AN INTELLIGENT DECISION SUPPORT SYSTEM FOR ROAD PAVEMENT DESIGN

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abstract: Road pavement design is a process consisting of two salient phases: conceptual design and detailed design. An understanding of both the conceptual and detailed design activities is needed to foster a truly holistic appreciation of the complete design process. While detailed design methodology is well documented, the conceptual design phase is poorly understood and taught. This paper presents the development of an innovative decision support system that technically integrates the conceptual and detailed design of flexible, rigid and interlocking block pavements. The system can assist both novice and senior designers; and teachers in their presentation of undergraduate courses.

1. INTRODUCTION

A recent review of engineering education in Australia (IEAust 1996) and research by Doherty et. al. (1996) has confirmed that the layered structure of engineering undergraduate courses focuses on complex analysis techniques and closed-form problem solving; at the expense of conceptual design methodology. Professor Peter Johnson (1996) states that we need to *"change the nature of engineering courses, to provide graduates with a better understanding of the broad human, economic and environmental consequences of professional tasks"*.

The need to provide intelligent decision support tools to integrate conceptual and detailed design is highlighted further when one considers that conventional Decision Support Systems (DSS) providing low level cognitive support and Knowledge-Based Systems (KBS) that are preoccupied with modelling an expert's heuristic knowledge have not been embraced by industry (Coats, 1988; Alter, 1992; Turban, 1992; Radermacher, 1994; Duchessi and O'Keefe, 1995).

In response to the decision support and engineering education restructuring needs, a comprehensive modelling approach has now been developed to create engineering design systems that provide quantitative output to support the judgement and intuition of decision-makers. One such design system is the road pavement intelligent decision support system (IDSS); which is outlined in this paper.

Section 2 describes design as a decision-based process that is dependent upon both deep (scientific) and shallow (experiential) knowledge; prompting the need for intelligent decision support. The engineering design process is investigated in Section 3, and dominant activities are modelled in terms of conceptual and detailed design.

An overview of the road pavement IDSS is presented in Section 4 to explain how its three-tiered hierarchical search and contain logic integrates design process phases. In Section 5 the reader is guided through a typical road pavement IDSS consultation to obtain a better understanding of system input and output. Encouraging verification and validation results confirm the value of the system in terms of quality and applicability (Section 6), while research findings are summarised in the concluding section of the paper.

2. THE NEED FOR INTELLIGENT DECISION SUPPORT IN DESIGN

Design is a process used to translate a perceived need into a solution for that need (Holgate, 1986; Addis, 1990; Medland, 1992). During design, designers must make progressive decisions to help bridge the gap between an idea and reality. Design can therefore be viewed as a decision-based process.

Turban and Meredith (1994) have examined what they consider to be the major factors that affect decision-making, and have drawn conclusions regarding current trends and corresponding results/impacts on decision-making. A primary conclusion is that decision-making in the current environment is more complicated than it was in the past due to two dominant reasons. Firstly, expanding technology and communication systems have spawned a greater number of feasible solution alternatives from which a decision-maker must choose. Secondly, the increased level of structural complexity and design competition typical of today's problems can result in a chain reaction magnification of costs if an error should occur. These views are reflected by Cross (1994); with particular application to modern design decisions.

If we are to accept the foregoing conclusions, decision-making based on intuition and trial and error is not suited to the design environment of the 1990s. In addition to personal experience and judgement, it is now timely to provide industry with systematic and quantitative tools which can complement designers by supporting their decisions.

Decision Support Systems (DSS) evolved in the early 1970's from Management Information and Operations Research/Management Science streams (Gorry and Scott-Morton, 1971; Keen, 1980; Silver, 1991; Angehrn and Jelassi, 1994). At that time, it was identified that technological support for decision-making must facilitate ad hoc (problem-specific) retrieval of data and managerial control over model manipulation (Silver 1991). Decision-makers did not wish to be locked into systems they could not control.

A conventional decision support system (DSS) shall be broadly defined as an interactive computer-based system that utilises a model to identify and draw upon relevant data in order to aid decision-making (Rhodes, 1993; Turban, 1993). The word system implies that a DSS is a set of interconnected components. Traditional DSS typically consist of software for the management of a data base, a model base and a user interface (Samson, 1988; Rao et. al., 1994; Turban and Meredith, 1994; Pearson and Shim, 1995).

The DSS does not make decisions. Human decision-makers use a DSS as a judgement aid when making decisions. Consequently, a DSS must be responsive to decision-making needs. It should not be constructed as a "black-box" optimisation model, since these models are frequently criticised for not sufficiently involving decision-makers in the problem-solving process (Little, 1970; Mintzberg, 1982; Silver 1991). This has led to the conviction by DSS pioneers that *"DSS designers should take special pains to ensure that DSSs not be allowed to dominate the decision process"* (Blanning and King 1991).

Problems with traditional DSS that provide low-level cognitive support have arisen *"from the fact that the decision-making process is based not only on data analysis, but also on preferences, judgements, intuition, and the expertise of the human decision maker"* (Bonarini and Maniezzo 1991). The term *'satisficing'* was coined by Simon (1977) to describe most real-world decision making situations which are subject to *bounded rationality.* Due to incomplete information, misinformation, uncertainty and the changing preferences of decision makers, the list of technical constraints imposed by rational models of choice (optimisation models) should be bounded by the inclusion of subjective constraints (eg. aesthetics, safety, durability etc.). Artificial intelligence provides a *"methodological basis for these higher cognitive levels of support"* (Radermacher 1994).

Consequently, an integration between knowledge-based system (KBS) and DSS capabilities is appropriate in ill-structured situations such as conceptual design where:

- logical reasoning needs to be simulated
- the problem model is difficult to build (i.e. decision support algorithms are not readily apparant)
- problem data is partially unknown
- more than one evaluation criterion exists for decision making
- deep interaction with the human decision maker is required
- a low cost solution is needed in a short time frame

(Elam and Henderson, 1983; Bonarini and Maniezzo, 1991; Klein, 1992)

Knowledge-based systems (KBS) are a product of artificial intelligence (AI), the computer science branch dedicated to developing software programs that aim to reproduce intelligent problem-solving behaviour. KBS have evolved from expert systems, computer programs that were designed to package the knowledge of a single expert or many experts and make it available on a computer for user advice (Mockler and Dologite, 1992; Turban and Frenzel, 1992; Durkin, 1994).

A dated but popular KBS definition by Gaschnig et.al. (1981) is cited in many engineering texts (including Fenves, 1986; Maher and Allen, 1987):

> *"Knowledge-based expert systems are interactive computer programs incorporating judgment, experience, rules of thumb, intuition and other expertise to provide knowledgeable advice about a variety of tasks".*

While KBS have the ability to represent all forms of knowledge (declarative, procedural and heuristic), emphasis has been focused on simulating the design heuristics of human experts (Frenzel, 1987; Tuthill, 1990; Klein and Methlie, 1995). Furthermore, KBS have been traditionally designed and built by computer scientists interacting with design experts on an as-needed basis (Bielawski and Lewand, 1988; Mockler and Dologite, 1992; Turban and Frenzel, 1992). Rather than creating systems that are practical in nature, attention has been ill-directed attempting to add features dictated as necessary by AI literature. Consequently, *"there are few, if any, design KBS in everyday use"* (Miles and Moore 1994).

Future design KBS should therefore aim to complement human skills by allowing the combination of designer and design KBS to generate better designs than may normally be achieved by the designer working independently. We propose that this aim can be achieved by coupling both deep and shallow knowledge in problem-solving algorithms.

There is increasing support for the concept of integrating knowledge-based technology with conventional DSS to overcome DSS limitations and improve the quality (effectiveness) and efficiency of decision making in complex environments such as design (Blanning and King, 1991; Gottinger and Weimann, 1992; Turban, 1993; Rao et. al., 1994; Klein and Methlie, 1995).

It would appear that the inclusion of a knowledge base (containing expert heuristics and equation reasoning algorithms) would improve the scope of traditional DSS by offering an environment which:

- is more interactive;
- is applicable to routine (repetitive) and adaptive (complex) design;
- contains all categories of knowledge and permits limited DSS reasoning;
- provides the opportunity for user learning.

Rao et. al. (1994) write that active user-computer involvement (in contrast to purely passive involvement) is now essential due to the increased complexity of decision making. They maintain that an intelligent menu-driven interface between the computer and the user can foster a symbiotic environment to facilitate greater computer usage and improved user learning.

Before proceeding further, formal IDSS definitions shall now be presented:

> *"An intelligent decision system implements the analysis of a class of decisions using the technology of expert systems to give decision analysis guidance to the user and to deliver domain knowledge."* (Holtzman 1989)
>
> *"...an intelligent decision support system (IDSS) is an interactive tool for decision making for well structured (or well-structurable) decision and planning situations that uses expert system techniques as well as specific decision models to make it a model-based expert system (integration of information systems and decision models for decision support)."*(Gottinger and Weimann 1992)

By partially cloning human expert knowledge and supplementing it with deep algorithmic knowledge, it seems likely that successful intelligent decision support systems (IDSS) could improve user understanding and work productivity, reduce designer uncertainty and anxiety, and preserve the valuable knowledge of experts in short supply. They could also effectively save time and investment capital by making domain knowledge readily available throughout the design process.

3. MODELLING THE DESIGN PROCESS

The word design is ubiquitous and can take on a myriad of meanings dependent upon the context in which it is used and the user's background. From the sixteenth century onwards the Oxford Dictionary has defined design as either "*an intention to do something*" or as "*a drawing*." Nowadays, design is often used to refer to the creation of almost any product (buildings, t-shirts, hair styles) or to the look, image or style of an artifact (Addis, 1990).

Design in civil and structural engineering has been defined by Harris (1975) as "*...the determination of what is to be built and the preparation of the instructions necessary for building it*". This description has been further refined by Dym and Levitt (1991):

> " *Engineering design is the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints.* "

The primary selection objective for most designers is usually expressed in terms of payoffs (minimise costs or maximise profits). Secondary factors (constraints) are more subjective in nature and often apply only to the particular decision situation currently being considered (Dandy and Warner 1989).

In the engineering world, design is easier to represent and comprehend when described in terms of a '*design process*'. Engineering design problems are typically open-ended and ill-structured (Turban, 1993; Cross, 1994; Dym, 1994). In many situations, these problems are not solved immediately but are in turn decomposed into a sequence of defined work scope steps which are executed progressively in time. Thus, due to its nature, design can be thought of as a process.

During the process of designing, one needs to apply increasing levels of detail to abstract design statements in order to converge on the best suited satisficing solution. Design process steps may be thought of as follows:

(i) Clarification and weighting of the client's design objective(s) and constraints.
(ii) Ideation to identify feasible options.
(iii) Preliminary sizing and costing of structure components.
(iv) Life cycle assessment of feasible concepts.
(v) Selection of a single concept
(vi) Detailed refinement of the chosen concept
(vii) Documentation of the completed design

Engineering design is most commonly represented by descriptive and prescriptive models (Cross, 1994; Dym, 1994). While Asimow's (1962) descriptive design process model is too abstract for practical application, French's (1985) model has greater application potential. German-based prescriptive models (eg. VDI, 1987; Pahl and Beitz, 1988) have the potential to increase the risk of cognitive overload and designer error by depicting the design process as a lengthy and complicated procedure.

The writer's model groups and reclassifies French's (1985) 'analysis of problem', 'conceptual design' and 'embodiment of schemes' phases under a single phase, since the output of these activities usually culminates in a single conceptual design report. Hence the design process is described in terms of two salient phases: conceptual design and detailed design (Fig. 1).

For the purposes of this paper, the design process shall be defined as:

- 'a systematic problem-solving methodology involving the gradual (and sometimes iterative) progression from the clarification of the design work scope through the stages of conceptualisation, embodiment and detailing of an acceptable solution which best satisfies design objectives and constraints'.

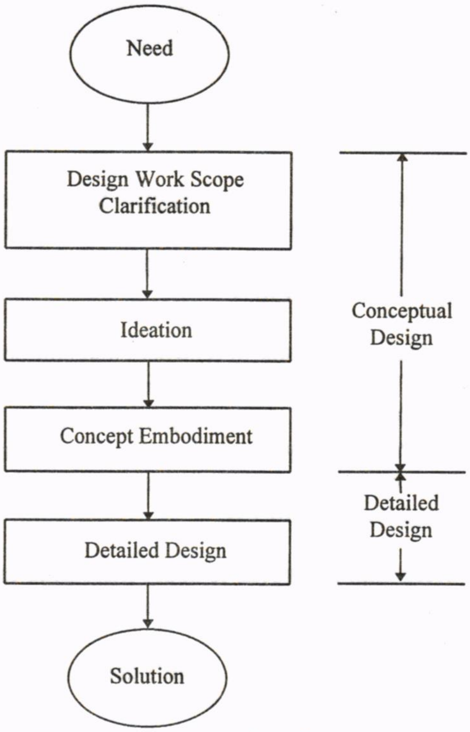

Figure 1: The Systematic Design Process

Conceptual design is defined herein as the generation of feasible outline solutions (concepts) that have the potential to satisfy design work scope objectives and constraints, and the recommendation of a single solution concept following evaluation (technical, social, political, legal, environmental and economic).

The significance of the conceptual design phase and the need for conceptual design research is emphasised in the literature:

> *"This phase of the design process .... takes the statement of the problem and generates broad solutions to it in the form of schemes. It is the phase that makes the greatest demands on the designer, and where there is the most scope for striking improvements. It is the phase where engineering science, practical knowledge, production methods, and commercial aspects need to be brought together, and where the most important decisions are taken."*
>
> (French 1985)

> *"The decisions made in this phase affect the building cost much more than most decisions made in the detailed design* [phase]. *Yet, while the technology and tools for detailed design (eg. beam, column and slab design programs) is well*

> *developed,....conceptual design has not been thoroughly investigated, and few tools are available to aid it."* (Haber and Karshenas 1990)
>
> *"Little or no work has been published on this conceptual activity....This is the area where the greatest benefit could occur, but the effort necessary to develop the techniques may be enormous."* (Medland 1992)

Detailed (or detail) design is *"the phase of the design process in which the arrangement, form, dimensions and surface properties of all* (design components) *are finally laid down, the materials specified, the technical and economic feasibility re-checked and all the drawings and other* (design documentation) *produced".* (Pahl and Beitz 1988). In effect, detailed design amounts to refining the embodied concept to a level of *detail* that will enable the desired artifact to be fabricated to satisfy stated objectives and constraints.

Detailed design is procedural in nature. The procedures themselves are either expressed as specific rules, formulae and/or algorithms, or may be described in procedural (standard) codes of practice or design manuals and reference textbooks. Consequently, the deterministic nature of detail design has enabled many of the established procedures to be readily encoded and available as conventional software programs.

The use of detailed design algorithms to check the strength and serviceability of designated member cross-sections for structural adequacy is perceived by many undergraduate engineers as *'design'*. This view is often reinforced during the initial years of professional practice when duties may consist solely of ensuring that routine details comply with standardised procedures.

The shortcomings of neglecting to emphasise the importance of conceptual design in engineering curriculums is poignantly summarised by prominant Australian design authors:

> *"One of the most difficult aspects of creative engineering work for students who have been trained in the classroom to solve the typical, closed-form analytical problems of mathematics and physics, is to come to terms with real-world problems which do not have single 'correct' answers."* (Dandy and Warner 1989)
>
> *"Successful engineering design demands a high level of conceptual thinking. Rote learning of techniques of mathematical manipulation is anathema* [an object of abhorrence; a curse]. "Lewis and Samuel (1989)

4. THE ROAD PAVEMENT IDSS: AN OVERVIEW

Knowledge acquisition (KA) has been singled out as a major contributing factor towards KBS failure (Bell, 1985; Coats, 1988; Alter, 1992; Turban, 1992; Duchessi and O'Keefe, 1995). The road pavement system model uses a rigorous approach to apply explicit subject domain knowledge to ill-structured (adaptive) design problems to reformulate them as structured problems. This approach is in keeping with the views of Simon (1984) who argues that the application of research and analysis can transform problems previously regarded as 'ill-structured' into 'well-structured' problems.

The new three-tiered system permits subjective and nebulous conceptual designs to be quantified, and integrates both conceptual and detailed design in a holistic manner. A "strong" hierarchical generate and test search methodology is employed to promptly isolate a near-optimal solution and then quantify its technical and cost characteristics (refer Fig. 2).

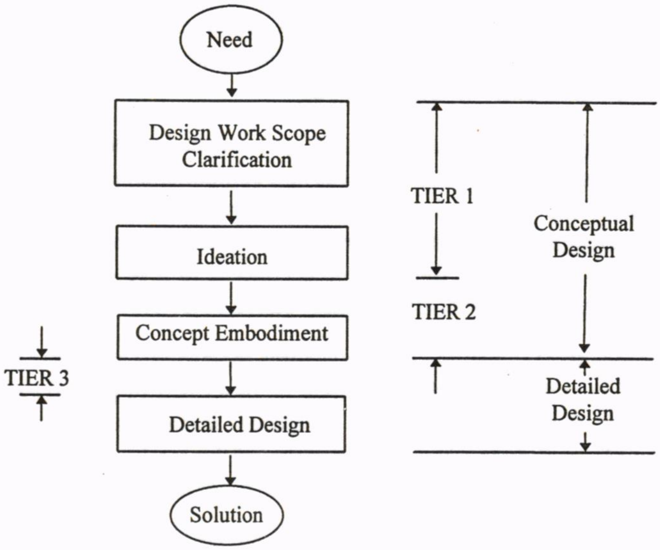

Figure 2: The Three-Tier IDSS Modelling Technique

Tier 1 of the road pavement IDSS is initially used to help identify the range of feasible solution concepts for specific design problems. It then relies on heuristic (shallow) knowledge and client input pertaining to subjective constraint impacts on design output to reduce the need for exhaustive generate and test solution searches. In this manner, ill-structured problems are transformed to structured problems; the potential for combinatorial explosion is minimised; and the most likely candidate solutions are isolated using bounded rationality (preference modelling) principles.

Tier 2 of the system couples abridged detailed design algorithms (deep knowledge) and unit costs in a directed-depth solution search to replace the approximate heuristics that designers intuitively use during conceptual design. Preliminary outline dimensions and cost estimates (initial and whole-of-life) are generated for subsequent detailed design convergence checking. Moreover, Tier 2 software enables the designer to conduct output sensitivity analyses in order to rapidly assess the inbuilt uncertainty of critical design variables.

Tier 3 of the modelling approach requires that a comprehensive list of passive subject-domain flowcharts is formalised for designer guidance once a decision is made to proceed with detailed design. The member dimensions and costs derived using Tier 2 principles are rigorously checked by following the methodology detailed in the Tier 3 flowcharts.

5. CONSULTING THE ROAD PAVEMENT IDSS

A comprehensive literature guide listing the most commonly designed types of road pavement is not published by technical authorities in Australia. By consulting commonly used road pavement detailed design guides (including ARRB, 1993; AUSTROADS,

1992; CACA, 1984; CACA, 1985; CACA, 1986; Knapton and Mavin, 1987; Mulholland, 1989) four principal classes of new road pavement have been identified:

- Unsealed flexible pavements
- Sealed flexible pavements
- Rigid (concrete) pavements
- Block (interlocking segmental) pavements

The authors have identified sixteen common types of new road pavement that are constructed in Australia and which fall under the four principal taxonomies nominated above. Asphalt and block overlays provide alternate solutions for pavement upgrades (Knapton and Mavin, 1987; Mulholland, 1989; AUSTROADS 1992), but will not be considered further in this paper which specifically addresses the design of *new* road pavements.

Medland (1992) argues that *"the ideal CADCAM system ... should be hierarchically structured to align with the 'search and contain' nature of the engineering approach. That is to say that the system should be structured to allow the problem to be contained with the minimum of data."*

Accordingly, a preference modelling facility quantifies subjective constraint decision variables in Tier 1 of the IDSS model to reduce the amount of viable decision variables input into Tier 2 from a complete enumeration state (eg. 16 road pavement alternatives) to the enumeration of one or two solution alternatives.

The road pavement IDSS simulates (and yet quantifies) the natural selection process by prompting the designer/client to manually assign certainty weightings to linked subjective constraint/heuristic statements. Uncertainty is reduced by the IDSS responses to user inputs, whilst the dynamics of real-life constraints are allowed to vary with each design considered. While a non-quantified natural selection process suffices for personal decision-making, engineering designers need to justify their decisions to satisfy their own scientific training and imposed quality assurance requirements. This view is supported by the industrial designer, Richard Stevens (cited in Cross, 1994):

> *"A lot of engineering design is intuitive, based on subjective thinking. But an engineer is unhappy doing this. An engineer wants to test; test and measure. He's been brought up this way and he's unhappy if he can't prove something."*

Each design problem is considered as a *branch and bound* problem (where feasible solution categories constitute the 'branches' and subjective constraints constitute acceptable solution 'bounds' or 'boundary conditions'). The application of *"short-cut heuristics"* (Miles and Moore 1994) effectively *"prunes branches of the tree that are unlikely to yield a solution"* (Dym 1994). The increase in computational efficiency of this approach to problem solving is claimed to be so significant that the rapid isolation of a near optimal (satisficing) solution will usually more than compensate for the cost of not finding the optimal solution (Dwyer and Evans, 1981; Dym, 1994; Turban and Meredith, 1994).

Simon (1977) argues that most individual and organisational decision makers are willing to settle for satisficing solutions that are *"less than the best."* However, satisficing solutions should not be considered as being inferior to optimal solutions, since there is no guarantee that the "best" solution will ever be obtained using optimisation techniques. Medland (1992) reinforces this viewpoint:

> *"Such a technique optimises the model utilised by the program, but only if there is an 'optimal' fit between model and problem will an optimal solution emerge."*

Hierarchical (top-down) problem solving methodology is used in the system to 'buy' information which will guard against unsound decisions being made at any particular level of the decision tree. Consideration of secondary selection criteria effectively eliminates unsuitable solution options and avoids *"frequent back-tracking up and down the levels of hierarchy in the decision tree"* ; a concern relating to top-down decision-making which is raised by Cross, (1994).

Tiers 1 and 2 have been constructed within a development shell called GURU, distributed by Micro Data Base Systems (mdbs) Incorporated. The knowledge requirement of the IDSS catalysed the decision to employ a development shell. The literature recommends GURU as an appropriate software shell for integrating the capabilities of KBS and DSS (Holsapple and Whinston, 1986; Blanning and King, 1991; Bonarini and Maniezzo, 1991).

The initial screens provide an introduction to the program and describe Tier 1 logic by presenting linked constraint/heuristic statements. Project-specific weighting of listed constraints is accomplished by the consultant/client assigning a number between 0-9 next to each constraint in Table 1:

Table 1: Road Pavement Design Subjective Constraint Menu

SUBJECTIVE (SOFT) CONSTRAINTS

Client Preferences (Construction/Material)		
	1. Block/Pavers	: 0
	2. Flexible/Asphalt-Gravel	: 4
	3. Rigid/Concrete	: 2
Environmental/Social Constraints		
	4.Aesthetics	: 2
	5. Minimal Surface Noise	: 1
Functional Constraints		
	6. Stage Construction Potential	: 0
	7. Services Trenching	: 3
	8. Construction Under Traffic	: 0
	9. Design Speed > 60 kph	: 5
	10. Durability (Minimal Maintenance)	: 6
Safety/Legal Constraints		
	11. Light Reflectivity	: 4
	12. Skid Resistance	: 5
	13. Traffic Control Visual Delineation	: 0

Constraints assigned a value of 9 are adjudged as being of paramount importantance to the design, whilst those given a value of 0 are not considered to be of any importance.

In this model, the value input for each constraint is multiplied by either 0 or 1 for each road type. If the heuristic dictates that a particular road type (eg. flexible pavement) is well matched to a constraint (eg. stage construction) a 1 is allocated. For the stage construction constraint, a 0 was allocated in the database table for block and rigid pavements. This database table (TSOFT.ITB) is based on known experiential outcomes for each of the constraints listed. It contains data in encrypted format and is not visible to the user.

When constraint inputs (examples of inputs are included in Table 1) are multiplied by database values, scores are summed for each road type. The road type with the highest score is recommended by the program as most suitable for satisfying the subjective constraints of the design application being assessed.

Furthermore, a certainty factor is calculated by dividing the proposed road type score by the summation of each road type score.

$$\mathrm{CF} = \frac{\mathit{Proposed\ Road\ Type\ Score}}{\sum(\mathit{Road\ Type\ Scores})} = \frac{X_{(\max)}}{\sum_{i=1}^{j}(X_i)} \qquad \text{Equation 1}$$

When the values keyed into Table 1 are processed by the SOFT.RSC program, the corresponding output screen is shown below (Table 2):

Table 2 - Tier 1 Advice

```
Based on your selection of constraint weightings,
it would appear that a rigid pavement is most suitable

the certainty factor is = 0.524
```

A rule was fired and a rigid pavement recommended because the scores obtained were:

Block = 10
Flexible = 10
Rigid = 22

Dandy and Warner (1989) argue that *"highly simplified designs"* should be considered during the feasibility study (conceptual design phase) before being *"refined in later design steps."* It follows that the identification and evaluation of critical independent variables (in lieu of all pertinent independent variables) should provide a sound basis for the technical and economic evaluation of dependent variables (eg. road pavement options) during conceptual design.

If accurate critical design variables are not available, it is prudent to use readily accessed basic variables to identify representative "ball park" critical variables for use during conceptual design. Learning the most common *"default values and value ranges is an important aspect of design knowledge because it further defines the space in which a concept sits"* (Maher and Li 1992). Once again, the detailed design literature provided the source for defining presumptive (default) design variable ranges/values for road pavements.

Instead of using a weighted distribution of data sets to determine default values for numeric variables (Greer, 1979; Maher and Li, 1992) the road pavement IDSS aims only to identify likely values. In the tradition of decision support, the user is urged to conduct model simulations with differing design variable inputs to test output sensitivity. In this manner, attention (eg. site testing) can then be directed towards improving the designer's confidence in the most critical input variable(s).

When Tier 2 of the system is consulted, an introductory screen outlines the program aims, required user inputs and the generated IDSS output. To assist the inexperienced user, optional screens can be viewed to provide more detail about pavement components and pavement sub-categories.

The IDSS will then prompt the user to sequentially input the pavement site location, subgrade design CBR and design traffic (default values are listed). When all input is collected, the inference engine fires the rules whose premises are satisfied until the final consultation goal is achieved. Initial output comprises a screen summarising the values of the user inputs to each variable prompt (Table 3 displays inputs for the design of an urban rigid pavement).

Table 3: Data Input Summary

SUMMARY: DESIGN INPUT DATA

You have selected the following input data for your pavement:

You have selected CBR 2 (poor)
You have selected CV type 3
You have selected axle load of 14.2 tonne
You have selected the daily repetitions for this load to be 30
You have selected costing to be based on 1 (Melbourne)

A conceptual design output screen follows which lists suitable layer thicknesses of base concrete and sub-base material, combined with the type of reinforcing fabric contained in the base concrete. Having quantified the pavement thickness, the expected in situ cost of each component (per square metre of pavement) is calculated and summed to provide an initial total cost for the pavement (Table 4).

Table 4: Tier 2 Size and Initial Cost Output

```
SUMMARY: CONCEPTUAL PAVEMENT DESIGN AND COST

     All costs include material supplied in situ:

     The thickness of your base concrete should be 190mm.
     The thickness of sub-base material should be 150mm.
     The type of reinforcement you require is F82.

                          COST TABLE ($)

          Sub-Base Cost                        =  5.00
          Unreinforced Concrete Cost           = 28.88
          Fabric Reinforced Cost               =  7.50
          Total cost of road per sq metre is   = 41.38
```

To assist in benefit/cost assessment, a life cycle cost estimate in terms of net present cost is also included. The consideration of maintenance and salvage costs has become increasingly important in the justification of extended-life design concepts (Table 5).

Table 5: Whole of Life Cost Assessment

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              WHOLE OF LIFE COSTING (Life cycle costing)

           Life cycle costing provides evaluation for the following:
                              - First Costs
                              - Maintenance Costs
                              - Salvage Costs

          For this configuration of rigid pavement ,
                    the net present cost is  $44.50

     Would you like to know the break down of these extra costs (y/n)? : y
```

Should the user select the "yes" option above, the break down of maintenance and salvage costs could be as detailed in Table 6.

Table 6: Typical Details for Rigid Pavement Net Present Cost Assessment

TABLE OF BREAK DOWN COSTS FOR NET PRESENT COST

TREATMENT	COST	YEAR	COMMENTS
Route + Seal Cracks	**$ 0.08**	**3**	**Assume 5m crack length in 50m of pavement**
30% Retexture	**$ 1.20**	**20**	**Use specialist diamond saw cost = $4.00/sq m**
4% Slab Replacement	**$ 8.80**	**28**	**4% of area at $220/sq m**
DG 14 AC overlay (50mm)	**$10.00**	**30**	**Provides surface protection and improves ride quality**
DG 14 AC overlay (40mm)	**$ 8.00**	**36**	**6 years is typical overlay life for 50mm AC**
Salvage	**$ 6.00**	**40**	**Salvage value is actually a cost**

All Tier 2 output has now been displayed and the program will terminate. The user is returned to the GURU command prompt where s/he can either exit GURU or conduct a *sensitivity analysis* using other input values.

A suitable road type and cost-evaluated conceptual design has been quickly generated for client approval prior to consulting the Tier 3 flowcharts and embarking on the detailed design stage of the design process.

All road pavement design procedures rely primarily on the prediction of pavement structure fatigue behaviour (Hodgkinson, 1982; CACA, 1986; AUSTROADS, 1992). *Empirical methods* produce thickness designs based on confidence limits once critical design variables have been evaluated (CACA, 1984; Mulholland, 1989; ARRB, 1993). *Mechanistic methods* used for flexible pavement designs employ finite element analysis to estimate pavement strains. The strains are used as input in adopted strain criteria equations, and the resulting number of axle road repetitions predicted to cause fatigue failure is compared with the design traffic value (AUSTROADS, 1992).

An extensive review of recommended design procedures coupled with their application in worked detail design examples was undertaken as part of the current research. The generation of design examples has enabled algorithmic step sequences to be clearly qualified and solutions quantified for all principal pavement classes. Expertise benefits that can result from a requirement for the knowledge engineer/expert to formalise design-specific algorithms are aptly stated by Knuth (1973):

> *" It has often been said that a person doesn't really understand something until he teaches it to someone else. Actually, a person doesn't really understand something until he can teach it to a computer, i.e., express it as an algorithm....*
> *The attempt to formalise things as algorithms leads to a much deeper understanding than if we simply try to understand things in the traditional way."*

Detailed design flowcharts can provide an effective means of visualising and referencing algorithmic design steps. Furthermore, each activity can be readily upgraded and diverse references easily incorporated in a single document.

Flowcharts for each pavement type (and subsection, where appropriate) were developed because:

- current flowcharts did not exist
- current flowcharts were too simplified or incomplete
- current flowcharts requiring trial pavement dimensions as input assume that all designers have experience or collated records to draw upon
- flowchart comparison enables critical design variables to be isolated

Quantitative pavement design algorithms are not applicable for unformed and formed earth pavements, since negligible introduced pavement thickness is provided (ARRB, 1993). Flowcharts for the thickness design of gravel (paved) unsealed pavements, flexible, block and rigid pavements have been developed during this research, and shall provide the major focus for a forthcoming paper (since space restrictions prohibit their inclusion herein).

6. IDSS VERIFICATION AND VALIDATION

System appraisal (also referred to as system evaluation or testing) is conducted to establish whether the IDSS actually functions as intended by the builder and expected by end-users. Adelman (1992) argues that a primary reason why DSS and KBS have thus far failed to fulfil their *"great promise"* is because their development *"is currently technology driven instead of requirements driven."* Consequently, little effort has been spent testing models early in the development cycle when the opportunity to make alterations is relatively inexpensive (Berry and Hart, 1990; Seun et.al., 1990; Meseguer and Preece, 1995).

Verification is concerned with establishing the *internal correctness* of the IDSS, or *"building the system right"*; while validation is concerned with establishing its *external correctness*, or *"building the right system"* (O'Keefe et. al., 1991). Verification and validation can be viewed as a set of logical and empirical tests that are applied during the build-test-refine cycles of an AI system. The tests include inspection of program flow, internal consistency checks for anomalies in the knowledge base, structural and functional testing, and field testing (Preece, 1990; Meseguer and Preece, 1995).

In effect, verification (technical evaluation) methods test whether a model has been constructed with the correct level of internal detail to provide the expected responses to user inputs. Investigating program flow proved useful for detecting syntax errors, while internal consistency checks verified both rule logic and forward chaining inferences. Consistency checking also demonstrated that alternate solution concepts could be equitably compared with one another.

The comparison of Tier 1 input/output pairs with likely outcomes of scenario-based design examples confirmed the anticipated outcomes. Calibration between Tier 2 input/output results and expected design chart results was close to exact, provided that the design charts (upon which Tier 2 rules are based) were not inconsistent to begin with.

Validation (empirical and subjective evaluation) methods require end-user data to test whether system input requirements and output results simulate real world behaviour. Adoption of a 'proactive' requirements definition by the system builder (readily facilitated by extending traditional research and planning activities; Section 4) improved the effectiveness of IDSS validation by allowing 45 targeted users (instead of 1 or 2 design 'experts') to react to model simulations of design problems.

Structured field interviews (incorporating open-ended questionnaires and system simulations of design problems) proved suitable for system validation. The field interviews permitted conceptual design activities and cognitive tasks to be identified and compared with system logic, while feedback over and above anticipated responses was elicited using open-ended questions.

The contention that *ideation* (conceptualisation) is at present primarily intuition-based was fully supported by 100% of the interviewees. Moreover, none of the interviewees used traditional brainstorming/synectic ideation aids, but instead selected ad hoc specialists to provide expert ideation advice; in a similar manner to the approach incorporated in the IDSS. The field interviews also revealed that the requirement for life cycle analysis is very much dependent on whether the client is the ultimate buyer or a contractor. If the client is a contractor (as in design-construct partnering), design teams will continue to use the lowest initial cost as the primary evaluation criterion unless project defect liability periods are extended to at least 5-10 years.

Ansoff and Hayes (1973) assert that a system model's value to industry can be assessed in terms of quality and applicability. Power (reliability) is used to judge a system model's quality, and is assessed as the amount of non-trivial inference produced by the system. It can be evaluated in terms of knowledge base consistency, completeness, traceability and correctness (Smith and Kandel 1993). When queried about the amount of non-trivial inferences output from the road pavement model application (i.e., model power), 93% of the interviewees confirmed that all model inferences were non-trivial; in other words, valid. The only structural modifications suggested involved minor alterations to some subjective constraint statements.

The road pavement IDSS was considered to be most powerful for design problem identification, preliminary costing and output sensitivity assessment. Further, Tier 1 was assessed as being most powerful for junior designers, whilst Tier 2 inferences were judged as being of greater power to senior designers. A comment from an interviewee is as follows:

> *"The model's real power lies in it's ability to support our intuition in a quantitative manner. It can also alter the decision we would normally make by taking us beyond our political and emotional preferences."*

Model applicabilty is primarily assessed in terms of relevance, validity and potential for use. An encouraging 91% of interviewees affirmed that system applications (similar to the demonstrated road pavement IDSS) would prove useful to their organisations for both engineer training and for incorporation as an industry total quality management standard procedure.

7. CONCLUSIONS

This paper has described a new modelling technique used to develop a road pavement structural design system that is more comprehensive than currently endorsed design methodology; and hence of greater benefit to design students, professional designers and the community. Use of the modelling approach permits improved design systems to be constructed, as envisaged by Miles and Moore (1994):

> *"...we do feel that there is scope for replacing human uncertainty (that is, uncertainty which is introduced owing to the heuristics which are used) in KBS to create improved systems which 'out perform' experts in certain areas."*
>
> *"...the overall aim is to produce a system which enhances and complements the skills of the designer so that the combination of designer and design* [system] *leads to a better product than that which would result from the designer working unassisted....To date we have not tried to construct such a system, nor are we aware of anyone else who has done so, but it seems to be a sensible way forward. Such a system would need to operate in such a way that the inexperienced user is able to gain sufficient knowledge to acquire the same skills as the experienced user."*

Research results have demonstrated that the road pavement IDSS prompts users to "buy" relevant decision information from clients, and then combine it with shallow and deep knowledge to reduce decision-making uncertainty. More specifically, the system's hierarchical search and contain problem solving approach is able to improve current design methodology by:

- identifying feasible precedent-based solution concepts for commom design problems;
- clarifying the content and interdependence of each design process sub-phase;
- quantifying subjective constraint impacts on alternative solution concepts;
- providing preliminary member size and cost estimate guidance for detailed design convergence;
- outlining life-cycle cost importance for infrastructure management review, and...
- presenting explicit guidance for subsequent detailed design algorithmic steps.

The verification and validation results have also shown that further development (and designer use) of IDSS model applications can provide a competitive means of compliance with industry total quality management standard procedure requirements and an efficient means of designer training.

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