Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 68 (1993)

Artikel: Development of a KBS for conceptual bridge design

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DOI: https://doi.org/10.5169/seals-51859

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.

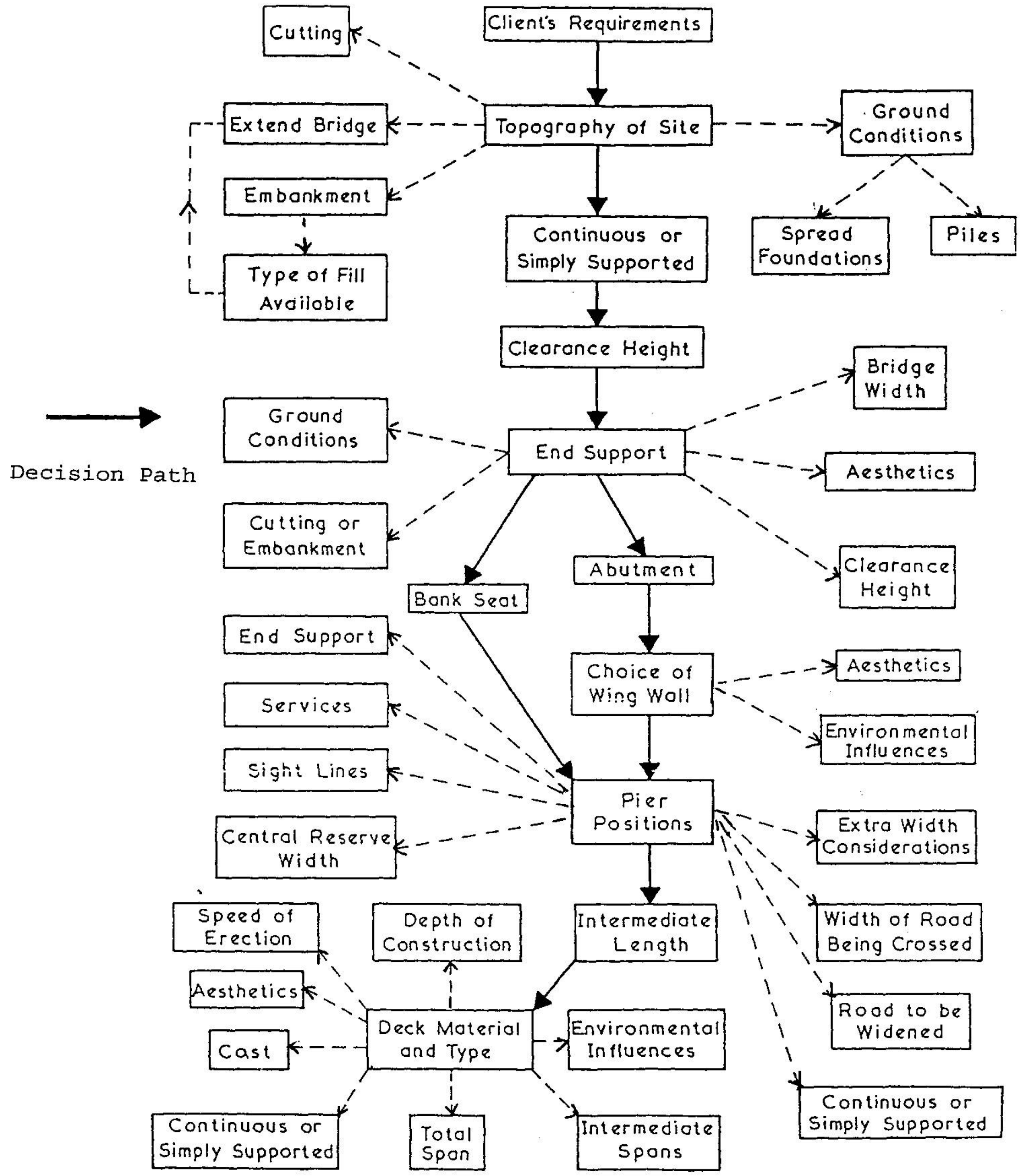

Figure 1: Domain Structure

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 / Type of Comment	ABRIDGE			BBRIDGE			CBRIDGE		
	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.

Acknowledgements

The authors would like to express their thanks to all the companies who are involved in their research, with particular reference to Sir William Halcrow and Partners, Cass Hayward and Partners, Mott MacDonald and Partners and Sir Alexander Gibb and Partners.

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