Artificial Intelligence in Bridge Engineering: Towards Matching Practical Needs with Technology

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In a special issue of *Microcomputers in Civil Engineering* on *Computer-Aided Bridge Engineering*

Key words: expert systems, bridge management systems, bridge design, machine learning, research methodology, life cycle, concurrent engineering, usability, engineering practice

Abstract:

The idea to use AI in civil engineering is as old as AI. Since the 50th, studies on AI applications in civil or bridge engineering have proliferated. Most of these studies have dealt with specialized isolated engineering subtasks. Few of the applications have been delivered to practitioners and were used to advance their work. This paper presents a model of the life-cycle flow of information in bridge engineering as an organizing framework for reviewing previous work on AI applications in bridge engineering. Several common patterns that emerge from the studies are summarized. A subsequent analysis of the status of the bridge stock in many countries suggests that a more integrated approach to AI applications may have a larger practical impact. Several practical areas that can benefit significantly from AI techniques are identified and several studies are proposed including the AI technology needed and the methodology according to which these applications should be developed.

1 Introduction

AI has been around since the 50s, and since then, it has fueled many visions, dreams, and hopes: "Contemplation of the similarity between the brain and computers promises to shed light on some of the mysterious workings of the mind and also suggest fruitful directions for computer design and programming," announced Dalkey (1958, p. 3) at the ASCE First Conference on Electronic Computation, in 1958. While acknowledging that the above similarity is only an analogy, he did not find it difficult to foresee in 100 years a remarkable era, "not because of the practical benefits which will flow from those remarkable machines, great as those benefits doubtless will be, but because the electronic computer will eliminate our last claim to special status in the universe." (p. 3) The details of realizing these promises included: a machine that will assist in its own programming (that is, a machine that learns), a machine that will be creative by evolving its programs randomly through mutations (that is, achieving creativity by genetic programming), and the improvement in hardware.

Eight years later, Spillers (1966) attempted to describe "a number of significant 'engineering' applications" of AI and estimated that a major breakthrough would occur in several years. This breakthrough did not happen, nor were the applications used by practitioners.

While these and other forecasts rested on the advocated (but never demonstrated) relation between AI technology and human thought, we do not in any way suggest such relation, nor do we need it to motivate the use of AI technology. In this paper, the term AI simply means a collection of mainly symbolic computational techniques developed in AI research such as: heuristic search, constraint propagation, inductive learning, etc., that may be useful for certain purposes. This usefulness may be realized if the functionality of an AI technique matches the functionality desired by the engineering task at hand and if its performance compared to conventional computational techniques is demonstrated.

As we see in Section 2, applied AI for bridge engineering has developed into a large collection of studies specializing in solving various engineering subtasks. In few cases, these studies were conducted closely with practitioners and in most others without such involvement. Even when the task addressed were significant, such as the conceptual design of bridges, the knowledge utilized was rather limited. This is no surprise because traditionally, AI applications took a specialized, narrow view of problem solving. This was reflected in some of the early guidelines for selecting appropriate problems for which AI techniques work (3): (1) the availability of reputable experts, (2) the problem can be structured by decomposition, (3) it requires narrow domain of knowledge, and (4) the problem domain is stable.

Just like any other engineering discipline, bridge engineering characteristics deviate from these requirements. (1) For some tasks there are no experts or there is significant historical knowledge that is unavailable to experts therefore could not be coded into traditional rule-based expert systems. (2) Bridge engineering tasks are coupled as we see in Section 1.1, and (3) their solutions require diverse and sometimes intricate knowledge. (4) Finally, bridge engineering evolves continually by the introduction of new loading requirements, new materials, new structural forms, new quality construction methods, limit state design methods, and other new technologies such as smart or intelligent structures (see, e.g., (4; 5; 6)). Observing these deviations with the guidelines and the proliferation of techniques developed using different assumptions and with different tools, it is unclear if and how do they fit together into the overall picture of supporting bridge engineering the way it is practiced, or even in a new way that would be acceptable to the practicing engineers.

1.1 The organizing framework

In order to understand what role can AI techniques play in bridge engineering it is instrumental to give an overview of the engineering tasks related to bridges. This overview will help organize existing research studies and point to areas that have the greatest promise to benefit from AI techniques and those areas which are in urgent need for such techniques (for an elaboration on these tasks see (7)). This overview focuses on the interaction between the tasks and the information flow between them (see Figure 1). The main tasks are:

1. *Decision to commission.* The decision to build a new or replace an old bridge draws upon many economical (e.g., budget, balance of needs), political (e.g., structure of industry, distribution of population), and cultural (e.g., aesthetic) issues. These issues determine much of the overall context in which a new bridge project is situated. By understanding them one can explain, for example, why almost all the bridges constructed in Pittsburgh were made of steel.

2. *Design.* The design of a bridge is very complex. It starts with surveillance to find potential locations for a bridge together with some rough designs that need to pass some public approval. The actual design follows through a conceptual design stage in which aesthetic and economical issues play a major role, and follows through a detailed design stage. Designers need to exercise their judgment regarding many issues such as aesthetics, cost, the determination of the loads (e.g., seismic, traffic) and failure modes (e.g., fatigue, corrosion), the selection of appropriate models and analyses techniques, the interpretation of analyses results, constructibility, and maintainability.

3. *Construction* involves a separate design stage in which the detailed design may be re-created by the construction company. Included in this design are the selection and planning of the erection method together with a strength calculation of the bridge in this stage. Construction involves many planning activities at various levels and finally, it involves the actual erection of the bridge.

4. *Operation* is the function for which the bridge was constructed. It may involve determining the flow pattern of vehicles at different times, monitoring the weight of trucks or the transportation of hazardous materials.

5. *Maintenance* involves routine and on-demand inspection of the condition of the bridge that may be followed by decisions to perform rehabilitation procedures, limit the bridge loads, or even close the bridge. This activity involves considerable judgment of many issues and their potential effects on the state of the bridge and its remaining service life. Maintenance decisions regarding one bridge are dependent on the overall status of bridges under the control of the same agency. Due to budget constraints, only critical bridges are rehabilitated.

6. *Replacement.* The decision to replace a bridge is part of the maintenance activity. It closes the loop back to the commission of bridges. In order to reduce cost and satisfy environmental concerns replacement must be carefully planned and even designed for in the early stages of bridge design.

The interactions between the tasks suggest that isolating a task from the others may result in misinformed solutions that may be inferior those which take into account information generated by other tasks. The situation is exacerbated since Figure 1 is only a model of bridge engineering at a certain level of abstraction, but if one breaks down each of the tasks depicted and details the information exchange between the subtasks, the figure can easily become clogged, yet more akin to the actual relationship between the subtasks in practice. Therefore, we expect to obtain practical benefit from AI techniques that are based on an overall life-cycle view of bridge engineering, which includes the interactions between the different tasks as depicted in Figure 1. Such an expectation

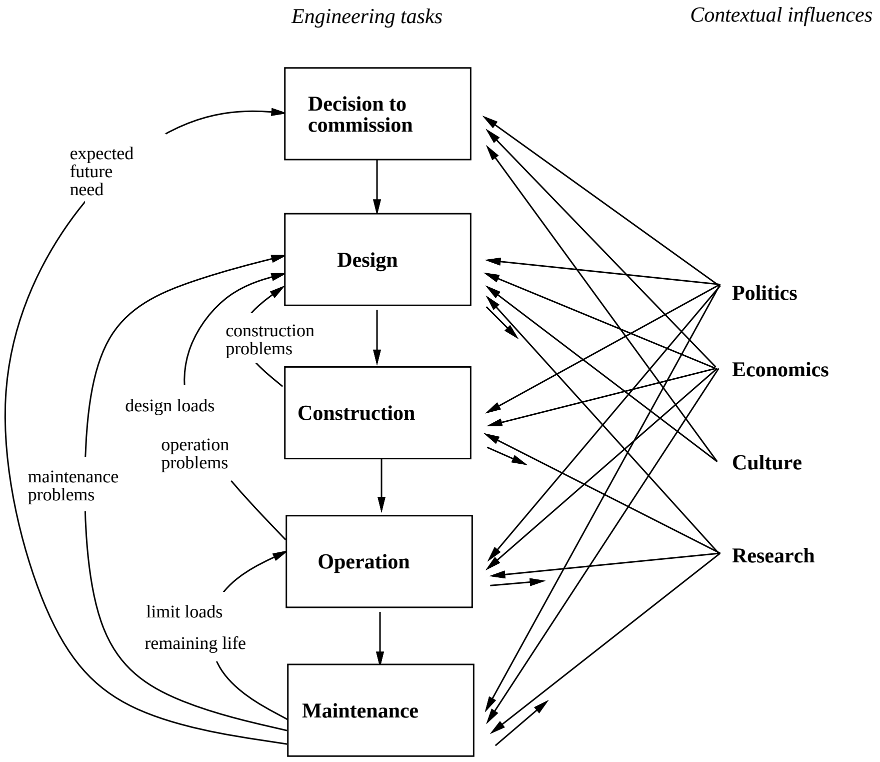

Figure 1: The life cycle flow of information of a bridge

is in correspondence with present interest in concurrent engineering in which life-cycle concerns are brought into the design stage where product quality can be designed for.

1.2 Preview

The remainder of the paper is organized as follows. Section 2 reviews the state-of-the-art in AI research for bridge engineering organized around the tasks in Figure 1. Section 3 elaborates on Figure 1 with information about the status of the bridge stock in many countries. This allows to locate several most critical tasks in bridge engineering that are presented as the grand challenge to AI applications. Section 4 discusses AI technology that can be used to address these grand challenges and how practical AI applications in bridge engineering could be developed based on previous experience with tool developments. Section 5 summarizes the paper.

2 State-of-the-art in AI research for bridge engineering

Work on AI techniques for bridge engineering has focused mainly on the two most critical issues in bridge engineering: design (mostly preliminary) and maintenance (mostly inspection). Design has been pursued because it is the task that has the largest impact on the success of any bridge project. It is also considered to be the creative or artistic of all tasks. Studies that developed tools for designing bridges often treated design in isolation from the remaining life-cycle issues. This isolation permitted the use of AI techniques for attempting to solve these isolated tasks. Nevertheless, in order to reflect the interaction between design and the other tasks depicted in Figure 1, the scope of design applications should be broadened and be informed by the information generated by the other tasks. The second critical issue — maintenance — has been pursued because it constitutes the most acute problem in bridge engineering as will be elaborated in Section 3.

This section reviews many applied AI projects in bridge engineering. The review is not comprehensive, rather, it reflects the diversity of topics addressed in these studies. Two notes should be made. First, few of the studies were reviewed solely based on abstracts of published reports. Second, there are many studies that are directly relevant to those reviewed but that did not make explicit reference to bridges, therefore were not reviewed here.

2.1 Decision to commission

There is no work on the application of AI techniques to this task. Nevertheless, there are numerous studies dealing with risk evaluation of large construction projects (8). The work cited describes the encoding of multidisciplinary knowledge on risk management for large construction projects into a system and using it over a long period of time by industry.

2.2 Design

Work on AI applications for bridge design has dealt with many issues at many levels. The relevant studies are classifies into conceptual design, aesthetics, analysis, loads, and other various subtasks.

Conceptual design. In this stage the precise location of the bridge at the site is determined together with its form and its major components. Many research projects addressed this task:

• Preliminary design of relatively standard bridges (9). The system was implemented in a commercial rule-based expert system shell.

• Support for early stages of preliminary design (10). The system uses dynamic constraint satisfaction algorithm that can handle continuous variables and can support changes in input requirements.

• Minimum cost selection of superstructure and substructure of a bridge (11). The knowledge was based on almost algorithmic procedure used in Japan for designing bridges. The system is implemented in a commercial expert system tool and briefly addresses some ease of erection and maintainability concerns. The system was further developed to address precise site selection through the integration with a geographic information system (12). It is interesting to note that selecting slightly different alignments or locations at a particular site results in minimal cost bridges of different types. This demonstrates the value of integrating different issues into support systems.

• Conceptual design of bridges (13). Knowledge for the system was extracted from several experts and was verified with the original experts, independent experts, and potential users. This development incorporates user-centered approach having observed that otherwise, a functional system can fail (14). This has lead to devoting explicit effort to address the human-computer interaction of the system (15).

• Preliminary design of bridges (16). Design is modeled as a mapping from a large number of input parameters to a large number of output parameters. This type of mapping was then captured by a neural network.

• Assisting in layout of truss bridges (17). In order to integrate the system with detailed analysis, default values are assigned to unknown parameters.

• Selection among types of prestressed concrete bridges (18). Knowledge acquisition revealed the difficulty in eliciting knowledge. The system was implemented using logic programming.

• Conceptual design of bridges (19). This study focuses on eliciting knowledge from several experts using several elicitation techniques. The issues raised are part of building any practical AI application.

• Selection of bridge superstructure (20). The approach incorporates uncertainties and ambiguities in its knowledge which was collected from diverse sources into a rule-based expert system.

• Preliminary design of cable-stayed bridges (21; 22). This experimental system shows that learning from existing designs can result in knowledge that can be used to synthesize bridges of a similar type. The system was implemented using two machine learning tools and is integrated with a detailed numerical analysis program. Whenever needed in the operation, including for interfacing the analysis program, learned default values are assigned to unknown parameters.

• Selecting types of bridge superstructure (23). The system is implemented as a rule-based expert system.

• Preliminary design of wooden structures (24). The system encodes design expertise in a formal ontology that allows to use a sound solution algorithm (i.e., whose performance is predictable, in contrast to the unpredictable nature of regular expert systems behavior).

• Design of several types of truss bridges (25). The approach integrates an expert system with analysis tools. Some of the expert system rules were constructed by learning from simulations.

• Design of small to medium size steel and prestressed concrete bridges (26). The system was implemented as a rule-based expert system and was integrated with an analysis procedure.

It is useful to mention several other projects that have dealt with bridge design using traditional mathematical or software development techniques; for example, the design of conventional highway bridges for minimum cost (27) or the shape design of small steel truss bridges (28). These approaches were based on optimization and not AI techniques and show that traditional technologies for developing design systems can be useful. A third project developed a system for designing highway bridges including their drawing production (29). This system was written using a traditional software approach and has been used in more than 200 bridge design projects. It sets up a base line performance to be desired from any system based on AI techniques.

Aesthetics. Some bridges are large structures that can easily dominate the landscape, making their aesthetics a major concern. Recently, several projects have addressed this issue:

• Learning to design aesthetic cable-stayed bridges (30). The approach used a learning algorithm to learn both proportions between various bridge elements as well as encode overall aesthetics concerns using a case-based approach.

• A quantitative evaluation of the aesthetics of different bridges which includes the landscape (31). The approach in based on rules extracted from questionnaires of people including bridge designers. This work extends the work in (11) and together with (12), presents a system that deals with cost, aesthetics, maintainability and constructibility of bridges including their site.

• Assisting in producing aesthetic bridge forms (32). A CAD tool was developed that integrates knowledge and image processing capabilities.

• Aesthetic evaluation of bridges (33). Since subjective judgment is hard or impossible to extract from experts, the approach uses case-based reasoning to enable the capture of aesthetic judgment embedded in existing designs.

• Developing rules about aesthetic bridge forms (34). The rules are extracted from experts and public surveys and potentially intended to be used in an expert system.

Analysis. While analysis is perceived to be quantitative and precise, its actual practical execution involves substantial expertise and heuristics. Several studies have addressed it:

• Determining dynamic response of highway bridges to random traffic loads (35). The system integrates heuristics extracted from many sources with numerical analyzes.

• Design critique (36). A generic tool for building design critics is developed and used to implement a bridge design critic and a constructibility critic for reinforced concrete buildings.

• Static load analysis of bridges (37). The system includes the preparation of finite-element models for analysis and the analysis itself.

• Assisting designers in designing against fatigue (38). This study describes several systems developed over eight years, from several prototypes implemented in expert system shells and using conventional programming languages to a commercial product.

Loads. Part of bridge analysis is the determination of its loads. One study addressed it while others may be related to it:

• Estimation of seismic loading for assisting in design critique (39). The system was implemented in a in-house developed object-oriented language where objects are associated with rules and procedures that encode knowledge.

We can easily observe the nesting of issues dealt with by expert system tools. The determination of loads or modeling choices is part of analysis which is also supported by expert systems. In turn, analysis is a part of design which also benefits from expert system support. An integrated system to address conceptual design would have to be built out of several interacting (or cascading) knowledge modules.

Design subtasks. There are other subtasks of design for which AI applications have been developed. Some of them are:

- Design of bridge abutments and piers (40). The system was developed using an expert system shell.

- Design of safety structures (41). The system was implemented with a rule and frame-based shell and was integrated with a finite-element analysis program for analyzing its candidate designs. It also included visual scanned images for assisting its use in practice and education.

- Selection of bridge foundations (42). The system was developed with a commercial expert system tool.

- Design of bridge foundation (43). The system was developed using a commercial expert system tool and is intended to be used by junior engineers and students.

2.3 Construction

The work on AI applications to bridge construction is relatively little, perhaps because work on constructibility in general applies directly to bridge construction.

Planning. This stage involves determining the construction work needed including finding candidate optimal schedules.

Scheduling construction work from drawings (44). The expert system is intended to interpret drawings and determine the construction work needed and schedule it. The system is implemented in a conventional programming language.

Determining the course of actions needed to eliminate the effects of errors in bridge fabrication on bridge performance (45). The system was developed with a panel of experts and potential users that participated early on in the project so that their feedback could be incorporated. The system is implemented with rules augmented with some object-oriented features.

Erection. This stage involves planning the erection process including construction of falsework and making sure that the bridge sustains the loads during erection.

- Welding advisors for steel structures (46). A commercial system was developed by a consulting firm and has been used on site for the selection of appropriate welding procedure and diagnosing field welding defects. The system uses production rules implemented using commercial expert system and spreadsheet tools.

- Evaluation of safety during bridge construction (47). The approach uses rules and fuzzy sets to represent ambiguities in knowledge processing.

- Selection of an erection method (47). The approach uses logic programming to implement rules.

2.4 Operation

The work on AI application to bridge operation is relatively little. Yet, if information about operation is coded it can have a significant impact on the design stage.

Monitoring function. This task involves monitoring the function for which the bridge was built.

• Regulating the flow of hazardous materials over a bridge (48). The problem was formulated as a classification task and used knowledge about material compositions and properties.

• Prediction of bridge frost conditions (49). A system was developed from analysis of meteorological conditions data and was tested against human forecasters and proved equal or superior to their judgment.

• Traffic safety evaluation (50). Accidents data together with knowledge from the literature were analyzed to yield a fuzzy set model for evaluating the safety of bridge traffic.

• Determining truck attributes (51). The approach uses a neural network to estimate truck velocity, axle spacing and loads from readings of structure strains. This can be used to enforce weight limits on trucks. If collected over time and analyzed, this information may be useful for obtaining better estimates of the operational loads on bridges to be used for subsequent bridge designs.

Monitoring structure. This task involves the continuous checking of the structure condition.

• Bridge monitoring in-situ (52). A blackboard system was developed that contained knowledge about interpreting measured signals from radar sensors. A preliminary experiment with data collected suggested that the approach could be useful for the analysis of bridge deck deterioration. Once fully developed, such a system could influence the practice of inspection.

• Providing early warning against collapse (53). The system compared the dynamic response of the bridge due to normal loading to a predetermined bridge signature.

• System identification by neural networks for in-situ dynamic analysis of bridges (54).

• Monitoring of a cable-stayed bridge (55). An expert system was developed to assist in the signal processing, and data handling and interpretation. The system can also detect faults in its instrumentation.

• Monitoring single-spanned bridges and reducing mid span deflection and forces by an actuator and real-time neural network system (56). This approach may change the technology available for bridge design.

2.5 Maintenance

Significant work has been done on AI applications to bridge maintenance including support for inspection, evaluation, retrofit, and scheduling activities.

Inspection. This task involves locating weak bridge parts to direct inspectors.

- Providing assistance in bridge fatigue investigation (57). The system would focus inspectors on potential problems and would be used for training.

- Estimating bridge scour using neural networks trained with field data (58).

- Determining the scour susceptibility of bridges (59). The system uses diverse knowledge sources for aiding inspectors . The system is implemented as a rule-based expert system.

We can again mention a project implemented using conventional software that provides assistance in the preparation of inspection documentation (60). It is estimated that once inspectors become familiar with the software, their inspection time will be reduced and the quality of document improved.

Evaluation. This task involves classifying a bridge based on its inspection data.

- Rating of highway bridges (61). The expert system is actually an interface to a bridge rating program built with conventional software in order to improve its usability. The program also interfaces a database and a finite element program.

- Estimating the cumulative damage of highway bridges (62). The approach used fuzzy probabilities incorporated in a Markov chain model.

- Bridge condition evaluation (63). The approach uses fuzzy sets to aggregate multiple deterioration factors into a single evaluation. A slightly different approach was presented later (64).

- Structural damage assessment (65). This work reviews several methods for performing approximate reasoning in rule-based expert systems for assessing structural damage.

- Damage assessment of reinforced concrete decks including an assessment of remaining life (66). The approach is implemented as a rule-based expert system that makes use of fuzzy sets for knowledge representation and inferencing.

- Prestressed concrete pile damage (67). The study demonstrates that learning rules by a machine learning program, i.e., ID3, can result in rules better than by interviewing experts.

- Diagnosing fatigue and fracture of steel bridges (68). The system uses qualitative reasoning to integrate quantitative and heuristic knowledge. The knowledge was extracted from existing cases of fatigue cracking of steel bridges.

- Evaluation of corroded reinforced concrete bridges and scheduling of future inspections (69).

- Bridge condition evaluation (70). The approach employs multi-attribute decision making with fuzzy sets.

Retrofit. This task involves proposing rehabilitation activities.

- Recommending retrofitting actions for fatigue cracking in steel bridges (71). The knowledge was extracted from the same source used in (68). The system implements a new inference engine that uses causal relations and can learn from user feedback.

• Evaluation of bridge condition, need to paint, selection of painting strategies, and determination of the cost of these activities (72).

• Estimating the recoating period (73). The system was based on coating exposure tests data and was intended to be used by practitioners.

• Assisting in the inspection and rehabilitation of steel bridges suffering from fatigue (74). The system assists in where to inspect, what to look for, and how to calculate the remaining life of the bridge. The system is intended to be used for consulting and training. The training aspect was taken into consideration when designing the system. An earlier prototype of this system was evaluated by experts (75). The system was implemented with a commercial expert system tool.

Scheduling. This task involves scheduling inspection and rehabilitation activities.

• Identifying bridges most vulnerable to collapse following an earthquake (76). The approach is based on an expert knowledge gained from past earthquakes.

• Cost estimation of rehabilitation projects (77). The approach integrates a database with an expert system and is intended to be used by practitioners.

• Prioritizing bridge improvements alternatives under budget constraints (78).

2.6 Interface issues

By and large, the aforementioned applications dealt with specialized engineering tasks that were isolated from the remaining tasks. There are very few studies that have addressed the interface between different tasks. Some studies that might be relevant to several tasks were mentioned above; another study is the following:

• Learning from failures of bridges (79). Common patterns could be detected from descriptions of bridge failures and could potentially be used to influence design choices. One way of transferring the knowledge learned is by building a structural safety expert system.

2.7 Summary

The majority of work has concentrated on the conceptual design of bridges (including some aesthetic criteria) and the inspection and evaluation of bridges. The computational technology, whether AI or conventional software, used for building these applications for design applications included: databases, expert systems, machine learning, integration with numerical models, user interfaces, and information systems (geographic and others). The techniques used for implementing applications for maintenance were: fuzzy logic, neural networks, and traditional probabilistic models for summarizing subjective judgment or for analyzing measurements, expert systems, and user interfaces. From the review it seems that there is some consensus about certain development and implementation choices.

- Conceptual design of bridges must include an integration with analysis procedures that check whether candidate designs satisfy the relevant design codes requirements.
- Whenever values of design parameters are missing for detailed analysis, default values could be used if selected well.
- Most design systems have dealt with small to medium size bridges where sufficient experience as well as acceptable design procedures exist. Except for few preliminary cases, life-cycle issues have not been included in the systems reviewed.
- Fuzzy sets (or logic) has been the preferred method for aggregating subjective assessments from multiple components into a single bridge evaluation.
- Neural network were employed for various real time operations such as signal processing and interpretation for control, monitoring and in-situ inspection.
- The most common vehicles for implementation are various rule-based expert systems tools. Few systems use newer AI technology such as case-based reasoning, machine learning, or qualitative reasoning. When experts are unavailable or where some knowledge cannot be extracted from them, new techniques such as machine learning or case-base reasoning could be used.
- Knowledge acquisition from multiple experts and from diverse sources was practiced to improve the coverage and quality of knowledge extracted for the AI applications developed.
- There are few long term projects that succeeded to move to practice. There are no reports on sustained practical use of systems that include the feedback from practitioners.

3 Where are the golden nuggets?

Bridge engineering is responsible for keeping the bridge infrastructure up with the growing transportation demands by designing and constructing new bridges and by maintaining the condition of existing bridges. In the previous section we reviewed AI applications in all areas of bridge engineering. In this section we wish to identify the areas where AI technology can really win for bridge engineering or where it is most urgently needed. For this purpose, it is instrumental to review some facts about bridges. These facts augment the life-cycle flow of information presented in Section 1.1.

The bridge stock in most, if not all, countries is in an extremely deteriorated condition (80). Significant resources are needed for reconditioning or replacement of bridges, and preventing further deterioration that can lead to the loss of traffic safety, enforcement of load limitations, or the expenditure of substantial resources for premature replacement or emergency maintenance. Bridge management decisions are based on many concerns such as: cost, existing load limits, safety, route, remaining life, class of highway, traffic, possible coordination with other construction work, urgency, length of detour, etc. The selection of near-optimal solutions as opposed to *ad hoc* management decisions can have a significant positive economical impact. The many factors influencing choices make bridge management extremely difficult.

The condition of bridges is determined by inspection. Unfortunately, the inspection of bridges is a complex and time consuming task that requires substantial expertise. The subjective evaluation of a bridge during its inspection, consisting of bridge condition evaluation, assessment of load carrying capacity, and the maintenance needed, serves as raw data for management decision making. Therefore, it is extremely important to collect accurate and relevant data and enable its timely analysis. Unfortunately, there is a shortage of inspection personnel and no improvement in this condition is foreseen.

Based on this situation, there is a great need for: (1) making maintenance decisions that are informed by all information that can be made available; (2) assisting in inspection procedure including where particular bridges are expected to fail thus need to be checked, and supporting the time-consuming document handling; (3) bringing the information about bridge performance back to design so that bridges are designed, rehabilitated, or maintained better. These needs have been discussed elsewhere. For example, a recent OECD document discussed several critical areas of research including maintenance, prediction of deterioration and service life, and bridge management systems (81). The document stated:

> An improved bridge management system should also be able to provide information on how to learn from past mistakes and use these findings for the design and construction of new bridges. It should be possible to compare the life-cycle costs of various types of bridges and to obtain rational criteria for the selection of bridge types, materials and systems under given conditions. This evaluation of materials and systems should also include those used in maintenance work. In this way, not only the initial construction costs would influence the decision, but the total life-cycle cost, including expenditure for inspection, maintenance, user costs during maintenance work, demolition and replacement. (p. 125)

Also, the prominent US bridge designer, G. F. Fox argued:

> I think we should be developing databases, or knowledge bases, as well. Unit cost, technical data, historical costs, and failures could be put into these databases. Right now designers aren't able to get to the information that's out there. (7)

If all the information available on bridges, including historical records of performance and maintenance, is communicated effectively engineers working in design, maintenance, or the other tasks, bridge engineering could be transformed from a set of rather sequential misinformed tasks to an integral set of activities that can yield better bridge designs, reduce maintenance cost, reduce inspection time, increase inspection interval, and reduce cost by reducing margins of safety through a better determination of loads and using online monitoring and control. Referring to Figure 1, this means that much more attention is paid to the feedback arrows between the tasks.

Such effective communication relies on two issues. First, data needs to be collected and organized. Second, information needs to be compressed into some comprehensible, usable form to be communicated and used. These issues interact. Given limited resources, one does not need to collect information that cannot be processed or influence engineering decisions and merely waist collection, storage, and maintenance resources. On the other hand, data that is estimated to have a large impact on engineering decision better be collected and processed effectively.

The first issue receives increasing attention (82). New sensors are developed and new ways are studied to analyze data (54; 55; 51; 52). Beside such data collection, different countries have established projects to collect more information about bridges, such as the National Bridge Inventory (NBI) which contains information on about 550,000 bridges. Moreover, different states and local agencies are developing more elaborated information systems called bridge management systems (BMS) to manage their bridge inventories that is adapted to their own needs. In spite of these activities, no serious practical advantage is gained from present bridge database projects, because the second issue, compressing the enormous amount of information and its effective communication is not addressed. Improving the use of bridge information is the first challenge to AI applications in bridge engineering.

The second challenge of AI technology in bridge engineering is very simple. Beside moving down stream information into the design of bridges, there is also an urgent need (at least in the US) for developing the computational infrastructure for supporting bridge management activities. Engineers that were in charge of developing the highway system (including its bridges) in the US are retiring and their expertise is lost including the history of projects in which they participated (83). Unless AI or other tools are built to capture and integrate their expertise, it will be lost.

4 Addressing the challenges

Based on the summary of Section 2 and the previous section we can propose some AI techniques to address the potential and need for AI tools and discuss the methodology for building them for practical needs. Since the methodology influences the technology, it will be discussed first.

4.1 Research Methodology

Designing AI applications for practical needs is totally different from developing prototype research tools (38; 84). There are some obvious differences that can be termed *technical*. First, the scope of domain knowledge included in a research prototype is usually narrow. Second, in order to fit real domains into computational tools many simplifying assumptions are made, some of which may not be appropriate, and all of which may be forgotten after a short time. Finally, tools developed in research need not be in production use therefore, need not be usable.

The less obvious differences are the *social issues* related to an application. Often, it is not clear whether the application addresses a problem that practitioners want to surrender to a computational tool or whether a task is so critical that they want to invest the effort to change their working environment. Research organizations are not built to reward applied research and therefore, application transferred to practice will not benefit from much maintenance or subsequent support. This is hardly the fate that practitioners wish for their valuable tools.

A recent analysis of research on automated standard processing revealed the same issues (85). The research failed to impact practice for several reasons. It failed to demonstrate how the techniques could be integrated into a design process with centralized product model (i.e., the integration framework was missing); it was not implemented into usable tools; there was a wrong selection of the initial application which had properties less desirable for the purpose of the tools than other applications; and the tool did not cover the complete standard processing evaluation. The social issues related to individuals and groups dynamics associated with the tools or applications, including the separation between practitioners (or potential users) and researchers.

These difficulties have long been recognized in civil engineering (86), but they did not impact research practice seriously. This suggests that not only are practitioners resistant to change, but so are researchers. Since computational technologies can have a significant impact on practice as was demonstrated by the success of the finite element program STRESS (87) (see (84), for an analysis of STRESS' success versus the failure of automatic standard processing research), these issues must be dealt with to help additional applications move toward successful practical implementations.

There are few principles that can address the aforementioned problems (84). Research that is performed in the *context* of practice has better chances to be successful. Research in context, sometimes called *participatory action research*, requires involving practitioners in the formulation of the research problems so that research addresses real practical concerns. Instead of estimating what practitioners need, research become a collaborative effort, making practitioners more willing to accept a solution.

Collaboration with industrial developers (beside users) can lead to developing quality software rather than prototype tools and this software has better chances to be usable to practitioners, because if tools are not usable, they fail (14). Such collaboration, however, is not trivial and can also fail (38). It is critical that such failures be recorded, analyzed, and studied, so that they can be avoided.

Usability also entails *integration* with existing tools. Few practitioners could afford to use a tool that requires much effort in preparing input and analyzing results unless this is part of the regular way of practice in that field. If a new tool is integrated well into the regular engineering environment, resulting in minimal changes, and not disturbing the usual way of practice it may have better chances of being used and be successful.

By now, we have mentioned integration several times. It was apparent that a tool for conceptual design must integrate knowledge with numerical analysis code; that any AI tool must integrate with existing tools; and that the lack of integration around a common product model may lead to a failure of a technique (e.g., the automatic standard processing). The need for integration extends beyond these because of the nature of real design: different tasks interact closely and influence one another as already discussed in Sections 1.1 and 3. This was demonstrated by a system that integrated two closely related tasks: precise site selection and bridge type selection (12), where slightly different sites resulted in the selection of different bridge types. If we consider that the problem of site selection may involve much more detailed knowledge and can require its own computational support (88), and that all these issues are part of the input to the overall decision to launch a project through calculating its risk (8), we can appreciate the need for tight integration of tools.

The difficulties researchers encounter in transferring results to practice have led some to target their systems to the educational market. In few other cases the target is said to be training and practical use. It must be noted that the educational or training goals need to be given full attention because they are very different from one another (see, for example, the relationships and differences between MYCIN (performance tool) and GUIDON (educational tool) (89)). One example that such attention was paid is described in (74).

But before even starting with large collaborative projects there are several rudimentary issues that need to be addressed in relation to research methodology. They mostly involve the testing of research projects. Research tools should be tested seriously. There are several ways of conducting tests, each of which provides different perspective. Testing against practice or practitioners can inform on the potential impact of a system (e.g., as in (13; 45; 49)). If a system performs poorly compared to practitioners, it will not impact practice.

Testing must include explanation about *why* a system succeeded to perform well. Otherwise it is not clear what has led to its success and how its design could be improved. Some understanding of the reasons for success can arise from statistical testings and some from "ablation" studies in which the system performs without one (or some) of its components.

In relation to testing, the summary of Section 2 mentioned some ideas for using techniques for certain purposes as were reflected by the studies. Nevertheless, in most studies it is hard to find the rational why a certain method works and other not or whether the choice of one method led to results significantly better than another choice. Since most of the systems are research prototypes, the ideas there are tentative.

Better testing can also include the use of common sources of knowledge (e.g., the two systems reported in (71; 68)), the testing on benchmark problems (e.g., as briefly reported in (70)), the sharing of systems' code or the testing of generic tools on multiple domains. All these can help compare between several research efforts and subsequently advance research. In spite of significant improvement in research methodology that can be done in the field of AI techniques applied to bridge engineering, and to put the aforementioned comments on research methodology in perspective, it must be commended that applied AI in bridge engineering is one of the few field in which applied AI work has been much aware of practical needs and has advanced significantly toward this end.

4.2 AI and related technology

It is clear that AI itself cannot provide an adequate answer for the challenges posed in Section 3. There are other computational technologies that need to be integrated together with AI. It is also obvious that all these new tools need to be integrated together with existing tools used presently by practitioners. How could a tool for bridge engineers be designed so that it would have high chances to be useful for practitioners? The tool would have to integrate three general facilities: (1) information modeling, (2) information analysis, and (3) information communication.

The information modeling facility will be used to model information originating from various data acquisition tools, such as sensors, or others, such as computerized documents (including records as described, for example, in (60)). It would have to support the creation of product models for serving as the core around which applications are built. It will have to allow users of the system to model all kinds of information including text, equations, pictures, etc. This facility would have to be adaptable easily to accommodate the needs of different organizations or even different individuals in these organizations as they see fit. Such adaptation cannot be assumed to be the task of researchers even if a project is developed collaboratively by researchers and practitioners.

The major technologies for supporting this facility are:

- databases for storing product models and other information related to bridges (e.g., historical performance, maintenance activities, present loads, etc.);
- user interfaces for handling all users interaction; and
- multimedia technologies which can add a new dimension to the understanding on knowledge embedded in systems and to the usability of the tools (90).

Some AI technologies can play a supportive role; they include:

- knowledge representation techniques that can be provided and selected depending on the needs of particular information;
- knowledge acquisition tools for quick knowledge incorporation that are integrated with problem solving capabilities for immediate checking of the knowledge utility; and
- machine learning techniques could be used to create user interfaces that adapt their behavior to the level of users, as reflected in the use they make of the system.

The information analysis facility is in charge of analyzing the data based on user demand for extracting pieces of knowledge from the enormous amount of data. The technologies that play a major role in this facility are:

- machine learning tools for learning from databases so that the wealth of information stored can be communicated to all engineering tasks that may need it (91); and
- natural language processing tools for extracting information from textual information (92).

The communication facility relies on having compressed information into usable, comprehensible pieces of knowledge that can be transferred. These pieces can be in the form of sets of heuristic rules, relationships between parameters design and bridge performance parameters, etc. Networking and distributed database technology can provide the means for people to communicate and share the information stored in and generated by the system.

Providing these facilities is a major undertaking. One project that attempts to address these issues for supporting the collaborative work of engineers in diverse domains is n-**dim** (93). An outline of its use for information modeling and analysis of information in general is given in (94; 92), and its facilities for communication in (95). An outline of its expected use for knowledge extraction from bridge databases was given in (91).

5 Conclusions

This paper rest on several premises. First, the term AI is interpreted as a particular suite of computational techniques. Their utility is determined solely based on their ability to improve practice and not by reference to human thought. Second, bridge engineering is a complex practice that includes many interactive activities and generating significant amount of information.

Following these premises, we reviewed the state-of-the-art of AI techniques applications to bridge engineering. We saw the diversity and specialization of the studies, and their treatment of isolated tasks. Even if some of these applications will be used in practice, there are areas where AI technology can impact significantly on bridge engineering. These areas were identified along with the AI techniques that are suitable to address them.

It is clear that the benefit from AI techniques will result in its integration with other technologies such as multimedia information systems, CAD, analysis systems for simulations, and other tools that are useful to bridge engineers. The way to develop these applications and move them to practice was also outlined.

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