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Computational Decision Support For Preliminary Bridge Costing

Aide informatique à la décision pour le calcul du coût d'un pont

Computerisierte Entscheidungshilfe für die Vorkalkulation von Brücken

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SUMMARY

An innovative support system for the preliminary costing of bridges is based on the principle of heuristic substitution. It provides the designer with an efficient way of obtaining a preliminary bridge costing which can be easily amended and compared to other designs. This paper describes the system and the findings of the practical evaluation. The principle of heuristic substitution and the benefits of applying it in this instance are also discussed.

RÉSUMÉ

Un système innovant pour l'estimation du coût d'un pont est basé sur le principe de substitution heuristique et fournit au concepteur un moyen efficace d'obtenir cette estimation. Celle-ci peut être facilement modifiée et comparée à d'autres projets. L'article décrit le système, les résultats d'applications pratiques et les avantages de la substitution heuristique.

ZUSAMMENFASSUNG

Ein innovatives Unterstützungssystem für die Kostenvorkalkulation von Brücken basiert auf dem Prinzip der heuristischen Substitution und stellt dem Konstrukteur eine leistungsfähige Methode zur Verfügung, die auf einfache Weise ergänzt werden kann und auch das Vergleichen verschiedener Konstruktionen ermöglicht. Der Beitrag beschreibt das System, die Ergebnisse seiner praktischen Bewertung und die Vorteile der heuristischen Substitution.

Introduction

In recent years, there has been an increasing interest in the development of engineering design applications of Artificial Intelligence (AI), with a particular focus on expert or knowledge based systems [1,2,3]. However, practical applications of AI in engineering design are still very rare.

Cardiff has experience of developing innovative computer systems for civil/structural engineering, with particular reference to design [1,4,5,6]. Our research has always aimed to produce innovative computer systems which are of immediate use. To achieve this, close collaboration with the industry is essential, to ensure the applicability of the systems as well as providing new ideas and directions. This high level of industrial collaboration, combined with the experience gained when building early design systems, has produced an original approach to the research. We focus on building systems which can be implemented immediately; subsequently incrementally improving these systems with the help of industrial evaluation. The authors believe that this is in contrast to much other research which aims to build complex and powerful systems based on design theory and assumed industrial needs [7,8,9]. Both sides of the research spectrum are complementary and experience from both aspects will result in the development of innovative systems which are of real benefit.

This paper describes one system which has been produced at Cardiff as result of this 'bottom up' style of research. The idea relies heavily on previous and current associated work [10,11]. The system described is an enhancement of the knowledge base of Moore [1], assisting the designer with decision making in conceptual design. The underlying methodology is simple and yet has the potential to make a major impact on conceptual design processes.

Background Work

Work at Cardiff began with the development of 'standard' expert systems for conceptual design domains [1,12]: that is, associational, rule based systems which rely on a prescriptive question and answer format. These systems provided an insight into the KBS approach and using the accepted KBS approach resulted in restrictive and inadequate design systems. This work is detailed elsewhere [11]. Primarily, it was found that, because of their initial roots as diagnostic tools, associational KBS were unsuitable for most design domains, primarily because the demands of design are very different from diagnosis. For example, flexibility, innovation and creativity are only three of the criteria which are essential for design but which are less important or even undesirable for diagnosis. Also, there is rarely a single 'correct' design, making the examination of alternatives particularly important [11].

Our work has involved assessing the reactions of practising designers to our systems. This provides scientifically based knowledge of the utility of varying approaches and also is indicative of the importance of features which can be overlooked. For example the way in which information flows between the system and the user is very important [11,13]. Initial research has also shown that the domains which design systems originally tried to cover were very ambitious and hence tended to be complex and problematic. Experience has shown that it is preferable to break domains down into smaller, sub component systems which can be used individually or linked together. This has been implemented in our current research and the costing system described here is one component of a suite of such design systems [13,14].

The evaluation work also revealed that in some areas, the design KBS initially developed were trying to undertake tasks which designers were better equipped to perform. Designers are capable of many things which are difficult to emulate with current computing technology: most notably judgement, innovation and common sense. In other areas, the KBS were directly adopting simple heuristics obtained from expert designers [1], which were limited in terms of accuracy and efficiency. On examining these heuristics, it was found that they could often be replaced by more accurate computer based procedures thus producing a more reliable answers than was previously possible. The idea of heuristic substitution was therefore developed [10]. It is the development of this technique and the impact which it has had on the design engineers with whom we work, which forms the main topic of the rest of this paper. In the following section the reasoning behind and the concepts of heuristic substitution are introduced and the subsequent sections describe a practical application of heuristic substitution in bridge design.

Heuristic Substitution : What is it?

Despite the large number of design KBS reported in the literature, there are few examples of such systems being used by practising designers. As a part of our evaluation work, ways of making the systems more useful were investigated. On examining the knowledge bases, it became apparent that some of the heuristics elicited from expert designers could easily be replaced by more accurate methods which made better use of the computer power available. Further, it was found to be advantageous to classify heuristics into groups related to their knowledge and source [11,15]. For example, the heuristics could be used because no other more reliable estimate is available or because the underlying calculations are too lengthy to remember. Some basic classification groups are:

- Short Cut Heuristics
- Heuristics based on Background Knowledge
- Heuristics Based on Ill defined Concepts
- Heuristics based on Empirical Data
- 'Inherited' Heuristics

The groups are far from exclusive and for other domains, additional groups may be relevant. However, these groupings were found to be useful when dealing with engineering design and are described in detail elsewhere [11,15].

Fundamentally, the heuristics were classified empirically as this proved to be the best way of identifying the heuristics which could most profitably be replaced. This classification schema does not mirror the heuristic taxonomies derived by others working in psychological AI research [16]. These taxonomies tend to rely on breaking heuristics down according to their psychological function. The classification described has been developed purely through experience of the design process. In effect, current design practices have been developed to suit the capabilities of the human brain (large long term memory, small short term memory) and the above classification helps to identify areas of design where heuristics are adopted because the human cognitive processes fail to perform adequately. If this lack of performance is due to cognitive overload (fundamentally, the brain 'opting out' and using estimates because there are too many concepts to deal with at one time), then in some cases it is possible to devise new computer based design procedures to compensate this behaviour and hence provide more accurate answers than those given when heuristics are used.

When examining the type of heuristics where computer techniques can be used beneficially to supplant human heuristics, it is generally found that the heuristics have been developed because the original calculations are too complex or lengthy to conduct by hand. Consequently, short cuts or approximations are developed by the designer, hence inevitably introducing inaccuracies. When trying to derive a suitable computer based replacement, in some circumstances simply replacing the approximations with the underlying algorithms is not suitable, as the underlying calculations are still too lengthy for the computer to conduct in an acceptable time scale. It is then necessary to produce 'computer' heuristics: that is, new short cuts which can be used by the computer system to give a quick answer which is not theoretically complete but which is more reliable than the estimate originally used by the expert. Whether the full algorithms or new, expanded heuristics are used, generally heuristic substitution involves replacing heuristics with algorithms. While to some extent this may seem to transgress the earlier ideas of KBS which aimed to replicate human expert decision making, it is entirely in accord with more recent ideas on KBS, where more emphasis is placed on the quality of the input and consequent output as opposed to how the system achieves its goals [17]. It also complements the philosophy of the Cardiff group, which is to create support systems for areas in which people have difficulties as opposed to creating systems which emulate them in tasks at which they already perform well [11].

A parallel to heuristic substitution can be found in analysis, where such techniques as finite element analysis, which has enabled an accurate analysis of more complex problems than those which could be analysed by hand. This software succeeded purely because it enhanced human performance. Heuristic substitution offers a similar way of enhancing the performance of design systems.

The importance of heuristic substitution in practice has been shown by Hooper [5] at Cardiff, who developed a KBS for the strategic planning of sludge disposal. In this work, a genetic algorithm was used to find an optimal solution, replacing the previously used inaccurate hand calculation methods which were heuristically driven.

Applying Heuristic Substitution to Conceptual Bridge Design

During the development of the original conceptual bridge design system, one area which was found to be particularly problematic was preliminary costing, as this incorporates accurate costing difficulties as well as preliminary member sizing. Observations of design practice have shown that costing is an area which apparently relies on three types of estimate, offering completely different levels of accuracy. At the lower end when an overall price for a bridge is required, generally a price per m^2 costing is used to provide a quick estimate. This is based entirely on past experience. At a similar level of simplicity, when choosing an economic form of deck construction, experts use set ranges of spans to reach a decision. For example, reinforced concrete decks are generally thought to be economic for spans of up to 16m. However in contrast to these simple heuristics, when a more accurate costing is needed an almost complete design is performed and relevant quantities taken off. Typically this latter process would involve a minimum of one man week of work to cost two options.

There is no in-between form of costing, which provides the designer with a reliable estimate of the bridge cost but which is not too time consuming to be economic. Without such costing, comparison of alternative designs is currently both difficult and expensive. Our research has shown that a system which could provide accurate and rapid costs estimates would be beneficial in terms of time and money, facilitating not only better estimates but also enhanced comparison capabilities. Work has thus been conducted on the development of such a system which includes the creation of realistic, practically based costing models and the development of these is described in the following sections.

The costing process starts with an identification of the required components and materials and proceeds to member sizing. The level of accuracy with which the members are sized has a significant impact on the process. For example, a typical heuristic for sizing a bridge deck is to use a span:depth ratio (typically 20:1). However, for example, this can be substituted by using a grillage program which looks at all the possible loading combinations and hence provides a more accurate solution. Once member sizes have been fixed, it is a relatively simple process to take off the relevant quantities. From this, relative costs of the components for various options can be obtained by assigning current prices to the materials used. This is ostensibly a simple procedure, but there are several pitfalls in practice which are discussed below.

How Was The Information Obtained?

At the start of this project, some difficulties were faced as to how to obtain the necessary costing information. A knowledge base which contained many of the current 'expert' heuristics was available from previous work. These were focussed largely on the very approximate costing procedures described above. Simply moving to a full costing procedure based on a Bill of Quantities, as commonly used by a contractor when preparing a tender, was too cumbersome for our needs. Some way of obtaining an 'in-between' approach was needed.

In order to move away from Bill of Quantities style approach, an understanding of the components which comprised the bulk of the costing was required. Obviously contractors (particularly those involved in design and build style contracts) are better at reaching costing estimates than design consultancies and so two contractors were approached for help. One contractor provided a simplified costing system which his company used to initially analyse a Bill of Quantities. Instead of containing rates for hundreds of different items, as one would find in a typical bill, it contained just 10 rates, shown in Table 1. The contractor had found that this simplified costing method typically resulted in a price which was within a few percent of the final detailed estimate. This was acceptable for the aims of our system, as although it is important for the costs to be reasonably accurate, comparative costing is most important at the preliminary stage. However, this breakdown alone was not sufficient for our needs, as a greater level of detail was required.

Structures	Unit
Excavation	m^3
Bored Piling	m
Imported Fill	m^3
Insitu Concrete	m^3
Formwork (Horizontal)	m^2
Formwork (Vertical)	m^2
Reinforcement	t
Precast	m^3
Bearings	***no.***
Waterproofing	m^2

TABLE 1

Thus at this, the problem of how to cost the structure was largely solved. We still had to rapidly size the members and devise a system which allowed the user to easily look at options and take off quantities.

Using the preliminary costing breakdown provided, an outline of the proposed costing mechanism for the system was produced. From this, areas in need of further investigation were identified and these were used to structure a series of interviews with consulting engineers and specialist contractors These interviews researched costing methods currently used for relevant components.

The interviews were conducted on two different levels. Initially, the interviews concentrated on the costing of individual bridge components. First, the superstructure was examined. Designers were asked how a preliminary bridge cost would be determined for different superstructure types. The experts were prompted with simple diagrams of different span and deck types. The answers given ranged from consulting a manufacturer's precast beam catalogue to using a simple stress block analysis for cast in situ decks to using a grillage program for complex steel composite structures.

The next set of interviews focussed on the design and costing of the supports. Again a series of diagrams were used as prompts. The main finding was that the end supports should be designed as a retaining wall with various axial and lateral loads.

Finally, foundations, in particular piling, were examined by consulting a specialist piling contractor. These interviews initially aimed to elicit the type of pile which would be used for certain soil conditions. Once this had been roughly established, the price of the pile was developed by introducing hypothetical situations and asking the expert to build up a rough price for these cases.

The second stage of interviews were more general and involved the preliminary pricing of the overall structure. This included discussing such things as which were difficult aspects of the task, which were important, what could be neglected and what should be done in detail. This stage also incorporated working with the designers, producing preliminary estimates in their office and examining previous designs and costings.

By using the interviews and relevant Codes of Practice it was possible to build up a system which incorporated costing algorithms for the major contributing factors of a preliminary bridge design.

The System

The system has been developed using Microsoft's Visual C++ and the 'Windows' operating system. C++ was chosen because it offers a combination of benefits, namely: high flexibility, the ability to process numerical algorithms quickly and powerful graphical capabilities. By developing the system to operate in a Windows environment, an interface style has been adopted which is familiar to engineering designers. The decision to use C++ has proved to be beneficial in terms of both ease of programming and interface design.

Size: Currently the executable program is approximately 1.5 MB in size with the individual bridge designs needing less than 500 bytes. This gives the system the largest possible degree of implementation flexibility, allowing it to run on a 386 based PC. This was a project requirement as these machines are readily available in the smallest of regional engineering design offices.

Input: As the system aims to simplify and reduce the work load of the engineer, a simple input format was required. The philosophy of the system would be defeated if the designer had to spend hours inputting detailed dimensions. Hence, the minimum input which is accurate enough to give a realistic description of the bridge is required. There are approximately 70 different input variables consisting of numbers or strings given in list boxes. However, about half of these remain as default values and may not need altering for every design. For example some material properties will remain constant when comparing designs at a site. Typically, it takes 15 minutes to input a new design.

Calculations: The system aims to determine the preliminary costs which can be used to compare design options. As such, it does not perform a full structural analysis of the bridge but uses a mixture of heuristics and simplified design code procedures to reach a satisfactory estimate. An example of the different approaches used can be seen in the calculation of reinforcement areas. The areas in the abutment are calculated using design formulae from BS8110(1985) with highway loading and load cases from BS5400(1978). However the area of reinforcement in a pier is assumed as a percentage of the cross sectional area: an heuristic gained from the designers consulted. The difference arises because the reinforcement needed in a pier is fairly stable whilst there are many different parameters that can affect the load on an abutment and hence a more rigorous analysis is ideally needed.

Operating the system: In order to start a new design, data is input using approximately 9 different dialog boxes, which describe the entire bridge. The dialog boxes are controlled by conventional menu commands and toolbar buttons. These are listed below, together with a few examples of the variables which the dialog boxes include:

- *Summary*
  Allows the input of the name of the bridge, contract and a description. It also automatically updates the revision date and time.

Global Properties
Includes the number of spans, skew, curvatures and location.

Earthworks
Covers the type of end support, wingwalls and embankment or cutting dimensions.

Deck and Span
Dimensions the largest span and loading conditions. Also allows deck selection between cast, precast or steel types. It prompts the user with the recommended precast beam size.

End Supports
Allows input of the dimensions of various different support types and shapes. (Figure 1).

Piers
Inputs the size, location and shape of piers.

Foundation
Selection of foundation type and dimensioning.

Material properties
Input of any remaining properties e.g. soil and concrete parameters.

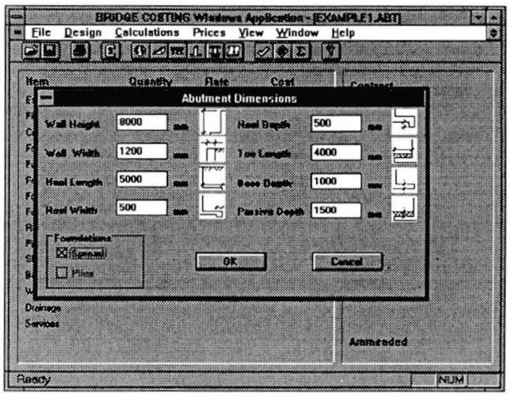
Prices
Input global prices e.g. reinforcement / tonne, vertical formwork / m^2, concrete /m^3 etc.

Once this has been completed, the structural stability of bridge is checked. The structure can then be redesigned, if it fails or is too conservative, by simply altering any of the dimensions or parameters input earlier. This can be repeated until the designer is satisfied.

The next step is to calculate the relevant quantities. This is achieved by simply selecting a toolbar button.

Finally the price of each item is allocated by the system and the total price is shown by selecting the summation toolbar button (Figure 2). The cost appears almost instantaneously.

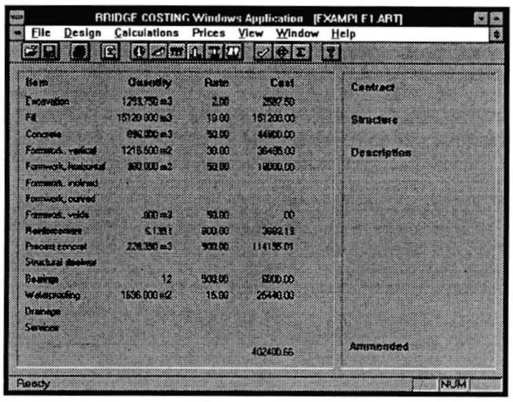
The design can now be fine tuned by simply altering any of the input variables and recalculating the design. Any aspect of the design can be altered in any order and the whole process does not need to be repeated to alter one parameter. When changing the bridge to a completely different form e.g. by altering the number of spans, deck construction material and/or end support, the structural stability and cost can be checked and obtained in under a minute. This can be compared to possibly half a man week, per major design change, which this process would currently take by hand.



Wall Height 8000 mm
Wall Width 1200 mm
Heel Length 5000 mm
Heel Width 500 mm
Heel Depth 500 mm
Toe Length 4000 mm
Base Depth 1000 mm
Passive Depth 1500 mm

Foundations
☒ Spread
☐ Piles

Figure 1.



Item	Quantity	Rate	Cost
Excavation	1293.750 m3	2.00	2587.50
Fill	15120.000 m3	10.00	151200.00
Concrete	896.000 m3	50.00	44800.00
Formwork, vertical	1216.500 m2	30.00	36495.00
Formwork, horizontal	380.000 m2	50.00	19000.00
Formwork, inclined			
Formwork, curved			
Formwork, voids	.000 m3	50.00	.00
Reinforcement	5.138 t	800.00	3692.13
Precast concrete	228.380 m3	500.00	114135.01
Structural steelwork			
Bearings	12	500.00	6000.00
Waterproofing	1636.000 m2	15.00	25440.00
Drainage			
Services			
			402400.66

Figure 2.

Practical Experience with the System

The system is now undergoing preliminary evaluation in industry and to date the evaluation has proved to be very successful. The reviewers have stated that the system is both applicable and useful for practical bridge costing and have cited beneficial additional development work. For example, life costs, the overall weight of the bridge and the areas of reinforcement required could be included.

The evaluation has shown a number of things. Firstly, it has shown that the system does provide a better cost estimate than can currently be achieved by accepted approximate methods. In addition, it has shown that a considerable saving in time can be obtained. Also, once the initial design factors have been input, the system allows small changes to be rapidly made to the design enabling ready calculation of alternative costs. This level of flexibility facilitates the comparison of alternative designs and enables the designer to refine a design by making small changes to the chosen alternative, helping to ensure an optimal solution. It is anticipated from the reception which the system has received that this will encourage the designer to experiment and compare a greater number of alternative designs than would currently be considered possible. This should in turn result in better conceptual design as fairer assessments of economic alternatives will be possible [11].

An additional advantage stated by the engineers involved in the evaluation is the flexibility that the system offers. Currently, in design offices, one 'expert' is responsible for most of the costing, and their expertise allows them to conduct costings more efficiently than non-specialists. Using the same person can also help to ensure a degree of standardisation. However, reliance on a single person has obvious disadvantages The system evaluation has shown that designers feel that this software will provide a degree of standardisation and release the 'costing expert' from some of his/her duties.

The evaluators have also suggested that the enhanced preliminary costing techniques provided by the system could potentially be very useful for dealing with contractors. Frequently, contractors will suggest an alternative design which they claim is cheaper. The system would provide a quick and relatively easy mechanism for checking alternatives.

An additional benefit recognised by the evaluators is that as more designs are costed, they can be stored as files within the system. These files can then be retrieved if similar design costings are needed, effectively creating a database of design costs. By retrieving suitable past costings, small amendments could be easily made to assess their influence. This idea could be extrapolated to provide a case based structure which could retrieve similar designs on the criteria given and hence give a preliminary costing breakdown for that design.

Overall, the system has had a very good reception from the evaluators who suggest that the time saving aspects of the system combined with its enhanced flexibility will be invaluable.

Why is this System Different?

It is recognised that the development of a computer based costing system to aid design decision making is not unique. For example Retik et al [19] describe a probablistically based costing system for planning housing schemes and Syrmakezis and Mikroudis [20] describe a costing system for building design which costs solutions produced by an expert system. For bridges in the UK, there is a design costing tool called BRIDGET [21] which is based on database technology and uses specifically designed costing heuristics which are an improvement on the 'expert' costing heuristics normally used but nevertheless still incorporate a substantial degree of approximation. The costing model described here undertakes a considerable amount of detailed design analysis to provide member sizes which are very close to those provided by a full analysis. All this is achieved within less than a second of CPU time on a 486 PC. More important, however, is the route by which we arrived at the need for design costing models. This proves that heuristic substitution is beneficial for identifying areas where it is possible to provide enhanced computer based design procedures.

The system described here also differs in that the systems mentioned above do not provide a ready means of comparison nor do they incorporate heuristics actually used by designers. In addition, this system tries to be open to change and alteration, hence making it more suitable for use in practice.

Future Work

The system is currently undergoing further refinement, according to the comments of the reviewers. Further to this, a help system is being created. The system is also about to move on to the second stage of the evaluation: that is, testing the systems using case studies. The engineering companies involved in the evaluation have offered previous comparative designs which can tried on the system to provide a better indication of the system's performance. In addition to this, there is still a large amount of work to be done which will complement the system as it currently stands. The most important part of this work involves the development of 'risk' quantifiers. These are measures which will be incorporated in the system to give an indication of which criteria are most difficult to cost reliably. This will provide the designer with an appreciation of the most imprecise areas and hence enable him/her to make a better assessment of the cost provided.

Work is still needed to enable the system to fully interact with the other design systems being developed at Cardiff [14]. Once this work has been completed, the authors believe that the system will be useful and beneficial, both as a stand alone application and as part of a design suite.

Commercial development of this software is also being explored. Many of the approaches used in the costing system are largely generic and so alternative fields of application are being investigated.

Conclusions

A costing system which was initially developed as a result of findings of previous research has been developed. The system is based on the principle of heuristic substitution, and provides a preliminary costing estimate which can be used in the conceptual design process. The system, like all others developed at Cardiff, has been created in close collaboration with industry and hence is intended to be used as a practical design aid within the near future. This aim has influenced the style of development and it adheres to the philosophy that innovative systems should aim to enhance and support human design behaviour as opposed to supplant it.

The system evaluation has already shown that it is potentially a very useful tool which will enable designers to reach a better estimate for bridge costs more quickly and efficiently than is currently possible. It has also shown that enhanced comparative capabilities is one of the main strengths of the system and it is believed by the authors that the implementation of the completed system will enhance the preliminary costing process currently used in design offices, which will in turn improve conceptual design processes.

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