Using a Knowledge-Based Expert System and Fuzzy Logic for Minor Rehabilitation Projects in Ohio

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In the selection of a proper treatment for the rehabilitation of a deteriorated pavement section, engineers may encounter a situation in which factors besides distress conditions also contribute to the decision-making process. These factors are, among others, the expected structural integrity, functional adequacy, and performance life of a pavement section. In general, engineers make their selections based on their experience, judgment, and the use of past maintenance data, if available. For young engineers, such a selection process may lead to a poor decision. Even experienced engineers may still reach erroneous results. This study presents a methodology to overcome such problems by employing a knowledge-based expert system (KBES) and fuzzy logic. A KBES serves as a preliminary selection in which a set of alternative treatments is chosen based on pavement distress conditions and other related factors. An ordinal multiobjective decision-making model using fuzzy logic is then used to recommend the proper treatment. A computer program was written to implement such a methodology.

As required by the 1991 Intermodal Surface Transportation Efficient Act (ISTEA), the Ohio Department of Transportation (ODOT) developed a pavement management system, PMS III (*1*), to manage its highway at the network level. This system is currently being implemented. To enhance the PMS III, the development of a project-level PMS is essential. One of the objectives of the project level PMS would be to aid engineers in the selection of proper maintenance and rehabilitation (M&R) treatments. M&R treatments in Ohio are classified into three categories based upon pavement condition: major rehabilitation, minor rehabilitation, and maintenance. Pavement condition is assessed using a pavement condition rating method which provides an overall condition of a pavement section through a pavement condition rating (PCR) index (ranging from 0 to 100; the higher the number, the better the condition), and the structural condition through a structural deduct (STD) index (ranging from 0 to 65; the lower the number, the better the condition). Table 1 lists the conditions used to categorize M&R treatments (*2*).

Basically, this classification serves as an initial screen for the management of deteriorated pavement sections in a systematic fashion. Major rehabilitation projects range from structural overlay to reconstruction. On the other hand, minor rehabilitation and maintenance projects are used to restore or maintain the functionality and structural integrity of pavements. Thus, they range from crack and surface treatments to nonstructural overlay. This study focuses on the selection of proper treatments in minor rehabilitation projects. Because the selection process is usually based on experience and judgment of engineers, we propose a methodology that can be used to computerize such a process by employing a knowledge-based expert system (KBES) and fuzzy logic.

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MINOR REHABILITATION TREATMENT SELECTION STRATEGY

In general, a minor rehabilitation treatment is selected based on primary and secondary factors. Primary factors can be defined as those directly affecting the improvement in pavement performance, such as distress condition and traffic volume. On the other hand, the secondary factors are not directly affected but more concerned with the degree to which a treatment is able to rehabilitate a pavement, and such other factors as time or budget constraints. With this in mind, we propose that the selection strategy should consist of two steps: preliminary selection and final selection. The preliminary selection involves choosing treatments by considering only the primary factors. If more than one treatment is possible then a proper treatment is selected based on the secondary factors in the final selection step.

The selection process described above is a decision-making process in which the experience and judgment of engineers play an important part. Hence, to computerize such a process, two techniques that have been proven as efficient tools to simulate the human thinking process are employed: a KBES and fuzzy logic. The KBES is used in the preliminary selection phase. In the final selection phase, an ordinal multiobjective decision-making model using fuzzy logic proposed by Yager (*3*) is employed.

KBES FOR PRELIMINARY SELECTION

The first step in the selection of a minor rehabilitation treatment is to assess pavement distress conditions. In Ohio, distress conditions are measured in linguistic terms for their severity (as low, medium, or high) and extent (as occasional, frequent, or extensive). This assessment is performed following the guidelines provided in the *Pavement Condition Rating Manual* (*4*). This information together with other factors, such as traffic volume and/or the location of the pavement section, are then used as the basic criteria to select rehabilitation treatments. This selection process may look simple when performed by a human. On the other hand, to encode the knowledge and simulate the human thinking process in a computer is not an easy task. Recently, a KBES, which was developed from the field of artificial intelligence, has proven to be an efficient tool in performing such a task. A comprehensive survey of KBESs in transportation is summarized and discussed by Cohn and Harris (*5*).

TABLE 1 Classification of M&R Treatments (2)

M&R Treatment	PCR and STD
Major Rehabilitation	PCR < 50 **OR** STD > 25
Minor Rehabilitation	PCR > 50 **AND** STD < 25
Maintenance	PCR > 50 **OR** STD < 25

Basically, the development of a KBES involves five steps: problem identification, knowledge acquisition, knowledge representation, implementation, and validation and extension. The problem identification phase identifies what the problem is and ensures that a KBES is more suitable than a traditional computer program in solving it. The second phase is the acquisition of knowledge from experts. This is usually done by interviews. The knowledge gained is then represented using an appropriate knowledge representation scheme. The most common scheme is the production rule system, which is also used in our study. The implementation phase encodes the knowledge in the form of production rules into a computer program. Many software packages for developing a KBES are commercially available and thus make it less difficult to program. These software packages are known as expert system shells. Once a prototype is completed, it will be tested and the validation can begin. The validation is performed by both participating and independent experts. Modification or extension can also be done, if necessary.

Based on the knowledge gained from experts, we have classified rehabilitation treatments for flexible pavements into three main categories according to the type of the problem to be corrected: cracking, surface defect problems, and structural problems. These problems can be treated using crack treatment, surface treatment, and nonstructural overlay (one- and two-course overlay), respectively. The following rules exemplify general knowledge of the experts, more refined rules have been incorporated into the knowledge base of the system.

Rule 1:
IF (Longitudinal Joint Cracking Severity is *medium* OR Longitudinal Joint Cracking Severity is *high*)
AND (Longitudinal Joint Cracking Extent is *frequent* OR Longitudinal Joint Cracking Extent is *extensive*)
THEN Treatment is Crack Treatment

Rule 2:
IF (Bleeding Extent is *frequent* OR Bleeding Extent is *extensive*)
AND (location is *intersection* OR location is *curve*)
THEN Treatment is Surface Treatment

Rule 3:
IF (Potholes Severity is *medium* OR Potholes Severity is *high*)
AND (Potholes Extent is *frequent* R Potholes Extent is *extensive*)
THEN Treatment is Overlay

Rule 4:
IF Treatment is *Overlay*
AND Traffic volume is *medium*
AND (Wheel Track Cracking Severity is *high* OR Wheel Track Cracking Extent is *extensive*)
THEN Treatment is One-Course Overlay

Rule 5:
IF Treatment is *Overlay*
AND Traffic volume is *heavy*
AND (Potholes Severity is *high* OR Potholes Extent is *extensive*)
THEN Treatment is Two-Course Overlay

Rule 6:
IF Treatment is *Overlay*
AND (Traffic Volume is *medium* or Traffic Volume is *heavy*)
AND Structural Deduct value is greater than 15
THEN Treatment is Two-Course Overlay

To illustrate how the KBES reaches the conclusion, let us consider a flexible pavement section subjected to distress conditions described in Table 2.

In addition, suppose that the traffic volume on this pavement section is medium. In this case, using the *Pavement Condition Rating*

TABLE 2 Example of Flexible Pavement Condition

Distress	Severity	Extent
Longitudinal Joint Cracking	There is multiple cracking or wide single crack greater than 1/4 inch with some spalling.	More than fifty percent of the joint length has center line cracking.
Potholes	Average depth of potholes greater than six inches in diameter is between one to two inches.	Potholes occur along ten to fifty percent of the area.
Wheel Track Cracking	There is single or intermittent multiple cracking with average crack width less than 1/8 inch or barely noticeable.	More than fifty percent of the wheel track length is within the section which exhibits cracking.

Manual (*5*), an engineer would assess the severity and extent of longitudinal joint cracking as *medium* and *extensive*, that of potholes as *medium* and *frequent*, and that of wheel track cracking as *low* and *extensive*. When this information is sent to the KBES, Rules 1, 3, and 4 are fired (using forward chaining), resulting in selecting one-course overlay. If more than one type of one-course overlay are applicable, then the final selection is performed to recommend the proper treatment. In other words, the secondary factors are taken into account along with their relative importance.

ORDINAL MULTIOBJECTIVE DECISION-MAKING FOR FINAL SELECTION

In the decision-making process, decision makers (DMs) often encounter the situation where they must select only one alternative from a set of alternatives subjected to a set of criteria or objectives to be satisfied. This type of problem is known as multiobjective decision-making. There exist many mathematical models that can be used to attack such problems, for example, mathematical programming techniques, which offer an acceptable solution when the assessments are made in a numerical fashion. An example problem would be, how to select the members of a structure that must result in a minimum weight structure while, to a certain extent, also satisfying strength, stiffness, and stability criteria. The assessment of alternatives with respect to these criteria could be done by carrying out a structural analysis. However, in many cases, such as the case of pavement treatment selection, the assessment of alternatives must be made by a DM. The DM, an engineer in this case, has to choose a treatment from a set of alternatives subjected to some criteria, such as how well the treatment would satisfy the functional and structural adequacy of a pavement.

Because humans frequently make their assessments subjectively, it may not be suitable to attempt to obtain this subjective information in a more precise way. Bellman and Zadeh (*6*) introduced an approach to tackle such decision-making problems in a fuzzy environment. Since then the use of fuzzy sets in this type of problem has been developed and has gained more and more popularity. Recently, a methodology for ordinal multiobjective decision-making based on fuzzy sets was proposed by Yager (*3*). Because of its suitability to the problem being studied, it has been chosen as a decision-making tool in the selection of minor rehabilitation treatments.

Based on the Bellman-Zadeh approach, Yager (*3*) developed a methodology to solve a special type of multiobjective decision-making problem in which the preference information about alternatives, criteria, and the relative importance of each criterion can be measured on the same ordinal scale. To illustrate Yager's model, the following notations are used:

$\{S\}$ is the finite set of elements used to indicate the preference information.

$\{X\}$ is the set of alternatives.

$Y = \{A_1, A_2, \ldots, A_P\}$ is the set of objectives (criteria) to be satisfied.

$A_i(x) \in S$ indicates the degree to which x satisfies the criterion specified by A_i.

G is a fuzzy subset of Y in which $G(A_i) \in S$ indicates the importance of the objective A_i. For the sake of simplicity, let $G(A_i) = b_i$.

$D(x)$ is the decision function from which the best alternative is to be selected.

$\cup$ is the disjunction (OR) set operator (which is equivalent to $\vee$ or a Max operator when elements are considered).

$\cap$ is the conjunction (AND) set operator (which is equivalent to $\wedge$ or a Min operator when elements are considered).

Yager proposed a general form for this type of decision function which includes the relative importance of each criterion as

$$D(x) = M(A_1(x), b_1)\ AND\ M(A_2(x), b_2) \ldots AND\ M(A_p(x), b_p) \quad (1)$$

where $M(A_i(x), b_i)$ indicates the objective A_i evaluated at alternative x, modified by its importance b_i. Yager proposed to use the following implication operation to compute $M(A_i(x), b_i)$ if S is a finite linearly ordered set:

$$M(A_1(x), b_1) = b_i' \vee A_i(x) \quad (2)$$

where b_i' is the negation of b_i. In this model, because $b_i \in S$, which is the finite linearly ordered set, the negation is defined as follows:

Let $\{S\} = \{s_0, s_1, s_2, \ldots, s_n\}$ where $i > j$ implies $s_i > s_j$. Then

$$s_i' = s_{n-i} \quad (3)$$

Hence, the decision set is

$$D = (b_1' \cup A_1) \cap (b_2' \cup A_2) \cap \ldots \cap (b_p' \cup A_p)$$
$$D = \bigcap_{i=1}^{p} (b_i' \cup A_i) = \bigcap_{i=1}^{p} C_i = C_1 \cap C_2 \cap C_3 \cap \ldots \cap C_p \quad (4)$$

where

$$C_i(x) = b_i' \vee A_i(x) \quad (5)$$

and

$$D(x) = \text{Min}\,[C_1(x), C_2(x), \ldots, C_p(x)] = \text{Min}_i\,[C_i(x)] \quad (6)$$

Hence, the best alternative is the $x \in X$ that maximizes D, that is,

$$D(x^*) = \text{Max}_{x \in X}\ D(x) \quad (7)$$

In the application to pavement problems, suppose that after the preliminary selection, the KBES suggests three possible alternative treatments that an engineer can select to rehabilitate a pavement section. An example would be three different types of one-course overlay that differ in material types and/or thickness. In order to select the best alternative, the engineer uses the following additional criteria: functional adequacy, structural adequacy, and expected performance life. In addition, the relative importance of each criterion can also be specified to satisfy his/her requirements. The preference information set, S, can be defined as

$S = \{\text{high, medium, low}\}$.

Note that Yager's model does not require membership functions for elements in the preference information set because the preference information set must be a finite linearly ordered set. The alternative set, X, is

$X = \{\text{Treatment 1, Treatment 2, Treatment 3}\}$.

The set of criteria, Y, is

$Y = \{\text{functional adequacy, structural adequacy, expected performance life}\}$.

TABLE 3 Degree of Satisfaction of Each Criterion

Treatment x	Functional Adequacy $A_1(x)$	Structural Adequacy $A_2(x)$	Expected Performance Life $A_3(x)$
1	*high*	*low*	*high*
2	*medium*	*medium*	*high*
3	*low*	*high*	*medium*

The degree of satisfaction of each criterion, $A_i(x)$, is indicated in Table 3. Note that $A_i(x)$ must be assigned using the grades from the preference information set, S. In addition, the degree of satisfaction of each treatment subjected to each criterion must be rated relatively to other treatments and no correlation is considered among the criteria. For example, the degree to which Treatment 1 satisfies structural adequacy, $A_1(x)$, is low implies that it is low in comparison with medium and high of Treatment 2 and Treatment 3, respectively. However, low structural adequacy does not indicate that the functional adequacy of Treatment 1 must be rated in the same sense as structural adequacy. In fact, it must be rated relative to other treatments.

The relative importance of each criterion, b_i, is

b_i = {high, medium, medium}

Using Equation 3, the negation of b_i is obtained as

b_i' = {low, medium, medium}

Equation 5 yields the following:

C_1 = low $\vee$ {high, medium, low} = {high, medium, low}
C_2 = medium $\vee$ {low, medium, high} = {medium, medium, high}
C_3 = medium $\vee$ {high, high, medium} = {high, high, medium}

Hence, the decision function, D, is obtained by using Equation 6.

D (Treatment 1) = Min {high,medium, high} = medium
D (Treatment 2) = Min {medium, medium, high} = medium
D (Treatment 3) = Min {low, high, medium} = low
D = {medium, medium, low}

The final solution is therefore obtained from Equation 7. In this case, we have a tie, that is, Treatment 1 and Treatment 2. In the case of a tie, the engineer has three options: select one treatment from the alternatives that have tied, refine the scale, or use the following procedure, which was proposed by Yager (*3*) as well.

If there are two alternatives, x and y, which yield the same decision, then $D(x) = D(y) = \operatorname{Max}_{x \in X} D(z)$. Because $D(x) = \operatorname{Min}_i [C_i(x)]$, there exists some k such that $C_k(x) = D(x)$. Similarly, there exists some g such that $C_g(y) = D(y)$. Let $D'(x) = \operatorname{Min}_i [C_i(x)]$, $i \neq k$ and $D'(y) = \operatorname{Min}_i [C_i(y)]$, $i \neq g$. If $D'(x) > D'(y)$ then x can be selected as the solution. In the case that we have additional ties $D'(x) = D'(y)$, then the preceding procedure can be repeated until the solution is found or all the criteria are exhausted. In the latter case, the final decision will have to be made by the engineer. In sum, the alternatives that generate the same decision are progressively eliminated from the decision set until a solution (a distinct alternative) is found.

In the above example, we have

D' (Treatment 1) = Min {high, ~~medium~~,high} = high
D' (Treatment 2) = Min {~~medium~~, medium, high} = medium
D = {high, medium}

Therefore, the final solution is Treatment 1.

COMPUTER PROGRAM

A computer program was written to implement the proposed methodology. Figure 1 shows the structure of the program which consists of four main modules: the Input Module, the Knowledge-based Module, the Multiobjective Decision-making Module, and the Output Module. The function of the Input Module is to obtain all the data needed for the Knowledge-based Module. Once the data

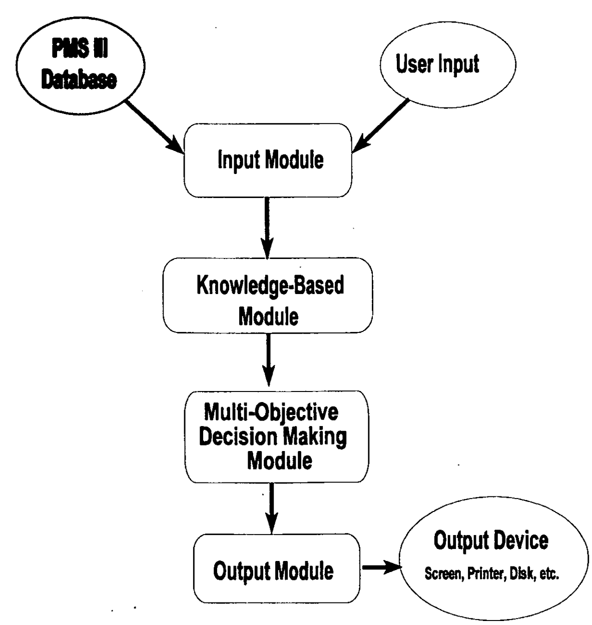

FIGURE 1 Structure of the program.

is obtained, the Knowledge-based Module proceeds with the selection of possible treatments. If there is more than one possible treatment, then the Multiobjective Decision-making Module is invoked to select and recommend the proper treatment. The solution is then reported to the user using the Output Module. Note that the Input Module also retrieves the past maintenance data from the PMS III maintenance database, which is a collection of rehabilitation project data in Ohio since 1985. The data consists of all the project records that have the same location as the new project and are presented in both graphical and text forms.

The program has been implemented using several software packages. Microsoft Visual Basic (VB) Version 3.0 (*7*) was used for the Input, Multiobjective Decision Making, and Output Modules, and Knowledge Pro Gold for Windows (KPWIN) Version 2.35 (*8*) was used for the Knowledge-based Module.

Figures 2 through 6 illustrate the above modules.

CONCLUSION

The methodology proposed in this study can be used to model the minor rehabilitation treatment selection process in Ohio. The KBES encodes the knowledge of experts at ODOT and serves as the preliminary selection tool in which a treatment or a set of alternatives are to be chosen. The ordinal multiobjective decision-making model using fuzzy logic can then be used to recommend a proper treatment by considering secondary factors along with their relative importance. Initial evaluation by the knowledge engineers and experts at ODOT indicates its feasibility and potential for use by ODOT maintenance engineers. More will be reported as the research progresses.

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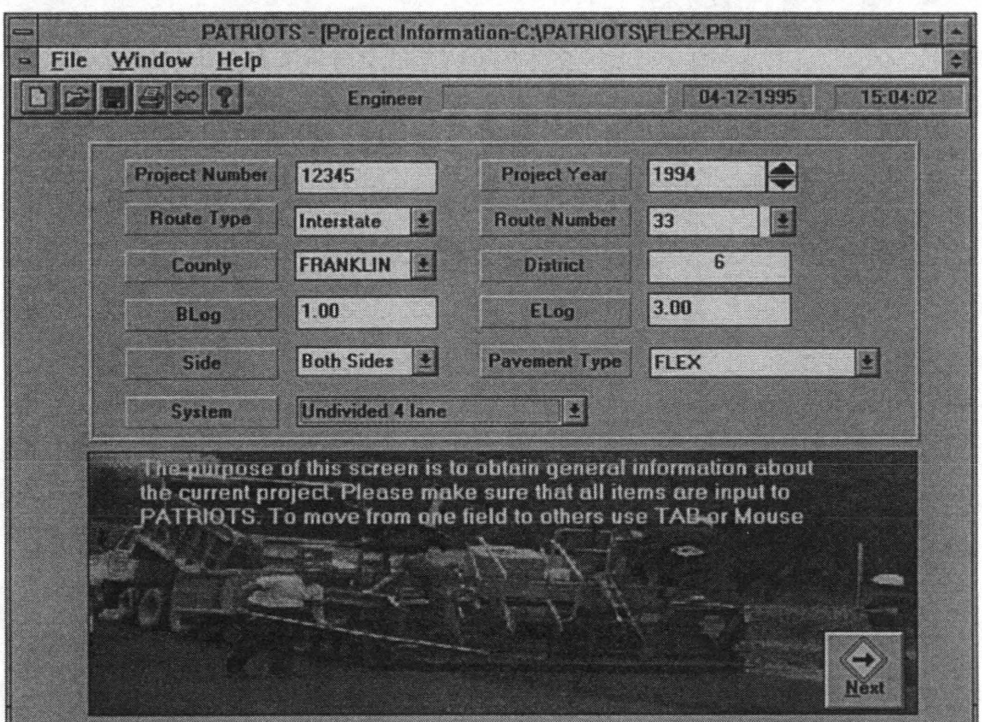
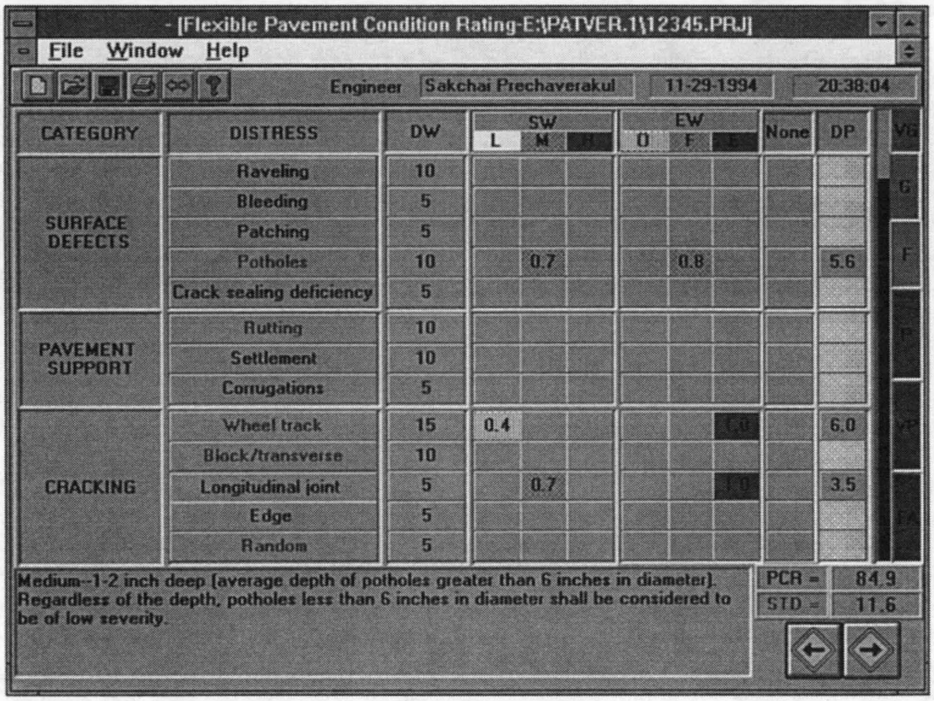


Note

Blog: Beginning Log
Elog: Ending Log

FIGURE 2 Project information (input module). Note: Blog, beginning log; Elog, ending log.



Note

DW:	Distress Weight	SW:	Severity Weight
EW:	Extent Weight	DP:	Deduction Point
VG:	Very Good	G:	Good
F:	Fair	P:	Poor
VP:	Very Poor	FA:	Fail
PCR:	Pavement Condition Rating		
STD:	Structural Deduct		

FIGURE 3 Pavement condition (input module). Note: DW, distress weight; SW, severity weight; EW, extent weight; DP, deduction point; VG, very good; G, good; F, fair; P, poor; VP, very poor; FA, fail; PCR, pavement condition rating; STD, structural defect.

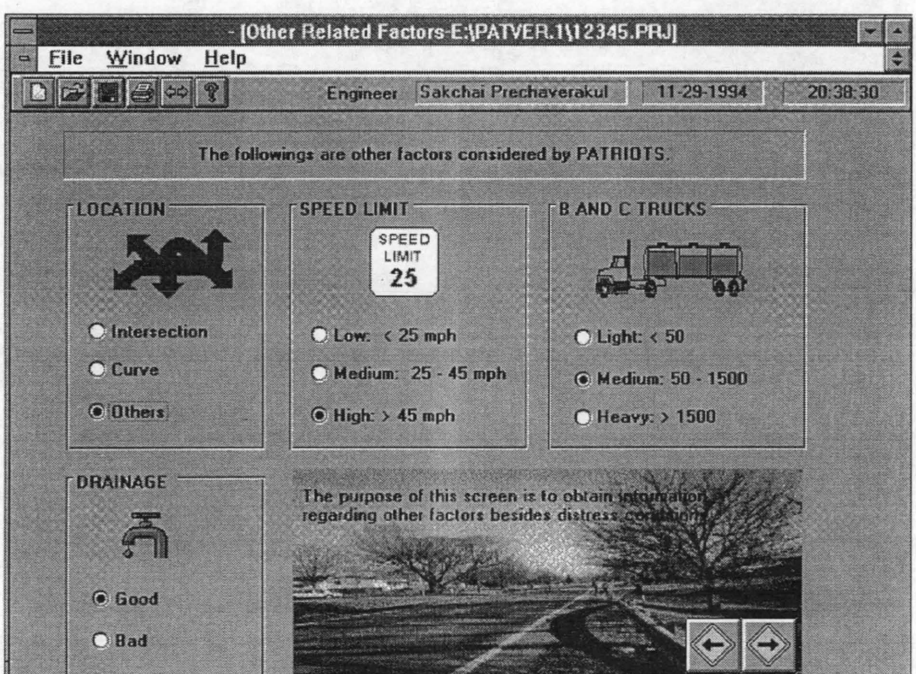


FIGURE 4 Other related factors (input module).

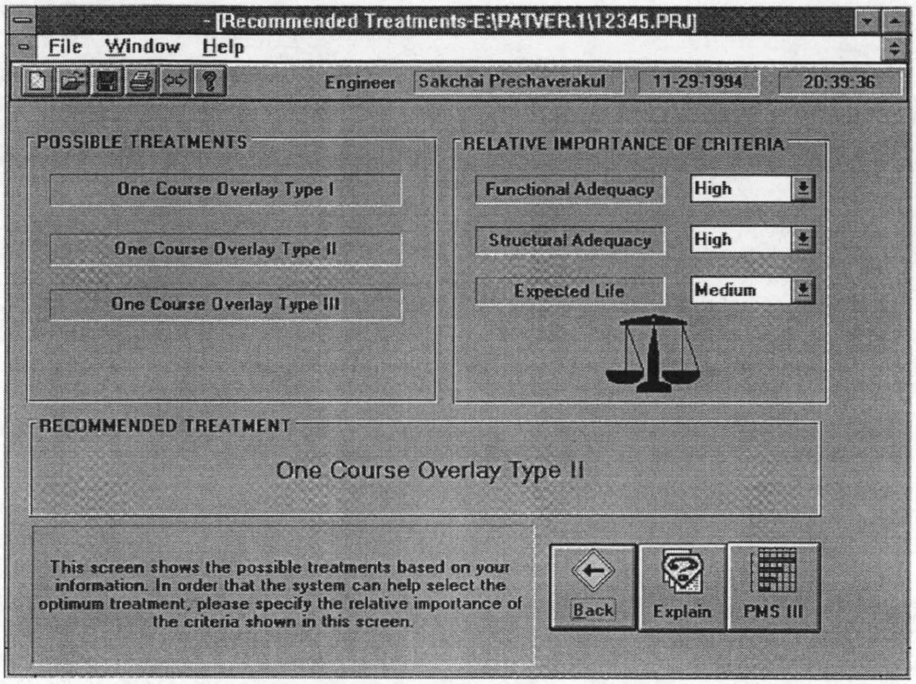


FIGURE 5 Multiobjective decision-making module.

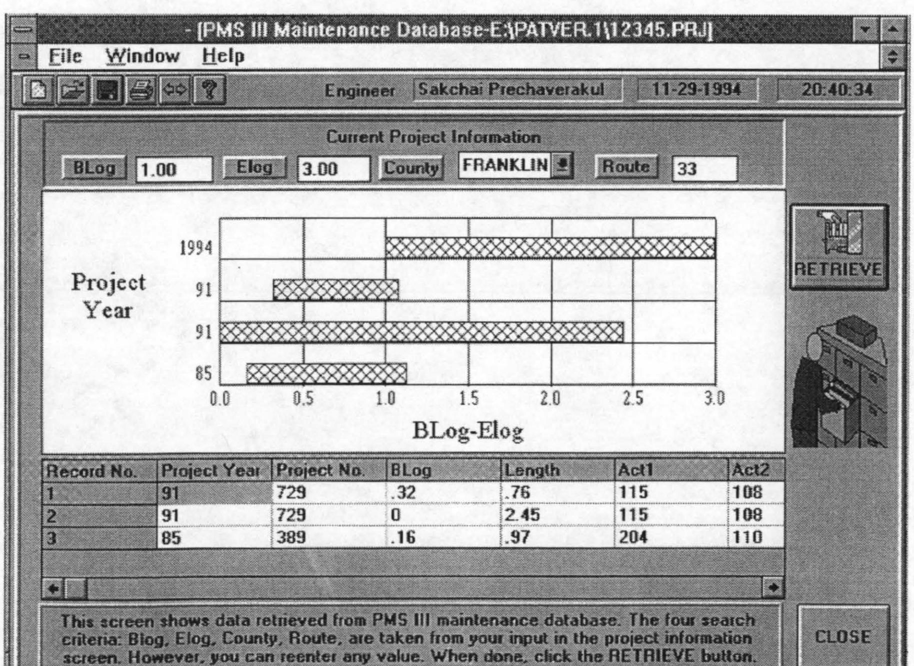


FIGURE 6 PMS III maintenance database.

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