Expert System To Cost Feasible Bridge-Painting Strategies

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Knowledge-based expert systems have been developed for many civil engineering applications including bridge deck condition assessment, selection of optimal strategies for bridge deck rehabilitation, and traffic signal setting. Such expert systems incorporate both heuristic knowledge and algorithmic approaches to problem solving. Identification of bridge-painting strategies is perfectly suited to such an approach. Bridge-painting decisions are based on measurement of condition; qualitative assessment of deterioration; and heuristics describing the incompatibilities among different types of steel, paint, and surface preparation. Further, uncertainty plays a crucial role because surface treatment, paint application, and bridge condition are nonuniform. Optimization or current approaches to decision making are unable to effectively include all of these variables. A prototype system, Bridge PIARS (Paint Identification and Ranking System), constructed using an expert system building program is based on a decision network. The system allows the user to establish the facility condition, evaluate the need for bridge painting, identify appropriate painting strategies, and cost the strategies. The system and its operation are described, and several areas for research to extend and enhance the system are identified.

More than 45 percent of the bridges in the nation's bridge inventory *(1)* are structurally obsolete or functionally deficient. The magnitude and extent of the bridge problem have spurred additional funding for bridge maintenance and rehabilitation, the development of innovative repair and rehabilitation methods, and the application of computer techniques to bridge management systems *(2)*. Such bridge management systems, based on the National Bridge Inventory (NBI), are used or proposed for use in Kansas, Maryland, Minnesota, New York, North Carolina, and Pennsylvania and are under development in an NCHRP research project. These approaches are structured within traditional algorithmic computer-programming frameworks. In comparison, Seymour *(2)* has conceptualized a bridge management system based on rule-based expert system application modules. One suggested module is a bridge-painting management system that includes establishing the facility condition and the need for repair and selecting an appropriate compatible and economic paint system.

A bridge-painting management system is designed to protect the investment in the bridge. Steel bridges are coated to prevent corrosion, which leads to loss of section and ultimately structural deficiency. Coatings include paint, galvanizing, and the oxidized steel formed on weathering steel or a combination of these. These coatings deteriorate as a result of exposure and the application of deicing salts, which necessitates their replacement from time to time. The impact of this practice on the lifetime costs of a bridge must be evaluated to select an appropriate time interval between paintings, the thickness and number of coats of paint, and a system for application.

The solution to this problem has been formulated and computerized in the Bridge Corrosion Cost (BCC) model developed by Frondistou-Yannis *(3)*. The model is based on simulations of the deterioration and coating costs over the life of the bridge. Because the model is programmed, with respect to the choice of painting systems, using a traditional algorithmic program, many judgments are left to the experienced coating and maintenance engineers. A knowledge-based expert system (KBES) that identifies bridge-painting strategies and their costs is described in this paper.

BRIDGE-PAINTING SYSTEMS

Coatings are used to prevent steel bridges from corroding. Paints are the most commonly used protection, but galvanizing, the application of a zinc coating to steel usually through hot dipping, and the use of weathering steel (A588) are other forms of protection. Paints are not used exclusively on low-carbon steel; they may also be used as additional coatings on galvanized and weathering steel.

Paints are applied using a brush, roller, or spray in several coats each a few mils thick (1 mil = 0.025 mm). The first coat is the primer, followed by intermediate coats and then top coats. Paint types include

- Oil-based paints with or without alkyd resins;
- Zinc-rich primers with organic top coats; and
- Vinyls, epoxies, and polyurethanes known as high-performance paints.

Good paint performance requires a good bond between the metal surface and the paint. The best bonds are achieved when the metal surface is properly prepared. Typical surface preparation specifications are defined by the Steel Structures Painting Council (SSPC) specifications *(4)*. Different paints have minimal surface preparation requirements. For example, zinc-rich primers require blast cleaning. Therefore paints should not be considered in isolation but as a paint system consisting of

- Types of prime, intermediate, and top coats and
- Surface preparation.

This expert system uses two sets of painting systems. The first set of systems is based on those defined by Frondistou-

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Yannis *(3)* and information in Hare *(5)*. This set includes 12 paint systems of which 4 are defined for low-carbon steel, 3 for galvanized steel, and 5 for weathering steel. The systems are based on common practice, paint compatibilities, system performance, and minimum surface preparation requirements. The 12 systems are summarized in Table 1. The second set is based on the SSPC systems *(4)*. Three other conclusions may be reached for any bridge:

13. Painting is not required,
14. More information is required or information is out of date,
15. Painting should be deferred because of other work pending or possible reconstruction of the bridge.

Several factors influence the choice of a painting system. These include the environment, the bridge condition, the coating condition, the existing paint, and some of the limitations of various types of painting systems. To describe environments effectively, yet avoid detailed measurements, the following four environments, in descending order of severity, are used by ASTM and the SSPC:

- Industrial or urban,
- Marine,
- Rural, and
- Desert.

In this study the desert environment was ignored. Definitions of environments can be confusing because of windborne ocean spray and pollutants, acid rain, and deicing salts. The most severe environment for a bridge is assumed to ensure minimum performance. For example, ocean spray or deicing salt classifies a rural bridge as being in a marine environment.

The performance of a coating system is measured using a grade from 0 to 10 as defined in ASTM D 610 and summarized in Table 2. Each grade is associated with a percentage of rust.

This performance measure is somewhat unsatisfactory because areas near the edges of members may have a rating of 0 when other areas have a rating of 10. Also given in Table 2 for each rating is the percentage of the bridge that needs to be painted. These values are derived in Frondistou-Yannis *(3)*. When 30 percent of the bridge shows rusting or the grade declines to 2 it is assumed that the complete bridge will be repainted.

TABLE 2 CORROSION PERFORMANCE RATING ACCORDING TO ASTM D 610

Rating	Description	Area to be Painted (%)
10	No rusting or less than 0.01% of surface rusted	0
9	Minute rusting, less than 0.03% of surface rusted	0
8	Few isolated rust spots, less than 0.1% of surface rusted	0
7	Less than 0.3% of surface rusted	0
6	Extensive rust spots but less than 1% of surface rusted	8
5	Rusting to the extent of 3% of surface rusted	18
4	Rusting to the extent of 10% of surface rusted	40
3	Approximately 1/6 of surface rusted	60
2	Approximately 1/3 of surface rusted	100
1	Approximately 1/2 of surface rusted	100
0	Approximately 100% of surface rusted	100

The existing paint and thickness and the year last painted influence the choice of a system:

- The system to be applied should be the same as the existing paint to ensure compatibility between the paint applied and the existing system, unless the complete bridge is to be blasted (Systems 3, 4, 11, and 12).
- The type of existing paint together with its age may also be used as an indicator to check the condition as represented by the grade described in Table 2. Frondistou-Yannis *(3)* gives performance curves for each painting system and environment as well as empirical adjustment factors for the type of bridge and thickness of existing paint.

Other variables and considerations that affect the selection of a paint system are summarized in Table 3 for each of the systems.

The cost of applying any bridge painting system varies with

- The system,
- The condition of the surface of the structure,

TABLE 1 PAINT SYSTEMS FOR HIGHWAY STRUCTURAL STEEL [modified from Frondistou-Yannis *(3)*]

Protection Method	Paint	Surface Preparation
Low-Carbon Steel		
1. Paint System I	Oleoresinous paints (oils and alkyds)	Hand cleaned
2. Paint System II	Same as above	Commercial blast
3. Paint System III	High-performance paints	Near-white metal or commercial blast
4. Paint System IV	Zinc-rich primers and organic top coats	Near-white metal
Galvanized Steel		
5. Zinc coating	None	None
6. Alkyds	Zinc dust or zinc oxide alkyd paints	Wash with soap then rinse
7. High performance	High-performance paints	Hand cleaning
Weathering Steel		
8. Steel surface	None	None
9. Paint System I	Oleoresinous paints (oils and alkyds)	Hand cleaned
10. Paint System II	Same as above	Commercial blast
11. Paint System III	High-performance paints	Near-white metal or commercial blast
12. Paint System IV	Zinc-rich primers and organic top coats	Same as above

TABLE 3 FACTORS THAT INFLUENCE PAINT SYSTEM SELECTION [modified from Frondistou-Yannis *(3)* and Hare *(5)*]

System	Advantages/Uses	Disadvantages/Limitations
1	Suitable for use on existing oil/alkyd paints	
2	Suitable for use on existing oil/alkyd paints	
3	Good system when existing lead paint removed	Difficult to apply on complex designs; requires skilled contractors
4	Good system when existing lead paint removed	Difficult to apply on complex designs; must be sprayed
5		Unsuitable in industrial or marine environments
6		Must be sprayed; use on unpainted or similar existing system
7		Difficult to apply on complex designs; use on unpainted or similar existing system
8		Unsuitable in industrial or marine environment
9	Suitable for use on existing oil/alkyd paints	Use on unpainted or similar existing systems
10	Suitable for use on existing oil/alkyd paints	Use on unpainted or similar existing systems
11	Good system when existing lead paint removed	Difficult to apply on complex designs; requires skilled operators
12	Good system when existing lead paint removed	Difficult to apply on complex designs; must be sprayed

- The number and thickness of coats, and
- Local conditions.

The BCC model *(3)* provides unit costs for estimating the total cost of applying a painting system. Similar costs are also provided by the SSPC *(4)*.

KNOWLEDGE-BASED EXPERT SYSTEMS

Knowledge-based expert systems (KBESs) are a major area of research in artificial intelligence. They are interactive computer systems based on the facts, rules of thumb, and approaches used by human experts to solve a problem. KBESs provide a practical alternative to conventional programs when the problem is ill-structured and solution algorithms do not exist or do not provide a complete solution *(6–8)*. The organization of KBESs, comparisons with conventional programs, applications, and the development of KBESs are described in detail elsewhere *(6, 8)*.

The success of MYCIN *(6)*, a large KBES developed in the mid-1970s for medical diagnosis, has led to development of small-scale KBESs for many different applications. In civil engineering, examples include traffic signal setting *(9)*, preliminary design of high-rise buildings *(10)*, and selection of bridge deck rehabilitation strategies *(2)*. These applications in civil engineering are often characterized by the integration of algorithmic programming, which typically identifies conventional programs, with heuristics and symbolic manipulation, which commonly identify KBESs. The result is a more complete and correct solution that no longer functions as a "black box" that is unable to explain or easily change the solution procedure used.

A KBES has four basic components:

- Knowledge base—contains all knowledge and rules used in solving the problem.
- Context—contains information that is specific to the problem currently being solved.
- Inference mechanism—links the knowledge base and context. The object of the inference mechanism is to reach a goal or conclusion and solve the problem.
- User interface—allows the user to interact with the system just as others confer and interact with an expert.

Although these elements are common to all KBESs, they may also include the ability to explain their reasoning and acquire knowledge.

The success of a system is dependent on whether an expert's method of problem solving, knowledge, and experience can be conveyed to the knowledge engineer. A number of language tools ranging from high-level languages to problem-specific tools and environments are available to implement the knowledge and problem-solving process *(6)*.

The knowledge acquisition component of the bridge-painting problem is described in the following section.

BRIDGE-PAINTING PROBLEM

Like other areas of bridge maintenance, bridge painting is often deferred because of financial constraints. For example, in Massachusetts for many years the budget for the Massachusetts Department of Public Works for bridge painting was on the order of $500,000. The department aims to paint bridges every 7 years, but with this budget limitation it is significantly behind schedule. To begin to correct this shortfall, the bridge-painting budget for fiscal year 1986 in Massachusetts is $5 million. The allocation of either a large or a small budget to particular bridges requires trade-offs. Furthermore, lack of trained inspectors and poor information on the condition of existing bridge paint make planning difficult.

In developing a bridge-painting program an agency often makes decisions hierarchically. At the uppermost level, a bridge-painting budget is set. At the next level, decisions about which bridge has to be painted are required. At the lower levels, type, thickness, and number of coats of paint; method of application; and amount of cleaning are decision variables. Because of problems with paint compatibility, local environment, and environmental conditions, there is usually a small subset of all possible painting systems that is feasible for a particular bridge. Identification of this feasible set of strategies is based on heuristics and qualitative data on the bridge, existing paint, environment, and local preferences.

The BCC model *(3)* seeks a strategy that minimizes the discounted costs of bridge painting over the life of the bridge. The optimal strategy for any one bridge is found by simulation. The simulation simply calculates the discounted bridge painting over the life of the bridge, for a range of reasonable thicknesses and for each possible value of the frequency of repainting until a minimum cost is observed. The process is repeated for each system that is appropriate for that type of steel. The minimum cost of all of the systems is identified as the optimal strategy. This approach fails to explicitly recognize that some systems may not be feasible for reasons of paint compatibility or local conditions. The expert system described in this paper interactively queries the decision maker to ensure that all available information is included in the identification of feasible strategies. The system heavily depends on the relationships and empirical data of the BCC model *(5)* to identify optimal strategies that are feasible.

The bridge-painting problem is ideally suited to the utilization of a KBES *(7, 9)* because

- The problem is well defined and has a relatively narrow problem domain,
- Experts exist and can describe their methods,
- The task does not require common sense but heuristic solution, and
- Expertise takes time to acquire and experts are in relatively short supply.

The knowledge base captures information from experts in the field and structures it in the form of an expert system to derive appropriate actions. The knowledge base is accessed for the identification of feasible painting strategies and determination of costs.

To isolate the engineer from the computer science–related details of building an expert system, tools to include problem-solving knowledge, allow the user and system to communicate, and complete problem solving are used. These tools, which are described in the following section, allow the knowledge engineer to focus on knowledge acquisition and inclusion.

BRIDGE-PAINTING IDENTIFICATION AND RANKING SYSTEM

The knowledge-based expert system Bridge PIARS (Bridge Painting Identification and Ranking System) is written in GEPSE (General Engineering Problem Solving Environment), a set of knowledge-based expert system building tools written by Chebayeb and Connor *(11)*. GEPSE is written in the C programming language and provides users with the flexibility to incorporate knowledge as rules and algorithmic procedures, but it also includes a predefined rule-based inference engine (forward chaining), interpreter, and mechanisms for the inclusion and alteration of objects, goals, and rules.

Bridge PIARS has two parts. The first part identifies feasible paint systems and the second part costs all feasible strategies for the bridge. Bridge PIARS defines objects such as a bridge or paint, which have attributes such as percentage corrosion. Relationships between objects and attributes are defined as rules. For example, if the attribute percentage corrosion of object bridge has a value of 10 percent, the attribute grade is set to 4. The inference engine fires rules until a goal is reached. In Bridge PIARS goals are reached at the end of the first phase. Functions are defined throughout the program to perform calculations, input, and output. For example, expected deterioration is calculated and compared with observed deterioration. The second part calculates the cost of each feasible painting system. The cost calculations of the second part can be repeated to perform a number of simulations and produce an optimal strategy similar to the BCC model *(3)*.

The first part of Bridge PIARS identifies feasible bridge-painting systems by asking the user a series of questions about the bridge and the existing paint. Alternatively, the program could query a data base if the appropriate data were available. The National Bridge Inventory as it now exists includes no information on the condition of bridge paint. The basic questions used to identify the most feasible system are

- Q1: What is the bridge made of?
- Q2: What type of steel is the bridge made of?
- Q3: What is the bridge painted with?
- Q4: What environment is the bridge in?
- Q5: Do environment regulations permit spraying?
- Q6: Is the bridge a truss or does it have complicated geometry?
- Q7: What is the bridge grade according to ASTM D 610?
- Q8: Are skilled operators available?

All questions are not necessarily asked for every bridge because a strategy may be decided on without asking all questions. In addition to asking the questions listed here, the system also queries the user about the painting history of the bridge. It then calculates the expected condition and compares this with the actual condition. If the conditions differ, the user is given the option of choosing the forecast or the observed condition or aborting the session.

The general relationships between questions and goals and objects are depicted in the decision network shown in Figures 1–4. Figure 1 shows the part of the decision tree common to all three types of steel considered by the system and the determination of the existing coating system. The intermediate steps required to reach a goal are shown in Figures 2–4 for galvanized, weathering, and low-carbon steels, respectively. The nodes on the network represent the questions listed previously. At each node identified as Q7 the system asks the user "what is the grade of the bridge?" At this node the user is also asked additional questions about the painting history of the bridge. This ensures that the actual deterioration is consistent with the deterioration predicted since the bridge was last painted. Each branch on the decision tree terminates when a goal is reached. The goals are depicted in Figures 1–4 as squares with numbers corresponding to the paint systems defined in Table 1 and the conclusion that painting should not be done.

The second part of Bridge PIARS estimates the painting costs. It uses the feasible paint systems derived in the first phase of the program. The user is asked to specify thickness. The calculation is repeated for each system and different thicknesses can be specified as shown in Figure 5. The program has a simple data base of unit costs and correction factors that the user can modify if necessary. It is this area of the knowledge base that could benefit most from further refinement.

Both parts of the program are interactive and ask the user for input for the particular problem to be solved. The user is given a menu of possible answers as shown in Figure 6. This question is one of several used to establish the painting history of the bridge to permit comparison of actual deterioration with predicted deterioration. The question and menu appear on the screen when a rule is fired. The user's choice is then assigned to an attribute through the rule. For example, the rule in Figure 7 asks the user "what type of steel is the bridge made of?" and assigns the answer to the attribute type of the object steel. The rule base includes approximately 80 such rules.

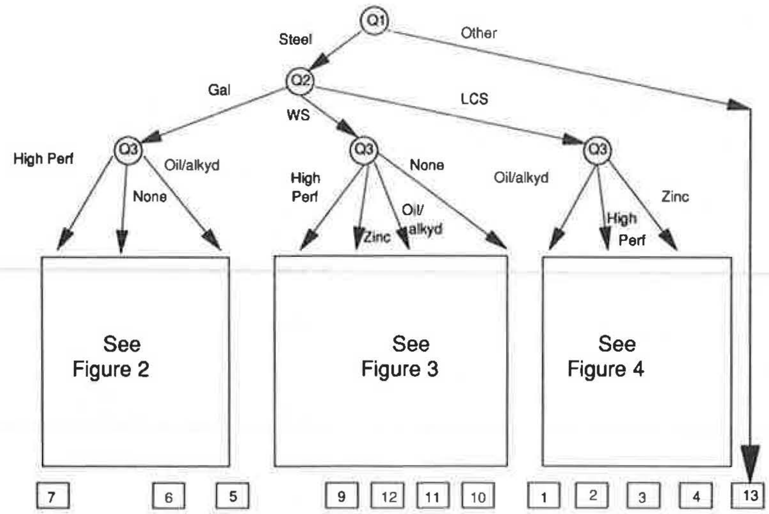

FIGURE 1 Decision tree for identifying feasible bridge-painting strategies.

To provide some preliminary testing of the program, Bridge PIARS was used to evaluate and cost bridge-painting strategies for two bridges that were recently contracted out for painting by the Massachusetts Department of Public Works. Both bridges were painted with the same painting system. Bridge PIARS identified three feasible painting strategies for each bridge including the one used. Table 4 gives a summary of the test results for the three bridges. For the actual painting system Bridge PIARS was within 12 percent of the lowest bid whereas office estimates tended to be around 30 percent under the lowest bid. The preliminary testing highlighted the role of the

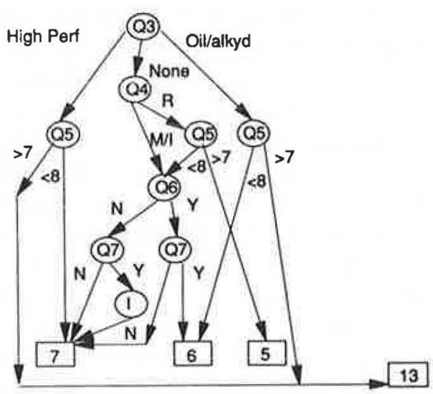

FIGURE 2 Decision tree for identifying strategies for galvanized coatings.

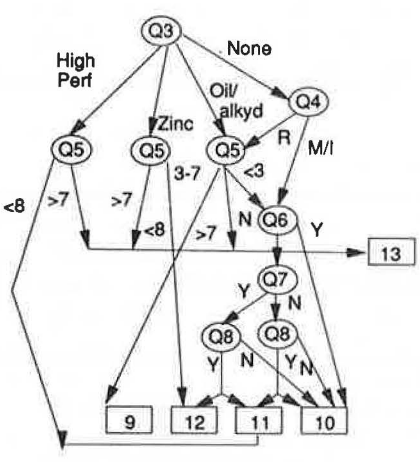

FIGURE 3 Decision tree for identifying strategies for weathering steel.

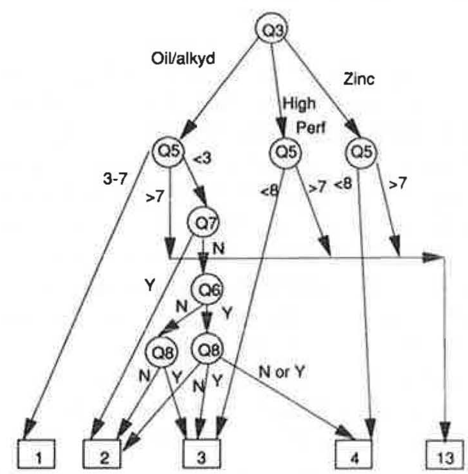

FIGURE 4 Decision tree for identifying strategies for low-carbon steel.

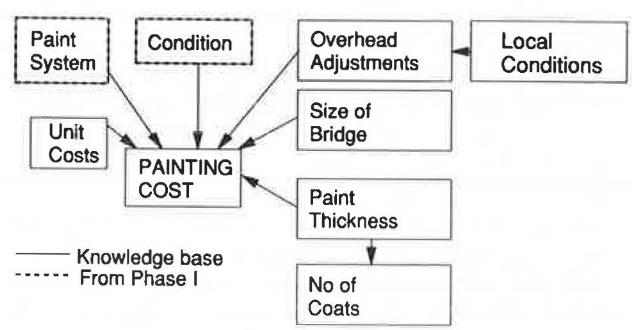

FIGURE 5 Determinants of painting costs.

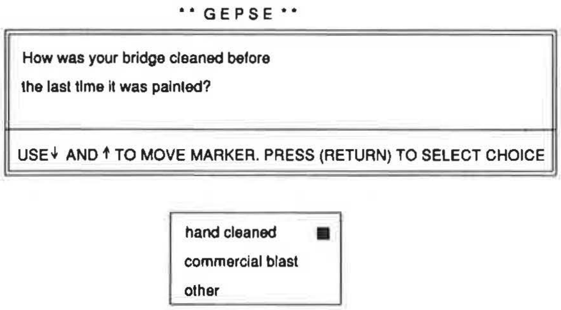

FIGURE 6 Typical user query.

```
(make-rule "typing"

    (is? type-of steel nil)

    (set type-of steel

      (menu 1
      "What is the type of steel?"
       3
      galvanized
      low-carbon
      weathering)))
```

FIGURE 7 Rules for finding type of steel.

TABLE 4 RESULTS OF PRELIMINARY TESTING OF BRIDGE PIARS

Bridge	Systems Proposed by Bridge PIARS	Cost ($)	System Used	Office Estimate ($)	Lowest Bid ($)
1	2	50,000	4	63,000	94,000
	3	65,000			
	4	89,000			
2	2	593,000	4	800,000	1,174,000
	3	779,000			
	4	1,056,000			

current version of Bridge PIARS as an aid and the importance of life-cycle costs in paint selection.

CONCLUSIONS

Bridge PIARS, as a demonstration prototype, shows the use of KBESs for solving engineering problems. The system shows sufficient potential that several enhancements are warranted. Improvements to the problem-solving approach include

- Determining the optimal painting system using optimization methods that incorporate budget constraints rather than using simulations,
- Accounting for the uncertainty and variability of the information provided by the user and the performance of coating systems, and
- Including the time-varying properties of paint reliability.

These features demonstrate the importance of an integrated approach to problem solving that permits users to include algorithmic approaches within a KBES. Other enhancements will be to the user interface and include refinements to qualitative questions about paint condition and the geometry of the bridge and the addition of an explanation facility and interfaces to a data base for historical information that is typically unavailable in the field.

To be completely robust, the system also requires some refinement of the deterioration relationships that are used to check condition, unit cost estimates, the use of multiple and alternative paint systems, and the ability to update cost information and alternative approaches for assessing paint condition.

Bridge PIARS has demonstrated the ability of KBESs to

- Provide friendlier user interfaces than have been common in algorithmic program solutions to similar problems,
- Integrate qualitative and quantitative information processing, and
- Present a more complete solution to a problem than is convenient in an algorithmic program environment.

The resultant system can assist in making decisions by consistently accounting for all the variables. However, the system is only as powerful as the knowledge base. The flexibility needed for the user to update the knowledge base and query the system is not included in the present problem-solving environment but may be an appropriate enhancement. However, the KBES approach to this problem allows the knowledge engineer to easily update the knowledge base to reflect new technologies in coatings, applications methods, and paint removal as well as changes in costs over time.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of Nina Ross in obtaining data, the comments and information provided by Jim Gould and Richard McGinn of the Massachusetts Department of Public Works, and the helpful and thorough comments of an unknown reviewer.

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