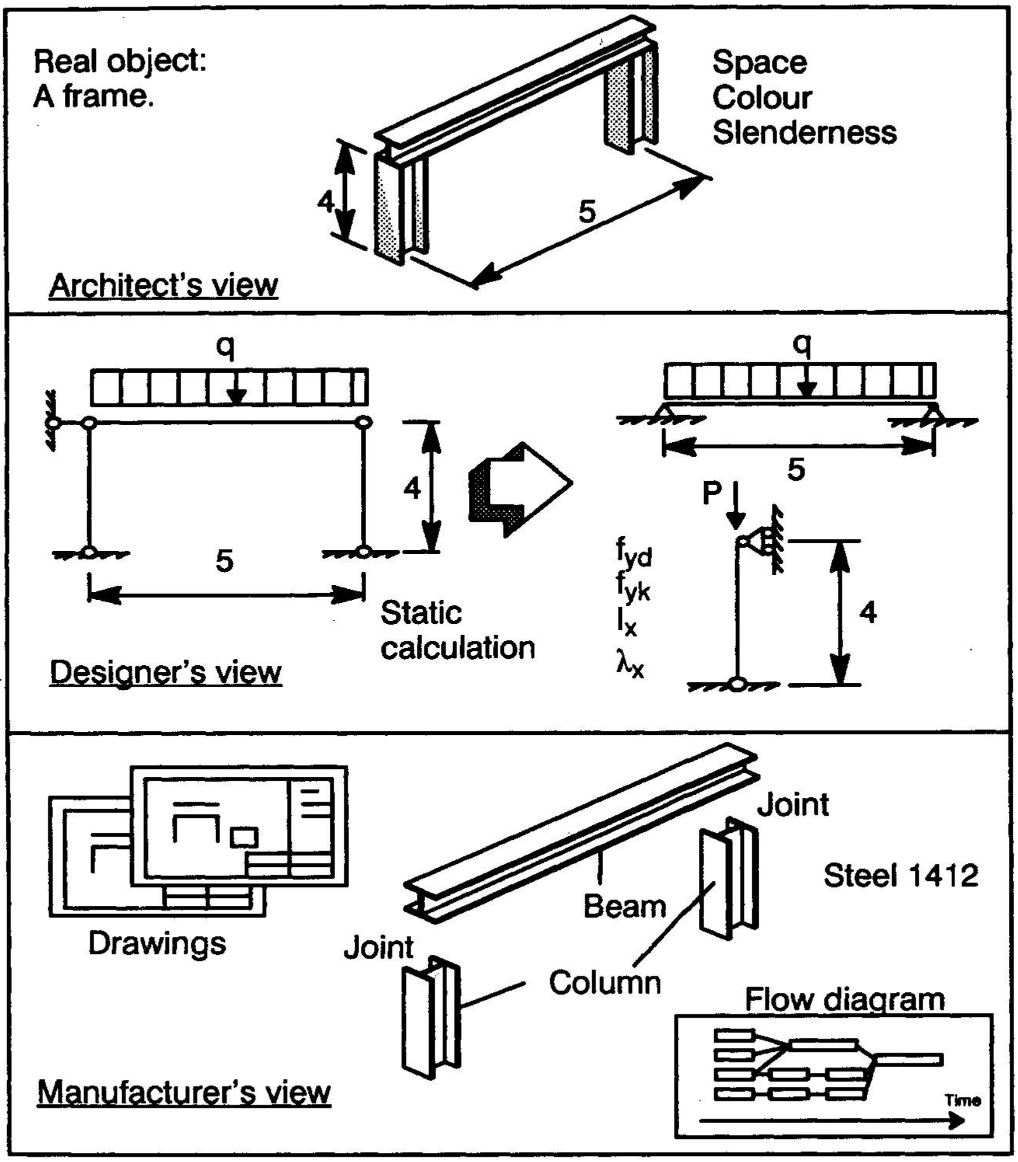


Figure 1. Different abstract representations used by different actors in the process of structural design and manufacturing.

The next generation of computer programs used for structural design must be able to exchange information between each other. The information to be exchanged is, except for geometrical data, such information as object properties, relations between objects, main function of objects etc. The latter are usually referred to as non–geometrical properties. These programs must also have access to knowledge such as experience, heuristics, codes etc. Heuristic knowledge, codes etc are often country or company dependent and are likely to change over time. It is therefore necessary to exclude this type of information from the computer program and to store it in a neutral replaceable format. This neutral storage format can also act as the medium by which different computer programs exchange information. The possibility to exchange information between computer programs will, as mentioned earlier, be crucial in future computer aided design. The medium which is used for the exchange of information and to store heuristic knowledge can be a shared database in which *product models* of the artifact, which is designed, are defined. A product model is a computerized model of a product component. If the shared database is coupled to a production system (expert system) it will be possible to include all necessary knowledge described above (heuristics, codes, non–geometrical information etc). Furthermore, the production system can include knowledge about the computer environment and therefore acts as an intelligent interface between the database and the different computer programs (figure 2).

The information stored in the database will consist of two parts. One part of the database will contain design rules, frames for product models, codes etc. This information is not likely to change during the design process. The second part of the database will contain unique information for each project. The information should be stored in such a way that all aspects and needs that different actors have during the design process can be utilized. In the the further discussion we will refer to the coupled system consisting of the shared database and the production system as the *intelligent database.*

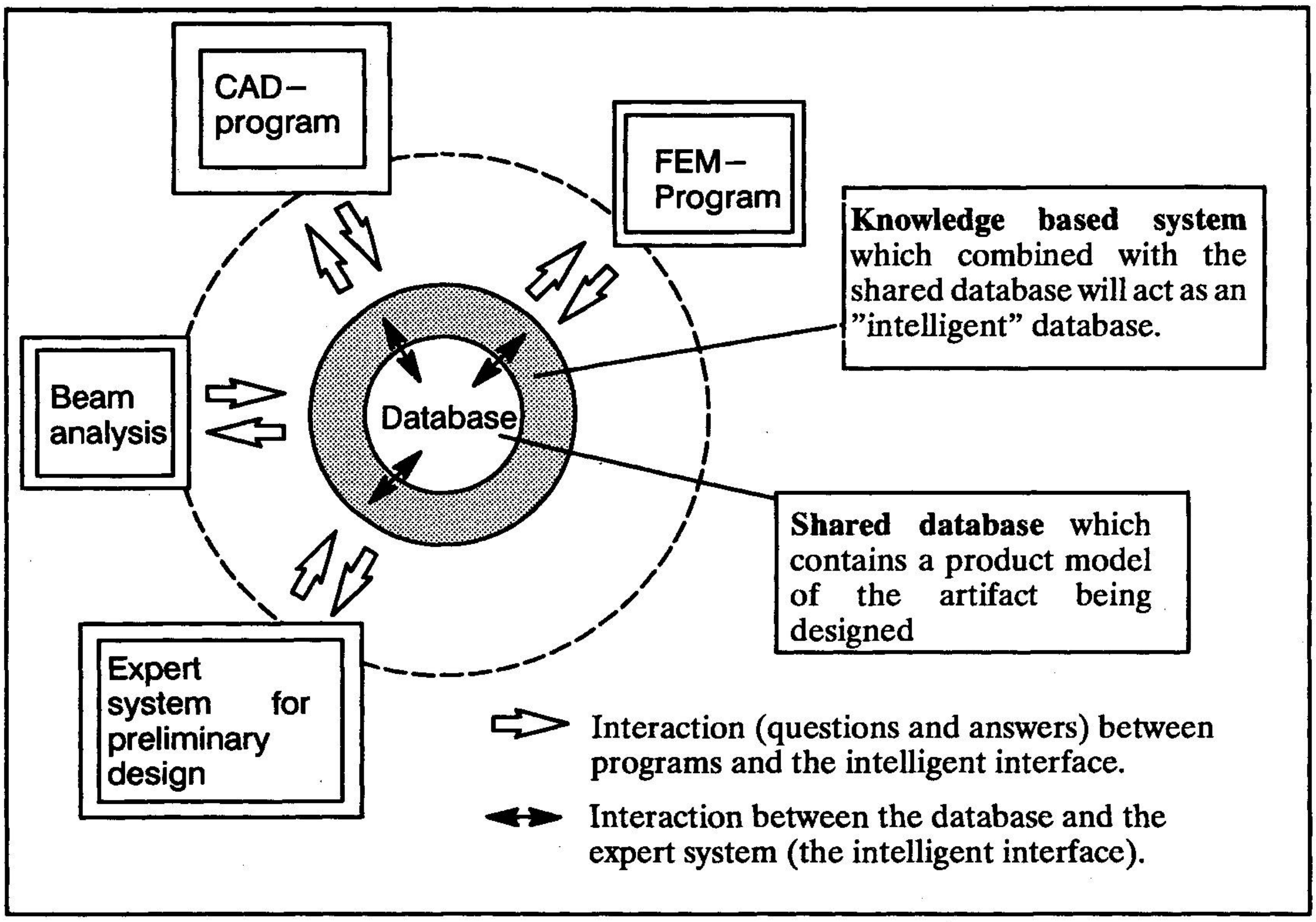


Figure 2. Expert system which will act as an intelligent database, e.g. when exchanging information between different computer programs.

The idea in this discussion is that the intelligent database should include product models which fully describe the artifact to be designed. Different computer programs should not be allowed to function as isolated units. All information should be stored in the shared database. The production system which includes heuristic rules, codes etc will check for any inconsistency in a proposed solution.

2.2 Product models

A product model is a computerized model of a product component. The product model should contain all necessary information about the product. This information includes geometrical shape, how the product should be assembled, tolerances, environmental dependencies etc. An ideal product model should also include a *history mechanism* which allows us to store information about different design steps. This will enable us to see why and how an artifact has been designed. The use of an object–oriented approach to build product models is perhaps the most promising method. In Sweden some work has been done to develop methods for classifying building details for CAD–systems (Lundberg et al., 1989). This work can among others be regarded as a first step towards the use of product models.

It is necessary that the product model we use can reflect all aspects of building design. Different actors in the design process have different needs. The product model must be able to describe the overall structure (house, bridge etc) as well as the structural subcomponents (frames, columns, doors etc). Each subcomponent as well as the assembled subcomponents will be described as a separate product model. The product model must — apart from describing the component itself — also be able to include information about the relations that the component has *both* to other components *and* to the main structure. It is therefore, when defining product models, necessary to use a technique that allows us to build hierarchical datastructures.

This hierarchical structure can easily be modelled by using an object–oriented approach. Objects are, in object–oriented systems, usually defined by using datastructures called *frames*. A frame is a datastructure which contains all information about a concept. A concept can be a general structural concept such as window, wall, house etc or a specific part in a building such as column–A3, window–B4 etc. Figure 3 shows a frame structure which defines the object "WINDOW–B4". Each object is defined by using *slots* and *facets*. The slots define properties of the object. Each facet defines the value of a slot property, how it can be retrieved and/or restrictions on the value. The frame–based model to store information is commonly used in knowledge–based programming and is fully described in the literature within the field, see for example Walters and Nielsen (1988), Coyne et al. (1989).

OBJECT: WINDOW–B4	
SLOTS:	**FACETS:**
IS–A	(VALUE WINDOW)
PART–OF	(VALUE WALL–1) (RESTRICTIONS (VALUE–IS–A OUTER–WALL))
TYPE	(VALUE M2–STD) (FETCH QUERY)
HEIGHT–OVER–FLOOR	(FETCH DEFAULT)
VERTICAL–PLACEMENT	(FETCH SNAP–TO–MODULAR–SYSTEM)
...	...

Figure 3. Product model definition using a frame structure.

The product model which defines an object must include all known information as well as information about how to retrieve unknown data, restrictions on a value, etc. We must also be able to link known data to its presumptions. A slot value must be recalculated or marked as "unknown" if the presumption to that value is changed. A product model which is used to describe a beam will typically have slots and facets which include information about which codes that are relevant, which program that can be used for structural analysis etc.

3. PREBRI

Preliminary design is a task which needs heuristics and experienced–based knowledge to be carried out. Within the field of preliminary bridge design this means knowledge about costs, material, strength, structural design etc. PREBRI is a prototype expert system, implemented by the ART programming tool, that shows how this type of knowledge can be structured and implemented in computer programs.

3.1. Application of ART (Automated Reasoning Tool)

The Automated Reasoning Tool (ART) is a programming tool for building expert systems. The ART version used in this project (version 3.0) is Lisp–based and runs on different UNIX workstations and mainframes. Here an Apollo workstation DN3500 with 16 MBytes of primary memory (RAM) and 380 MBytes hard disk was used. ART includes facilities such as, rule–based programming, frame–based knowledge representation and object–oriented programming. ART also includes a method for modelling hypothetical alternatives or/and situations that change dynamically over time ("viewpoint mechanism"). For detailed information we refer to the ART manuals [2][3].

3.2. Internal structure of PREBRI

An expert system for preliminary design requires heuristics and experience–based knowledge to give a useful solution. Within the field of preliminary structural design this includes knowledge about costs, materials, maintenance requirements etc. In all such programs it is very important that the user has full insight and control over the system. The expert system should be a support to the user in the design process and not just deliver more or less ready–made solutions.
An expert system for preliminary design should include the following parts.

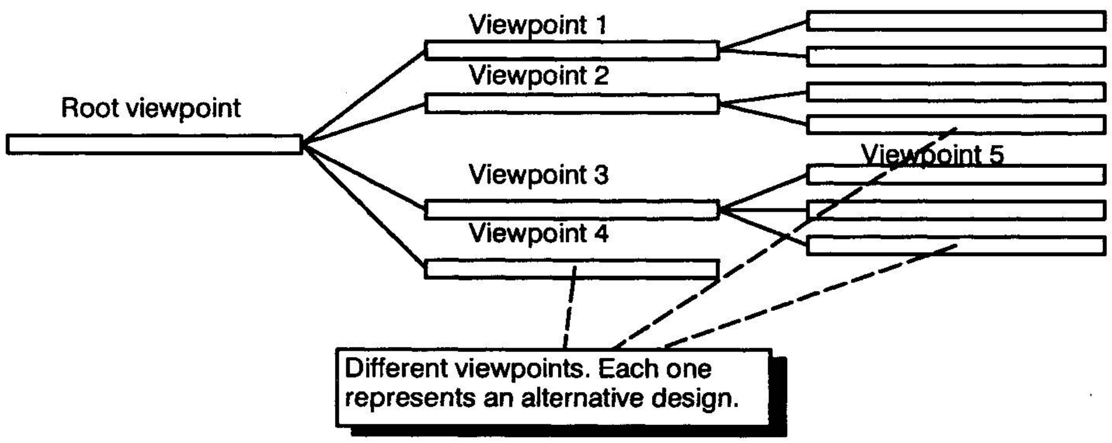
1. **User interface,** for interaction between the user and the program. The user interface should be developed and specialized for the actual problem under consideration. It must be able to represent knowledge in an effective and natural way.
2. **Domain description,** which includes knowledge such as codes, objects, relations between component parts etc.
3. **Process rules (for design),** which are rules that describe the solution process. These rules include knowledge about the actual design process within the problem field.
4. **Controlling rules,** which include knowledge for detecting errors, checking codes etc. These rules act in the background.
5. **Interface to external programs.** This is a very important part of many expert systems. It is important that a program can interact with other programs or databases in an easy way. This requires a standard for the exchange of information.
6. **Inference engine,** which uses rules and knowledge from points 2, 3, and 4 above to retract or assert information in the internal knowledge base.

The prototype PREBRI was developed in order to investigate how the parts defined by points 2–4 above could be suitable described and implemented in an expert system for preliminary structural design in general and for preliminary design of bridges for motorway crossings in particular. The knowledge in the prototype also include demands on the design such as structural and constructional constraints, costs etc. A simple user interface has also been developed to be used for testing of the prototype.

The domain knowledge (point 2) contains a general description of the objects in the problem domain of the design of a *bridge crossing a motorway.* A lot of effort has been spent in order to make a useful description of the bridge components and of their interrelations. These descriptions can be seen as a first step to a product model for short span bridges. The design rules (point 3) are rules which describe the design process for preliminary bridge design. These rules are the "engine" of the expert system. They propose new solutions, find and retract impossible solutions, recommend the next step in the design process etc. The controlling rules are of "general design" character and concern for instance overall geometry, beam depth etc.

The main idea with the solution process in PREBRI is that all types of solutions which are possible so far are described in different parts of the database (viewpoints). The information stored in each of these parts of the database is true under one or several assumptions (hypotheses) made by the program or by the user. This means that the program uses three kinds of facts, *truefacts, assumedfacts* and *consequentialfacts. Truefacts* are facts that are globally true. *Assumedfacts* are hypotheses made by the user or by the program. The assumptions offer a way to describe possible alternative solutions and they form an important part of PREBRI. *Consequentialfacts* are facts which are true under a certain assumption (figure 4).

Viewpoint structure



Contents of viewpoint 3
Assumption: (Bridge–type CONCRETE_FRAME)
Consequential true facts under the assumption above: (Max–length–of–bridge 70) (Min–length–of–bridge 25) Facts from the root viewpoint.

Contents of viewpoint 5
Assumption: (Number–of–spans 2)
Consequential true facts under the assumption above: (Bridge–type CONCRETE_FRAME) (Max–length–of–bridge 70) (Min–length–of–bridge 30) (Type–of–support–1 RIGID) (Type–of–support–2 RIGID) (Type–of–mid–support FREE) (Min–length–span 15) (Max–length–span 32)

Figure 4. Viewpoint structure.

The whole database (the set of viewpoints) that simultaneously describes different possible solutions forms a tree–structure. The *root–node (root viewpoint)* of that tree–structure is the "global database" which includes facts that are always true independently of all part–solutions chosen. This *root viewpoint* thus includes facts such as "site properties", "minimal bridge length", "minimal bridge width" etc.

From the *root viewpoint* we can make assumptions concerning different possible bridge designs. Each of these assumptions will create a new part of the database (viewpoint). From each viewpoint we can make new assumptions which create new viewpoints etc.

The advantages with this approach is that the user can choose which viewpoint (part of the database) to evolve further. This will probably be that viewpoint which in his opinion is the most promising one. The user will therefore have full control over the system. Assumptions can be made by the user or by the program. The program will make assumptions if it will find a small number of different approaches to continue from a specified point in the solution process. The user can choose to make assumptions if he wants to test an idea or if he is not sure which solution (among several) that is the best. If the user inserts new information in a viewpoint which makes child viewpoints illegal, then all the illegal viewpoints will disappear from the viewpoint structure and all its contents will be deleted.

3.3. Knowledge acquisition

An important part and perhaps the most difficult one when building expert systems is knowledge acquisition. Knowledge acquisition is widely described and discussed in the literature. See among others Harmon and King (1985), Hart (1986), Walters and Nielsen (1988), Wolfgram et al. (1987).

In structural design we have at least three sources from which we can retrieve knowledge. They are literature, domain experts and examples. In PREBRI we use all three forms of sources. The expert knowledge was received from three experts within the field of bridge design (having 23, 30 and more than 40 years of bridge design experience respectively).

The experts pointed out the importance of reusing previous solutions. Even though all bridges are individual it is likely that some bridges will have a lot in common. One way to reuse information is to build a database, which includes all relevant information about each bridge. The information stored for each bridge should be a description containing both background information and the final solution. When we wish to design a new bridge we may then match the information about that bridge with the background information in the database. In this way we can reuse solutions already made and make necessary changes in these. This method of using examples can be an alternative or complement to the method of using rules. In PREBRI we don't use such a database with examples. Instead we have used examples to write rules.

3.4. Knowledge representation

The domain knowledge in PREBRI is represented using an object–oriented approach combined with rules. The type of objects used in PREBRI are *classes*, *entities* (description of a "real object") and *relations*. In the present version of PREBRI there are about 450 objects and 10 types of relations defined. The *classes* are used to describe different types of bridges. The types with their subclasses are described using a so called class–tree which defines the hierarchical structure of the classification. Each node in the tree represents a specific class of bridges and includes information (attributes) specific for that class. The root node is the most general class. In PREBRI the most general class is the class "bridge". The leaf of the class–tree is the most specific description of a bridge type. Each subclass inherits information from its superclass.

The structural components of a bridge are also defined as objects. These objects are for example beams, supports, columns etc. The *entity* objects are descriptions of real world objects such as column, support etc. Several entities can be combined to form a new entity. Each entity is connected to its environment using relations such as *part–of*, *below*, *supported–by* etc. The object description of an entity contains information concerning location, size, function, connection to other entities etc. *Relations* are definitions of connections or relations between objects or classes.

The rules in PREBRI are of *if–then* type. The rules are of two kinds: *design–process rules* and *control rules*. An example of a design–process rule can be a rule for estimating the construction depth of the main structure of a bridge (figure 5). An example of a control rule is a rule which checks the system for inconsistency.

```
(defrule estimate-min-construction-depth-slab-bridge
  (schema ?name
    (instance-of slab-bridge)
    (type-of-bars normal)
    (number-of-span 1)
    (min-length-span ?min-length))
  =>
    (bind ?min-c-h (* 0.055 ?min-length))
    (modify (schema ?name (min-construction-depth ?min-c-h))
```

Figure 5. A typical rule in PREBRI.

3.5. Graphical interface

The aim of this project has not been to develop an efficient and sophisticated interface between the user

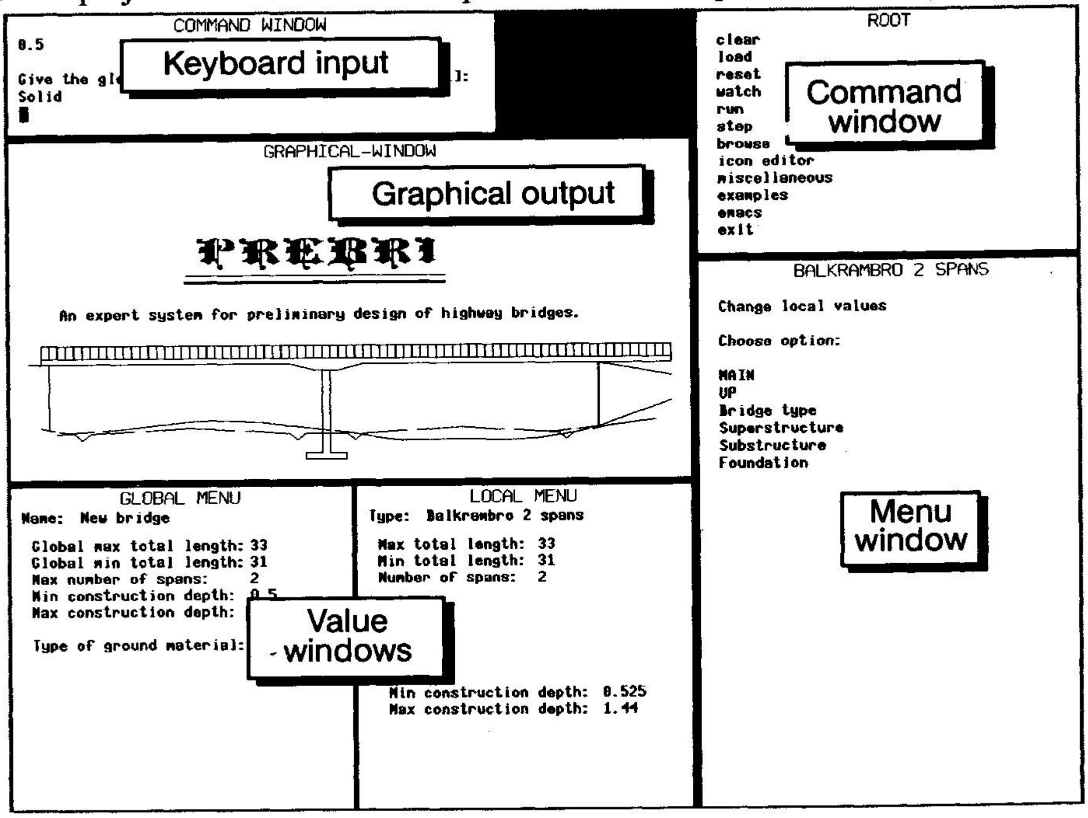


Figure 6. Graphical interface of PREBRI.

and the program. The building of such an interface is a complicated task which includes aspects such as visuality, clearness, usability etc. In order to accomplish a good interface we need better understanding of the design process, a mental model of the user etc. The interface of PREBRI is therefore rather simple and contains 5 windows, cf. figure 6. A keyboard input window, a graphical window to visualize the current bridge type, two value windows to show current values (length, bridge type, active hypothesis etc) and two menu windows, the ART programming tool command window and the PREBRI menu window. The command window can be used to inspect the viewpoint tree, browse facts and relations etc. The PREBRI menu window allows the user to interact with the program. The PREBRI menu system has been developed using object–oriented methods.

4. REFERENCES

1. AHLENIUS, P. (Ed.), Broprojektering – En Handbok (Preliminary Bridge Design – A Handbook. In Swedish), Vägverket, Borlänge 1988.
2. ART, Reference Guide, Volume 1–2, Inference Corporation, Los Angeles 1987.
3. ART, Programming Tutorial, Volume 1–4, Inference Corporation, Los Angeles 1987.
4. BRONORM 88, (Bridge Code 88. In Swedish), Vägverket, Borlänge 1988.
5. BROTYPER Tabeller, (Bridge types. Tables, In Swedish), Vägverket, Borlänge 1988.
6. COYNE, R. D., ROSENMAN, M. A., RADFORD, A. D., BALACHANDRAN, M., GERO, J. S., Knowledge Based Design Systems, Addison–Wesley, New York 1989.
7. GARRETT, J. H. Jr., Object–oriented representation of design standards, IABSE Colloquium "Expert Systems in Civil Engineering", Bergamo, October 1989.
8. HARMON, P., KING, D., Expert Systems, John Wiley & Sons, New York 1985.
9. HART, A., Knowledge acquisition for expert systems, Kogan Page, London 1986.
10. KATZ, T,. Engineering Design, Manufacture and Test, In (Winstanley, G., 1991), pp 151–193.
11. LUNDBERG, K., LUNDEQUIST, J., LOTZ–MATTSON, M., Metoder för klassifikation av bygg– eller mätdelar för CAD–system (In Swedish). Rapport R57:1989. Statens råd för byggnadsforskning, Stockholm 1989.
12. LÖFQVIST, P., Expertsystem för broprojektering (Expert system for bridge planning. In Swedish), Chalmers University of Technology, Division of Steel and Timber Structures, Int. skr. S 90:6, Göteborg 1990.
13. LÖFQVIST, P., Expert system for bridge design, Chalmers University of Technology, Division of Steel and Timber Structures, Int. skr. S 91:4, Göteborg 1992.
14. NISHIDO, T., MAEDA, K., NOMURA, K., Practical System for Type Selection of Bridge Crossing River, IABSE Colloquium "Expert Systems in Civil Engineering", Bergamo, Italy, 1989, pp 311–319.
15. WALTERS, J. R., NIELSEN, N. R., Crafting Knowledge Based Systems, John Wiley & Sons, New York 1988.
16. WINSTANLEY, G. (Ed.), Artificial Intelligence in Engineering, John Wiley & Sons, Chichester, 1991.
17. WINSTANLEY, G., The Engineering Domain and Systems, In (Winstanley, G., 1991), pp 1–32.

Development of a KBS for Conceptual Bridge Design

Développement d'un système expert pour le projet de ponts

Entwicklung eines Expertensystems für den Brückenentwurf

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SUMMARY

This paper discusses the continuing development of a knowledge-based system for conceptual bridge design. The development and evaluation of this system has led to a number of conclusions concerning the applicability of KBS in engineering design domains. Further research has illustrated the way in which such innovative design systems should be developed in the future in order to be useful. This paper discusses these findings in the context of practical KBS implementation in the engineering design industry.

RÉSUMÉ

Les auteurs présentent un système expert, en cours de développement, pouvant servir aux avant-projets de ponts. A partir de la mise au point et de l'appréciation de ce système, ils tirent un certain nombre de conclusions sur les possibilité d'utiliser des systèmes experts dans le domaine de l'ingénierie de la construction. Les auteurs montrent comment il faudrait, à l'avenir, développer les systèmes innovateurs en matière de conception, afin que ceux-ci soient vraiment utiles. Finalement, ils commentent les résultats de ces travaux dans le contexte d'une réalisation pratique au sein d'un bureau d'études.

ZUSAMMENFASSUNG

Der Beitrag diskutiert die noch andauernde Entwicklung eines Expertensystems für den Entwurf von Brücken. Aus der Entwicklung und Auswertung dieses Systems ergeben sich eine Anzahl Schlussfolgerungen für die Anwendbarkeit von Expertensystemen im konstruktiven Ingenieurbau. Aus weiterer Forschung wurde klar, wie innovative Entwurfssysteme in Zukunft entwickelt werden sollten, um nützlich zu sein. Die Arbeitsergebnisse werden im Zusammenhang mit einer praktischen Implementierung im Entwurfsbüro einer Ingenieurunternehmung besprochen.

1. INTRODUCTION

This paper describes the continuing development, evaluation and consequent expansion of a Knowledge Based System (KBS) for the conceptual design of bridges. This system has been developed in collaboration with industry, with bridge designers' expertise being used to construct the knowledge base [1].

The project has been underway for five years, during which time the KBS has undergone extensive testing in bridge design offices. During this evaluation, the system has exhibited an 86% success rate with the case studies used [2]. As well as assessing the accuracy and applicability of the KBS, this evaluation has enabled the computing requirements and the attitude of engineers to KBS to be analysed. This paper explains the findings of this research and discusses their importance in the context of developing effective computer systems for engineering.

An assessment of user interface design for engineers has also been carried out. The evaluation has led to extensive changes being made to the system, both in terms of its format and appearance (the content of the system has however been found to be almost entirely correct, so very few changes have been required in this respect). This paper describes the changes to the system and the effect of these changes on the utility of the system.

These changes have largely been instigated by the practising engineers involved in the project. Proposed future developments include interactive intelligent databases and daemon controlled systems. This paper discusses the feasibility of such developments, emphasising their benefit to the engineering industry.

1.1 Project Background

The ideas and much of the information in this paper have been obtained during the development of a KBS for conceptual bridge design. The system concentrates on small to medium span road bridges which cross another road; typically a motor way bridge. Although there are many computer programs which deal with the analytical stage of the bridge design process, there are few which deal with conceptual design. Therefore, this type of system was, at the time the project started, a precedent, aiming to prove the validity of such developments.

The project was started in 1987 and was originally funded on a three year basis by the Science and Engineering Research Council. The project originally aimed to investigate the applicability of KBS in design and to build a prototype system which would operate in the field of conceptual bridge design.

The two most important considerations were that:

1. A practical system should be developed as opposed to a research prototype;
2 The project should seek to establish the feasibility of applying KBS in engineering design.

The first of these two considerations inevitably demanded that the project was carried out in close collaboration with industry. Therefore, throughout the project (that is, the knowledge elicitation, system development and evaluation) a number of civil engineering consultancies were used. At each stage of the development, these engineering companies were consulted to ensure that the decisions being taken were appropriate to their needs.

The second consideration demanded an analysis of the way in which computers and KBS are accepted in engineering. The findings of this aspect of the research are discussed later in this paper.

The domain of conceptual bridge design is poorly documented and intrinsically relies on the designer's personal experience. Therefore the knowledge base had to be developed almost entirely from knowledge elicitation using a number of bridge design experts. This knowledge elicitation process is detailed elsewhere [1]. It is sufficient to say here that it was a time consuming and difficult process, but one which proved extremely worthwhile, resulting in a near complete and correct knowledge base.

1.2 The Domain and The System Structure

The domain of the system has been deliberately restricted to small to medium span road bridges which cross a road. There were three main reasons for this decision:

(i) It was important that the prototype system developed should be effective and useful. Had a larger range of bridge types been used there would have been a risk of creating an incomplete, unreliable and inaccurate system. It was preferable to choose a more realistic domain size which could be covered within the limited time scale available. This domain could be extended later if the project proved to be viable.

(ii) Small to medium span road bridges were chosen as these are the commonest form of bridge encountered by inexperienced engineers: the target user of the system. It was suggested by the experts involved in the project that these are the bridges most commonly designed.

(iii) This section of the conceptual bridge design domain is the simplest. If the prototype was to be successful it was sensible to begin with the simplest option, possibly extending to cover more complex designs.

The domain structure of the system is shown in Figure 1. This figure illustrates the major considerations involved when designing a small to medium span road bridge.

The system is rule based and built in the language PROLOG. The system is based on a tree like structure, relying on PROLOG's in built backtracking mechanism as its search structure. It currently contains some 60 questions and 700 horn clauses; of which two thirds are domain rules and the remainder are used to control the knowledge base [3].

Although the flexibility of the language proved to be advantageous, especially considering the long term nature of the project, the memory demanded by using such software did prove to be problematic. The authors restricted the system to a PC environment, as this was the only hardware which was readily available in engineering offices. This restriction, together with the memory demanded by the PROLOG software prevented the inclusion of some beneficial features; the most important of which was graphics. Recently, more space has become available due to better hardware and a reconfiguration of the software and graphics are now to be incorporated.

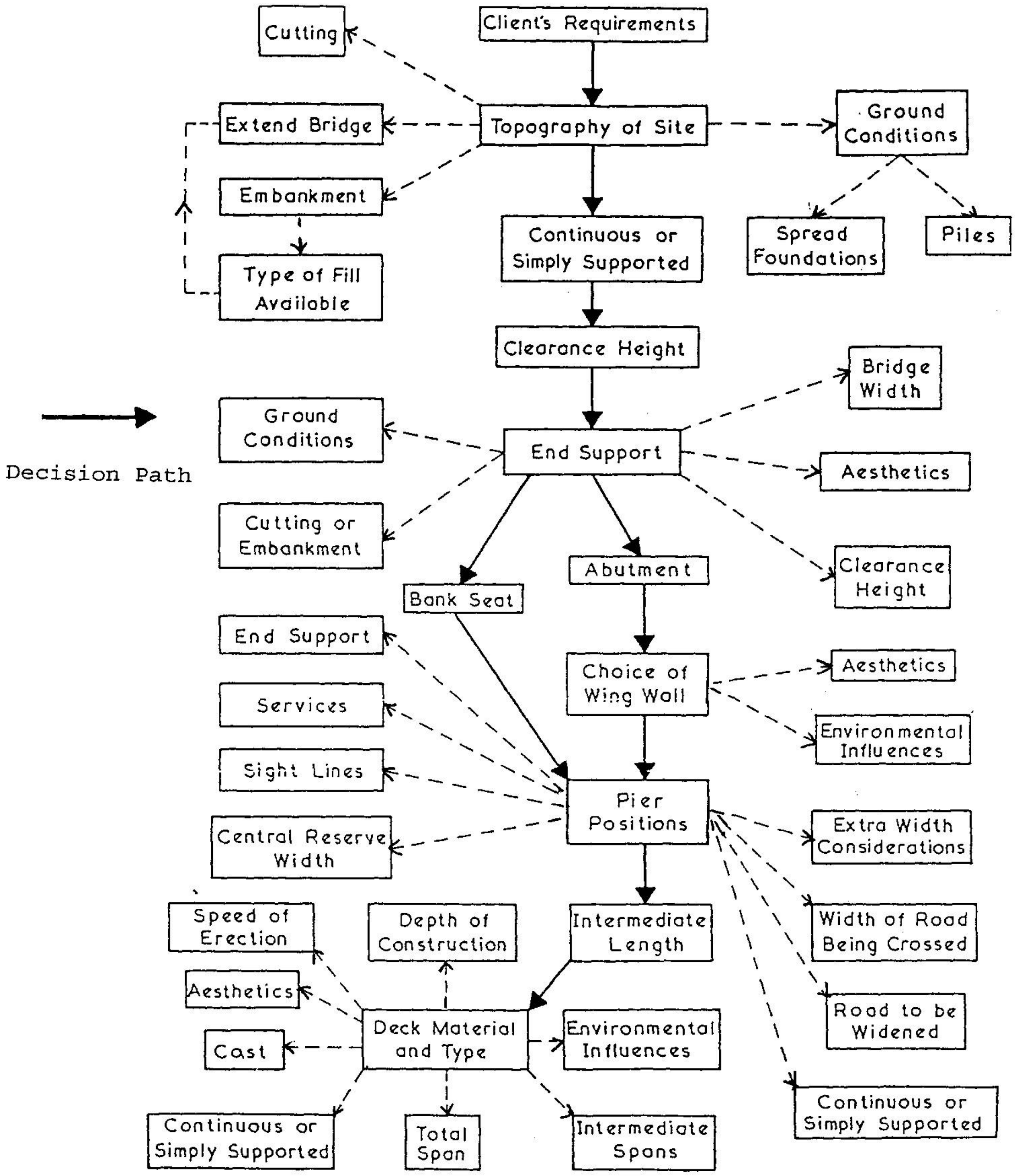

Figure 1: Domain Structure

2 THE USER INTERFACE

As has already been mentioned, the original system was intended as a design aid for engineers inexperienced in bridge design. It was also intended that the system should act as a training aid: educating engineers in the conceptual design process. Therefore, it was important that an effective and 'friendly' user interface was incorporated. A menu format was originally chosen for the questions, free input being restricted where possible as this was felt to be the simplest form of interface to use. However, the evaluation of the system showed that an alternative form of interface may have been more suitable. These findings are discussed in the following sections.

2.1 The Help System

As the system was to act as a tutoring aid as well as a design tool, it was necessary that sophisticated help facilities should be incorporated in the system. Throughout the consultation, the user is given the opportunity to access these help facilities, which consist of:

* a glossary of terms; which helps the user to understand terminology with which they are unfamiliar.
* a list of previous questions. This helps the user to keep track of previous answers and the solution path system being followed.
* the ability to change previous answers. This was a facility which was suggested by the evaluators. It enables the user to make small changes to the answers at the end of the consultation or to change their mind about an answer. This is inevitably important in a tutoring system.
* an explanation facility. This is in two parts: the first part provides a question explanation: providing additional information and suitable ranges of answers. The second part is a route explanation, explaining to the users the solution path which is being followed and why the questions are being asked.
* inevitably, the system provides the user with the option of starting again or quitting the system.

3. THE EVALUATION OF THE SYSTEM

It was recognised that if a practical and useful system prototype was to be developed, and if the acceptability and feasibility of KBS for engineering design was to be assessed, then some form of evaluation would be required.

The evaluation of the system was split into two stages: preliminary evaluation and extended evaluation. The preliminary evaluation involved sending the system back to the experts who were used to develop it. This ensured that the system fairly represented their expertise, and that, in their opinion, the domain was complete and correct. Once this had been achieved, the system was sent out to other independent engineers for evaluation. These evaluators ranged from potential users (i.e. inexperienced engineers) to expert designers who had not been involved in the knowledge elicitation. The system was left in a number of bridge design offices on a long term basis. The evaluators were provided with a diary in which they made notes and comments each time they used the system. These diaries were followed up by a series of interviews at approximately one month intervals. These interviews discussed the comments in the diaries and identified the changes which would have to be made to the system.

This long term evaluation has been underway for approximately two years and in this time some 40 people have evaluated the system. The evaluation process is discussed in detail in [2]. However, the major findings and the results since this 1991 paper are outlined here.

3.1 The Findings of the Evaluation Process

The results of the evaluation are summarised in Table 1. The information covers three versions of bridge and two of the companies involved in the evaluation of the system (C1 and C2). The results span approximately an eighteen month period. ABRIDGE, BBRIDGE and CBRIDGE represent iteratively developing versions of the system, each of which incorporates the changes and comments received during the evaluation of the previous version.

Table 1: Breakdown of Comments Received During the Practical Evaluation of Iteratively Developing Versions of the Bridge System

Version of System	ABRIDGE			BBRIDGE			CBRIDGE		
Type of Comment	C1	C2	%	C1	C2	%	C1	C2	%
Interface	25	15	*87*	8	10	*58*	7	25	*68*
Content	3	2	*11*	1	1	*7*	0	1	*2*
Development	0	1	*2*	9	2	*35*	3	4	*15*
Bugs	0	0	*0*	0	0	*0*	2	5	*15*
Total	28	17	*100*	18	13	*100*	12	34	*100*

C1 - ENGINEERING COMPANY 1 C2 - ENGINEERING COMPANY 2

Breakdown of Comments Received During the Evaluation

Interface: Comments concerning the interface.
Content: Comments concerning the content of the system,
Development: Suggestions/comments on the future development of the system
Bugs: Errors in the program.

Observations

1 No bugs found in the first two versions of the system. The bugs introduced in the third version of the system were due to programming conflicts with existing information.
2 Comments on the content of the system were few, reducing to virtually none (2%) by the third version. No major omissions were noted, proving the completeness of the knowledge base and the effectiveness of the knowledge elicitation.
3 The majority of comments received were directed at the system's interface, emphasising the importance of a good user interface.
4 Initially, virtually no comments on the future development of the system. However, once the evaluators saw BBRIDGE their interest in the future development of the system increased.

These results have instigated a further project dedicated to the investigation of user interface design. This project is being carried out in conjunction with the Psychology department and has involved a number of different interfaces being developed and tested both by trials and in practice. The findings of this project are detailed in [4].

The main changes made to the interface are in the screen layout. In the first version, only the question was shown on the screen at one time Any help or additional facilities were accessed via a menu bar shown on the screen. During the evaluation it became apparent that the users found this frustrating as they would have liked to have the help information available at the same time as the questions. This has been incorporated in the new interface, with a large amount of information now being available on the screen at one time. The additional facilities, such as the glossary are still accessed via a menu bar as it is felt that these would not be needed at all times throughout the consultation and would be irritating if they were constantly visible on the screen. The new interface was found to be similar in layout to other program interfaces which were regularly used by the engineering profession. The research has also shown that two levels of interface are required: one for users who are unfamiliar with the system and who consequently need all the help facilities and a second for users who are familiar with the system and who merely want to obtain a design solution.

The system has been tested on case studies during the evaluation. To date, the system has shown an 86% success rate. This success rate is promising but most of the failures have arisen because the designs fell outside of the system's rigid domain structure. To extend the system to cover many of these possibilities would be feasible but it would be a long and time consuming task. Even by doing this work, it is unlikely that all the possible options would be covered and thus there is a very strong chance that the performance of the system would only improve by 5%, thus still not reaching a 100% performance rate, which should be the ultimate aim of a system such as this.

This led to the conclusion that perhaps the best way forward for the system was not to use the standard expert/ knowledge based system approach. The rigidity of this approach makes eliminating error and covering unusual situations difficult. A more flexible method of manipulating and using human expertise is needed: thus better emulating the flexible way in which people deal with their own knowledge: coping well with new information and ideas and rarely degrading ungracefully at the boundaries of their expertise: a common problem with expert systems. The following sections discuss these ideas.

4. THE FUTURE OF THE BRIDGE SYSTEM AND OTHER DESIGN KBS

This project has revealed much about the attitude of engineers to the implementation of design KBS. The detailed evaluation described in the previous section has helped to identify these attitudes and, as discussed above, has led to certain changes in the system being made. The project has also led to a realisation that perhaps a standard KBS approach is not the best way forward for design systems. These thoughts are fully documented elsewhere [5],[6]. However, an overview is included here.

4.1 Computers and Engineers

Our work to date has shown that computers and engineers are rapidly becoming inseparable. Applications such as finite element analysis and CAD have brought computers to the forefront of engineering. However, in the conceptual stages of engineering, the decisions are still, quite rightly, left to senior members of the engineering team. This is never more apparent than in the design process. Bridge design is no exception to this. If the advantages of computers are to be fully recognised, then effective computer applications in these areas must be investigated.

It is interesting to look at the areas of engineering in which computers are currently most successful: CAD, Finite Element Analysis and large computational and analytical applications. Applications of these techniques in Bridge Design are numerous. What is the secret behind their success? We feel that the key lies in the fact that these programs aim to do tasks which humans find difficult, if not impossible. For example, CAD. Humans find designing by hand time consuming and difficult, albeit enjoyable. In the past, humans only tended to produce the final design option as a full drawing. CAD packages allow the rapid production of high quality drawings which can be used for comparative purposes. Modern CAD packages also provide a wide range of other facilities, including 3 dimensional analysis, rotation of the structure and an ability to place the design in a number of environments. A draftsman would find these tasks very difficult!

Similarly, finite element analysis relies on very large and complex computations which could be carried out by hand. The computer is thus being used in areas in which the human is deficient: carrying out complicated calculations at a greater speed and accuracy than that which could be achieved by hand.

There is something to be learnt from this. Many authors state that the apparent resistance towards engineering KBS is because the technology is new and unfamiliar. To a certain extent this is true: engineers are more comfortable dealing with analysis than conception and are happier with computer packages which deal with the numerical and theoretical stage of the design process. However, maybe their resistance in accepting KBS is also because they do not feel that the system is carrying out a task which they could not do equally well themselves. The aim of any tool, even KBS, should to improve a person's performance or to do a task which they are not capable of doing. Standard KBS, particularly in design currently do not achieve these aims. Therefore, systems must be developed which achieve these aims.

The evaluation of the bridge system showed these opinions to be true. The engineers involved repeatedly questioned the approach to design which was used, as shown by their attitude to the interface (Table 1). Although inexperienced engineers found the system beneficial, its validity as a stand alone design aid for all levels of engineer is questionable. The system does have its benefits: it encapsulates a large amount of expertise which had previously only been contained in people's minds and which would have been lost on their retirement. But this is not enough. Not only has the computer to utilise this expertise, it must recognise areas in which the existing expertise is deficient and aim to improve these areas. Therefore, an interactive interface is needed where the existing expertise can be used as platform on which to build new expertise as opposed to being treated as a ceiling of achievable levels of performance. Ways in which we feel this can be achieved are discussed below.

4.2 Heuristic Replacement

Heuristics play a vital role in any branch of expertise. Engineering design is no exception. Research in Cardiff has shown that it is possible to identify heuristics in engineering design which are used as short cuts to the original calculations [6]. These heuristics have been developed by experts as approximations to the formal calculations and enable them to make judgements very quickly. It is proposed that these heuristics could be replaced in KBS with the underlying theory in order to improve the accuracy of the systems, helping the program to perform better than their human counterparts. For example: preliminary costing. Our research has shown that a number of heuristics are regularly used to help experts quickly obtain an estimated bridge design cost.

This estimate is obviously highly inaccurate, due to the approximations involved and also because experts do not tend to update the heuristics which they use as often as they should [6]. By replacing this type of 'short cut' heuristic in a computer system with more accurate costing calculations, then the precision of the KBS could be improved. This system would enable alternative bridge designs to be rapidly and accurately cost compared.

4.3 Returning the Control of the Design to the Engineer

One major criticism which was received from the industrial collaborators during the evaluation of the BRIDGE system was that they felt that they were not in control of the design process: as the computer made all the design decisions and they merely provided the necessary information. Currently, this is the standard 'expert system' approach. The system makes the decisions using the elicited expertise, which is essentially contained in a 'black box' style knowledge base. Although the user can interrogate the system to find out the reasons for the answer which has been given, it is rare to find a system which maintains user control. Following these criticisms, it was realised that design systems which allow the user maximum control should be provided, as the human designer is far better at reaching innovative conclusions and dealing with extraneous information than a computer could ever be. This would help to overcome the problem of ungraceful degradation at the limits of the system domain, as the designer would still be allowed to have control of the decisions which are being taken. In order to be better than existing CAD systems, these systems would have to provide the designer with sophisticated help facilities. The system would have to interact with the user in such a way as to provide the necessary information and guidance as and when required. Thus a highly interactive 'watchdog' system would be developed which would maximise the benefits of human expertise (i.e. creativity innovation and flexibility) with the benefits of computers (memory, speed and dealing with large quantities of information).

4.4 Daemon Controlled Systems

One way of creating such a 'watchdog' system is by the use of daemons. Work is currently underway in this area. The authors envisage a system which would allow the user to carry out the design process on computer, providing help as and when required. The main difference would be that in the background a number of 'daemons' would be present. Daemons are essentially rules which only fire when triggered by the main operation of the system. Thus when the designer makes a judgement which is thought to be wrong or when he/she fails to consider a viable option, these daemons will be fired to ensure that the designer is not making a mistake. Thus the designer is still ultimately in control of the design process; the computer program will merely act as a sophisticated checker, incorporating design expertise which the user may not yet be aware of.

4.5 Interactive and Intelligent Databases

One of the main aims of current expert systems is to encapsulate expertise to prevent this expertise from being lost. There is an equal amount of 'expertise' stored in past designs. Past designs provide information on appropriate designs for certain situations, construction difficulties and aesthetics, as well as many other criteria. If an efficient way of storing, searching and manipulating these designs could be established then the wealth of information which is contained within these past designs could be utilised. Work is currently underway in Cardiff to investigate various techniques which allow the creation of such a database. Case Based Reasoning is one such approach to data management which would allow efficient storage and manipulation of previous engineering designs. Such a database is currently being developed for bridge designs.

5. CONCLUSIONS

To summarise, the development of a KBS for the conceptual design of bridges has has not only verified the viability of developing KBS for design domains, it has also shown the future for the development of better innovative design tools.

Although effective for inexperienced users, the suitability of the standard KBS/ES approach is questionable in engineering design domains. Alternative approaches have been identified which make better use of the designer's skills and which utilise the benefits of the computer. These findings have led to work in Cardiff which aims to develop such systems.

The research emphasised the importance of industrial collaboration in the development of practical design systems. Without the level of help and encouragement which we have received from our industrial collaborators none of the research discussed above could have been possible.

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References

1. MOORE, C.J AND MILES, J.C. (1991): KNOWLEDGE ELICITATION USING MORE THAN ONE EXPERT TO COVER THE SAME DOMAIN. AI Review, 5, pp 255-271.

2. MOORE AND MILES (1991): THE IMPORTANCE OF DETAILED EVALUATION FOR KBS IMPLEMENTATION IN THE ENGINEERING INDUSTRY. Computing Systems in Engineering. Vol. 2, No. 4, pp 365-378.

3. MOORE, C.J. AND MILES, J.C. (1991): AN APPLICATION OF PROLOG TO THE CONCEPTUAL DESIGN OF BRIDGES. 1st Int. Conf. on Practical Applications of PROLOG. LONDON. 1992.

4. PHILBEY, B.T., MILES, C AND MILES, J.C. (1991). THE DEVELOPMENT OF AN INTERFACE FOR AN EXPERT SYSTEM USED FOR CONCEPTUAL BRIDGE DESIGN, in Topping B.H.V. (Ed), AI and Structural Engineering, Civil-Comp Press, Edinburgh, 97-104.

5. MILES, J.C. AND MOORE C.J. (1991): CONCEPTUAL DESIGN: PUSHING BACK THE BOUNDARIES WITH KBS. In: Topping, B.H.V (Ed), AI and Structural Engineering, Civil-Comp Press, Edinburgh.

6. MOORE, C.J. AND MILES, J.C. (1992): IN DEPTH HEURISTIC ANALYSIS IN ENGINEERING DESIGN KBS. IEEE Digest, 1992/011, 6/1-6/4.