# Chapter 7

# Development of decision-support approaches for pavement prioritization and maintenance projects

## 7.1. Introduction

Once the condition evaluation of pavements has been performed successfully, either destructively or non-destructively, the next major step is the implementation of appropriate Maintenance and Rehabilitation (M&R) alternatives according to their assessed condition. Preventive maintenance is also imperative during routine inspections of pavements. However, before undertaking the M&R activities in field, generally a two-fold decision-making that consists of important sequential decisions is required. In the first step, prioritization and ranking of pavement sections to receive M&R is necessary by considering the future preservation needs. This is primarily due to budgetary constraints with the funding agencies. Therefore, it becomes challenging for the authorities to justify the necessity of M&R without any objective and rational approach, and procure funding. Secondly, deciding the type(s) of M&R treatment to be implemented on the pavement sections selected from the first step using site-specific engineering considerations. The second step does not pose much problem, whereas the first step is much more critical, and requires a judicious process as a tool for fund allocation because of multiple and conflicting attributes. Multi-Criteria Decision-Making (MCDM) techniques facilitate complex decision-making by evaluating the trade-off between several quantitative and qualitative attributes, and discussed in this chapter.

Prioritization of pavements can be performed based on a single indicator, such as pavement condition index, or a composite indicator combining several individual attributes. Inclusion of a number of performance indicators, and assessing their integrated impact on pavement condition to eventually prioritize pavement sections present a more holistic way rather than completely relying on a single characteristic. Therefore, this study uses different performance indicators to appraise the effect of structural health of pavements, their functional performance, and also the strength of subgrade soil. Nevertheless, it is not easy to inculcate multiple factors together. The studies compiled in this chapter present a few approaches to undertake this task. These approaches are demonstrated using the case study discussed in the previous chapter. Various indicators used in different approaches have been included such as surface deflection, structural index, subgrade modulus, Pavement Condition Index (PCI), and pavement thickness. The parameter deflection used in the present study is the maximum deflection value, measured directly beneath the falling load, being one of the most important parameter reflecting the structural capacity of any pavement. Structural index represents the impact of aircraft or traffic mix on the pavement as well as the competency of pavement to support the aircraft. It is one of the most relevant factor from the runway pavement point of view. The subgrade soil condition also deeply influences the pavement condition and its effect may be represented by subgrade modulus. PCI is a representative of functional performance and estimated visually by distress density, and its distribution. Lastly, pavement thickness, which is designed as per the anticipated traffic, also greatly relates to a pavement's structural capacity. However, not all the parameters have been used in each approach of pavement prioritization. These performance attributes are not solely based on qualitative assessments, and have been quantified, by physical means, by taking utmost care to obtain their precise estimates. The data for these attributes has been collected under non-destructive mode on airfield pavements, and already discussed in detail under Chapter 6.

Decision-making processes greatly depend on human judgement. Prevalence of subjective decision-making practices and lack of a systematic and logical approach while making M&R decisions pertaining to pavements has been one of the most influencing factors to undertake this study. Many times due to variation in field conditions, the testing devices may deliver inconsistent data. Also, due to multiple field experts involved in the process of M&R of pavements, each one of them may perceive, and report the condition differently which may be ambiguous to the decision-maker. Therefore, a lot of vagueness, subjectivity, and uncertainty is involved in these processes. MCDM and its fuzzy-logic based techniques have been widely used to mitigate these variations in human judgements for problems related to various areas, and offer an unbiased solution to the decision problem. Additionally, various challenges and prospects are faced by pavement monitoring and maintenance projects. These can be classified into internal factors (strength and weakness), and external factors (opportunities and threats), and need to be addressed.

This chapter illustrates a number of soft-computing techniques from MCDM to fetch a judicious process for prioritization of pavement sections, and warrant funding for their M&R. The chapter also presents the formulation of Strength-Weakness-Opportunity-Threat (SWOT) model and its hybrid mechanisms to identify the major problems faced in the pavement maintenance projects and present promising alternative policies for pavement M&R.

## 7.2. Analytic hierarchy process

Analytic Hierarchy Process (AHP), first introduced by Thomas L. Saaty follows the perspective of MCDM (Saaty, 1980). It presents the decision problem in the form of hierarchy and assigns suitable weights to each of its element. Systematic and quantitative comparison of the relative importance of the criteria and alternatives is performed. It is based on the principle that knowledge and judgement of individuals are valuable while making a decision. Thus, decision-makers are involved, and they are asked to judge the relative importance of each criterion and rate the preference using a scale called Saaty's scale, from 1 to 9 to eventually rank the alternatives (Saaty, 1990). To rank the various pavement sections, Expert Choice (version 11.1.3840) decision-making software has been used. This software is widely used to resolve various real-world decision problems by making use of expert judgements, structuring the problem, measuring the importance of objectives and alternatives, conducting what-if and sensitivity analyses.

The application of AHP technique was demonstrated using the case study of runway, over which field evaluation using NDT technologies was performed, as discussed in Chapter 6. The prerequisite for prioritization involved suitably dividing the runway pavement into a number of sections. For this purpose, the 3.05 km long runway was divided into six sections of 500 m each that served as alternatives (A1, A2,…, A6). The division was done from homogeneity, and ease of data collection point of view. Homogeneity of the sections were ensured from visual surveys. Moreover, since any of the repair or maintenance strategies could be successfully implemented section-wise or area-wise and not point-wise, therefore it was found better to divide the pavement sequentially. The division on the basis of thickness or deflection values would unnecessarily make the entire process of data collection very complex, and hence it was avoided.

Selection of performance indicators or governing criteria for pavement health, concerned with airfield pavements was identified as the next task. Comprehensive field investigations, as described in Chapter 6, facilitated the choice of these indicators, namely, deflection, structural index, subgrade modulus, and PCI, for this study.

### 7.2.1. Illustration of AHP approach

After successfully choosing the decision variables, the four-step procedure of AHP was adopted to prioritize pavements, as presented below:

*Step-1: Structure the problem into a hierarchy*

The six pavement sections of the runway, i.e., alternatives (A1, A2,…, A6) are to be ranked on the basis of four performance criteria, namely, deflection, structural index, subgrade modulus, and PCI. Figure 7.1 shows the hierarchy for this decision problem.

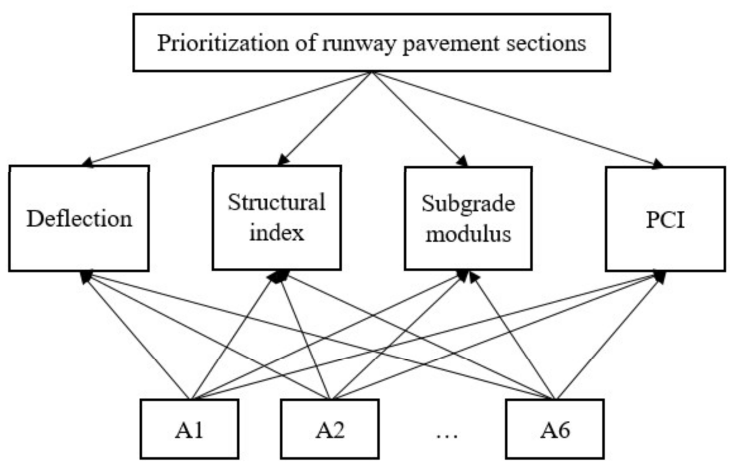



**Figure 7.1. Hierarchy tree for objectives, criteria and decision alternatives to the decision problem**

*Step 2: Generation of pairwise comparison matrices*

To assess the contribution of each criterion, suitable weights need to be allocated which is achieved by making pairwise comparisons among the various alternatives. For comparison purposes, Saaty's ranking scale has been used as shown in Table 7.1. Responses from ten field experts have been considered for making pairwise comparisons, and the pairwise comparison matrices are generated.

**Table 7.1. Saaty's 9-point scale**

| Scale | Definition |
|---|---|
| 1 | Equal importance |
| 2 | Weak |
| 3 | Moderate importance |
| 4 | Moderate plus |
| 5 | Strong importance |
| 6 | Strong plus |
| 7 | Very strong or demonstrated importance |
| 8 | Very, very strong |
| 9 | Extreme importance |

*Stage 3: Estimation of weights*

The matrices obtained from the judgement of decision-makers were then analyzed using Expert Choice software (version 11.1.3840), to obtain criteria and alternatives weights. Tables 7.2 and 7.3 present the obtained weights for criteria and alternatives, respectively. Deflection is allotted the maximum weight, followed by PCI, subgrade modulus and structural index. This is in accordance with the fact that deflections are a true representation of pavement's structural strength and high surface deflections indicate the weak structural strength of pavements. Moreover, low values of PCI are a strong indicator of deteriorated pavements. The inconsistency in judgement is 0.06, which is less than the prescribed limit of 10% (Ramanathan, 2001).

*Step 4: Estimation of the overall ranking of pavement sections*

The weights derived for pavement sections helped to rank them in order of their condition. From Table 7.3, the lowest rank and weight of pavement section A6 infers that this section is in the worst condition and heavily deteriorated. Hence, it requires immediate maintenance or repair, and accordingly, funds should be allocated. Section A1 of runway is in the best condition, among the other sections, and therefore application of any sort of M&R may be applied on this section at later stages. All other intermediatary sections may be improved according to their ranking.

**Table 7.2. Weights of decision criteria obtained using AHP**

| Criterion | AHP weights |
|---|---|
| Deflection | 0.547 |
| Structural index | 0.058 |
| Subgrade modulus | 0.110 |
| PCI | 0.285 |

**Table 7.3. Weights and ranking of alternatives obtained using AHP**

| Pavement section | AHP weights | Ranking |
|---|---|---|
| A1 | 0.230 | 1 |
| A2 | 0.142 | 4 |
| A3 | 0.206 | 2 |
| A4 | 0.134 | 5 |
| A5 | 0.166 | 3 |
| A6 | 0.122 | 6 |

AHP is a popular method due to its simplicity, ease of use, scalable and its flexible hierarchal structure to adapt as per decision-makers. However, it suffers from inefficiency in considering vagueness and subjectivity in judgements, since it allocates crisp values of weights, and pair-wise comparisons may induce inconsistency in assessment.

## 7.3. Fuzzy inference system

Fuzzy logic reasoning effectively handles the uncertainty, and ambiguity associated with subjective opinions of decision-makers, and ensure objectivity in judgements. In this study, one of the widely used Fuzzy Inference System (FIS) known as Mamdani method is applied for the decision problem of prioritizing pavement sections using MATLAB tool (version 9.2.0.556344 (R2017a)).

Mamdani fuzzy inference is based on formulating a set of linguistic rules using human expert knowledge. Each rule has its output in the form of a fuzzy set. Outputs from each rule are combined to form a single fuzzy set using aggregation method. The final crisp output is obtained by adopting one of the defuzzification methods. The three basic steps involved in this method are:

(i) Fuzzification of the input variables

(ii) Setting up inference rules

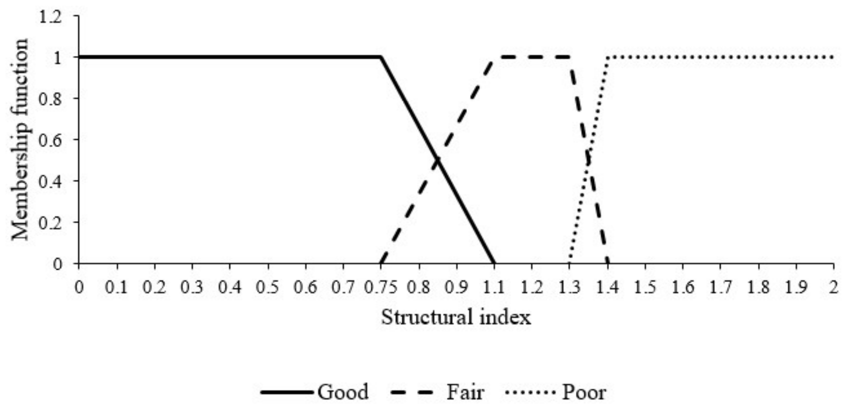
(iii) Defuzzification

In the process of fuzzification, the crisp data inputs are transformed into fuzzy numbers by using membership functions. The inference rules comprise IF-THEN statements based on the opinion of experts. The IF-THEN rules have the general form as IF $\mu_{ant}$ THEN $\mu_{result}$, where $\mu_{ant}$ and $\mu_{result}$ are the fuzzy values of rule antecedent and result or conclusion part, respectively. The antecedent may be comprised of other fuzzy entities clubbed together by the AND or OR logical operators. Defuzzification process decodes the fuzzy outputs into final crisp values. The decision criteria considered in this approach included deflection, structural index, subgrade modulus and PCI to prioritize six pavement sections (A1 to A6) of the runway.

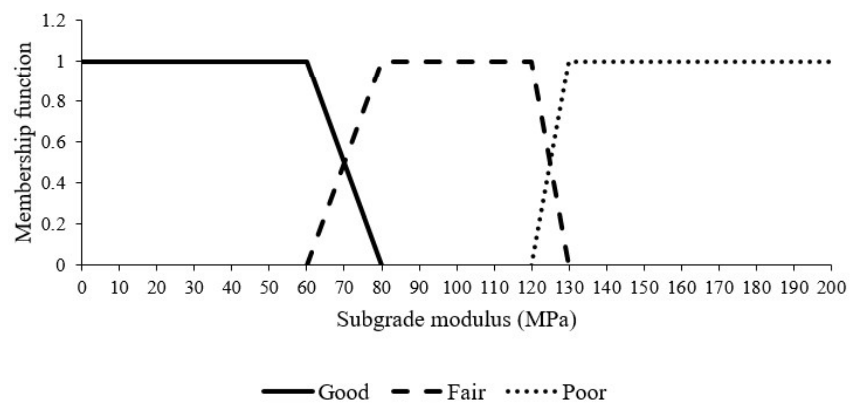
### 7.3.1. Illustration of FIS approach

The FIS in this study, consists of crisp input values in criterion set as U = {deflection, structural index, subgrade modulus and PCI}. The membership functions can be derived to express various qualitative terms using triangular trapezoidal, Gaussian fuzzy membership functions (Singh & Dubey, 2012). Trapezoidal fuzzy membership functions have been reported to be the most suitable for representing the ratings of pavement performance indicators, and thus, they have been adopted in this study (Singh et al., 2018; Zimmermann, 2011). The input parameters were linguistically expressed by three terms, viz., good, fair and poor, by setting their ranges according to the perception of decision-makers. For sound pavements, deflection, and structural index have lower values, whereas for subgrade modulus and PCI have higher values. The membership grades for input and output variables as defined in FIS of MATLAB are shown in Figures 7.2 and 7.3. These are suitably used to convert variables in the interval [0, 1]. In each figure, the horizontal axis represents different criterion, whereas the vertical axis represents membership grades in the interval [0, 1]. The FIS output is the condition of pavement, further classified as poor, fair or good.

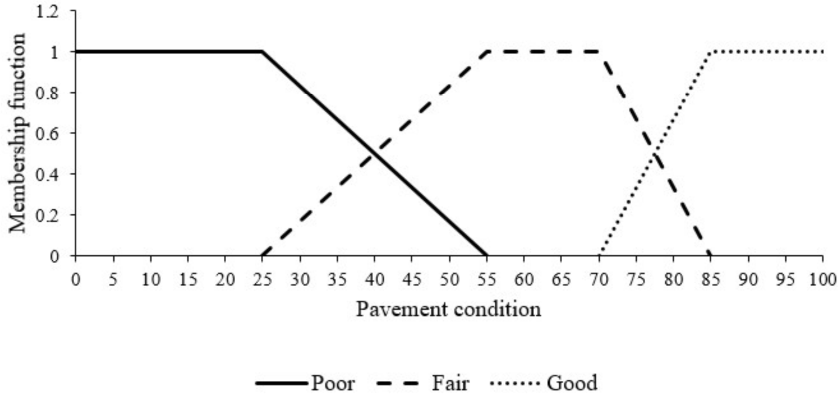

**(a) Membership functions of deflection**




**(b) Membership functions of structural index**




**(c) Membership functions of subgrade modulus**




**(d) Membership functions of PCI**

**Figure 7.2. Membership functions of input parameters**

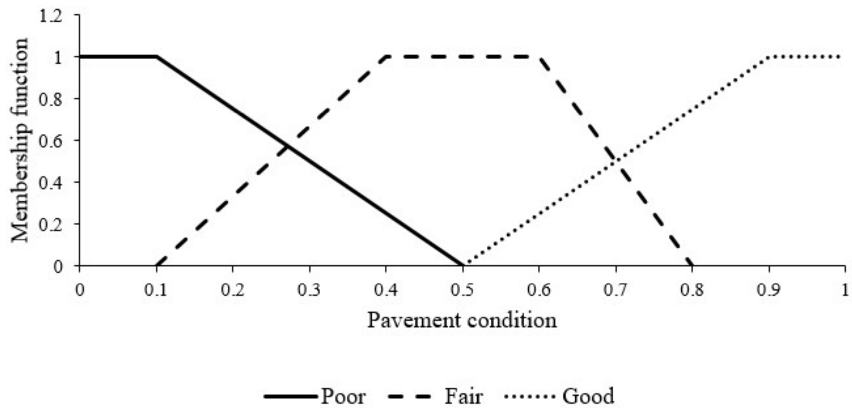



**Figure 7.3. Membership functions of output parameter (pavement condition)**

Various IF-THEN rules were defined and to obtain a single value for evaluation, the IF, and THEN parts are connected with a 'AND' fuzzy operator. The input values were then operated according to these rules to obtain a fuzzy output. Ten decision experts were consulted to form these rules, and they were framed using the fuzzy logic toolbox of MATLAB. A sample of important rules from the entire set, concerning this study are shown in Table 7.4.

**Table 7.4. Fuzzy inference rules setup in FIS framework**

| | | | Inputs | | Output |
|---|---|---|---|---|---|
| **Operators →** | **IF** | **AND** | **AND** | **AND** | **THEN** |
| **Criteria →** | **Deflection** | **Structural index** | **Subgrade modulus** | **PCI** | **Result** |
| Rule 1 | Good | Fair | Fair | Good | Good |
| Rule 2 | Good | Poor | Poor | Good | Fair |
| Rule 3 | Fair | Poor | Poor | Poor | Poor |
| Rule 4 | Poor | Fair | Good | Poor | Poor |
| Rule 5 | Fair | Good | Fair | Good | Fair |

Finally, the aggregated input values were evaluated based on the set of fuzzy inference rules to get the final measure of pavement condition for every section of the runway. Defuzzification of output fuzzy sets were performed using centroid method in which the crisp value is obtained as the center of gravity of the fuzzy set along the x-axis. The final scores obtained by FIS framework of MATLAB for all the six pavement sections evaluated on the basis of four decision criteria are presented in Table 7.5.

**Table 7.5. Output score of pavement sections using FIS framework**

| Pavement section | FIS Score | Normalized score | Ranking |
|---|---|---|---|
| A1 | 0.500 | 0.239 | 1 |
| A2 | 0.384 | 0.184 | 3 |
| A3 | 0.354 | 0.169 | 4 |
| A4 | 0.486 | 0.233 | 2 |
| A5 | 0.171 | 0.082 | 6 |
| A6 | 0.194 | 0.093 | 5 |

The lowest score and rank of section A5, followed by section A6 indicates that the poor pavement condition of these sections demand immediate attention for repair and maintenance. Section A1 has the highest score and therefore was concluded to be in the best condition among all the sections. Based on the availability of budget, the treatment must start with sections A5 and A6. Other sections may be repaired or rehabilitated in accordance with the scores, and budget availability. The ranking obtained using FIS is found to slightly vary from that obtained using AHP, and is more reliable. The reason for this could be contributed to the use of fuzzy numbers in FIS instead of crisp values in AHP.

## 7.4. Buckley's fuzzy analytic hierarchy process

Fuzzy Analytic Hierarchy Process (FAHP) combines the advantages of both AHP as well as fuzzy theory. It allows the pairwise comparisons to be made in terms of fuzzy numbers, and hence, reduces uncertainty in judgements. Buckley's approach of FAHP has been adopted for pavement prioritization which makes use of fuzzy ratio. While comparing two alternatives, it is sometimes difficult for the decision-makers to always assign exact ratio. Introduction of fuzzy ratio in place of exact ratio while making a pairwise comparison between the alternatives and criteria, automatically addresses the vagueness involved in such decisions (Buckley, 1985). The method uses trapezoidal fuzzy numbers and the process starts with the development of pairwise comparison matrices consisting of fuzzy ratio. These fuzzy judgement matrices are collected from all the decision-makers and are aggregated using the fuzzy geometric mean method for each row, defined by Buckley as given in Eq. (7.1) (Buckley, 1985).

$$\widetilde{m_i} = \left[\prod_{j=1}^{n} \widetilde{m_{ij}}\right]^{\frac{1}{n}}, \text{for all } i \qquad (7.1)$$

where $\widetilde{m_i}$ is the relative importance in the form of a trapezoidal fuzzy number whose elements are ($p, q, r, s$). The fuzzy weights ($w_i$) are then computed as defined by Eq. (7.2).

$$w_i = \widetilde{m}_i \otimes \left[\sum_{i=1}^{n} \widetilde{m}_j\right]^{-1} \qquad (7.2)$$

In the last step, the fuzzy performance scores and fuzzy weights are aggregated to derive corresponding fuzzy utility functions. The steps are more clearly explained using the case study in the subsequent paragraphs.

### 7.4.1. Illustration of Buckley's FAHP

The problem as stated earlier, requires the six pavement sections (A1 to A6) to be prioritized based on the four attributes (deflection, structural index, subgrade modulus, and PCI). Application of Buckley's FAHP method requires making pairwise comparisons between the criteria and alternatives using fuzzy ratio. As an example, the relative importance of alternatives (A1 to A6) for first decision criterion i.e., deflection, obtained from the experts' opinion is shown in Table 7.6.

**Table 7.6. Pairwise comparison of pavement sections for deflection**

| | A1 | A2 | A3 | A4 | A5 | A6 |
|---|---|---|---|---|---|---|
| **A1** | (1,1,1,1) | (3,4,4,5) | (2,2,4,4) | (3,4,4,5) | (7,8,8,9) | (9,9,9,9) |
| **A2** | (1/5,1/4,1/4,1/3) | (1,1,1,1) | (1/4,1/4,1/2,1/2) | (1/4,1/4,1/2,1/2) | (6,6,8,8) | (7,8,8,9) |
| **A3** | (1/4,1/4,1/2,1/2) | (2,2,4,4) | (1,1,1,1) | (2,2,4,4) | (7,8,8,9) | (8,8,9,9) |
| **A4** | (1/5,1/4,1/4,1/3) | (2,2,4,4) | (1/4,1/4,1/2,1/2) | (1,1,1,1) | (6,6,8,8) | (7,8,8,9) |
| **A5** | (1/9,1/8,1/8,1/7) | (1/8,1/8,1/6,1/6) | (1/9,1/8,1/8,1/7) | (1/8,1/8,1/6,1/6) | (1,1,1,1) | (3,4,4,5) |
| **A6** | (1/9,1/9,1/9,1/9) | (1/9,1/8,1/8,1/7) | (1/9,1/9,1/8,1/8) | (1/9,1/8,1/8,1/7) | (1/5,1/4,1/4,1/3) | (1,1,1,1) |

In the similar manner, the pairwise comparison matrices for all the criteria and alternatives were formed. In the next step, the geometric mean computations were performed, and are summarized in Table 7.7, for the first decision criterion namely deflection.

**Table 7.7. Computations of the geometric mean**

| **Alternatives →** | **A1** | **A2** | **A3** | **A4** | **A5** | **A6** | **Row sum** |
|---|---|---|---|---|---|---|---|
| $p_i$ | 3.2293 | 0.8982 | 1.9560 | 1.2702 | 0.2887 | 0.1767 | 7.8190 |
| $q_i$ | 3.6342 | 0.9532 | 2.0000 | 1.3480 | 0.3150 | 0.1908 | 8.4412 |
| $r_i$ | 4.0793 | 1.2599 | 2.8845 | 1.7818 | 0.3467 | 0.1946 | 10.5468 |
| $s_i$ | 4.4814 | 1.3480 | 2.9417 | 1.9064 | 0.3762 | 0.2134 | 11.2671 |

Let the row summations (7.8190, 8.4412, 10.5468, 11.2671) = (P, Q, R, S)

Then the performance scores $S_{j1}$, j = 1, 2, 3, 4, 5, and 6 are computed as:

$$S_{11} = \left(\frac{p_1}{S}, \frac{q_1}{R}, \frac{r_1}{Q}, \frac{s_1}{P}\right) = (0.2886, 0.3446, 0.4833, 0.5731)$$

Table 7.8 shows the performance scores obtained for six pavement sections for criterion deflection.

**Table 7.8. Performance scores of the pavement sections for deflection**

| | $S_{11}$ | $S_{21}$ | $S_{31}$ | $S_{41}$ | $S_{51}$ | $S_{61}$ |
|---|---|---|---|---|---|---|
| $p_i$ | 0.2866 | 0.0797 | 0.1736 | 0.1127 | 0.0256 | 0.0157 |
| $q_i$ | 0.3446 | 0.0904 | 0.1896 | 0.1278 | 0.0299 | 0.0181 |
| $r_i$ | 0.4833 | 0.1493 | 0.3417 | 0.2111 | 0.0411 | 0.0230 |
| $s_i$ | 0.5731 | 0.1724 | 0.3762 | 0.2438 | 0.0481 | 0.0273 |

Similarly, the fuzzy weights of the four decision criteria ($w_1, w_2, w_3, w_4$) are obtained and presented in Table 7.9.

**Table 7.9. Fuzzy weights of the decision criteria**

| | $p_i$ | $q_i$ | $r_i$ | $s_i$ |
|---|---|---|---|---|
| $w_1$ | 0.4365 | 0.5428 | 0.6336 | 0.7783 |
| $w_2$ | 0.0346 | 0.0421 | 0.0491 | 0.0618 |
| $w_3$ | 0.0733 | 0.0905 | 0.1088 | 0.1345 |
| $w_4$ | 0.2004 | 0.2452 | 0.2948 | 0.3680 |

The fuzzy utility functions ($F_j$) are calculated by combining fuzzy weights and fuzzy performance scores as given by Eq. (7.3).

$$F_1 = w_1 * S_{11} = \{(\alpha_1 * \alpha_2)\,[X_1, X_2], (\beta_1 * \beta_2), (\gamma_1 * \gamma_2), (\delta_1 * \delta_2)\,[Y_1, Y_2]\} \quad (7.3)$$

where, $S_{11} = (\alpha_1, \beta_1, \gamma_1, \delta_1)$;

$w_1 = (\alpha_2, \beta_2, \gamma_2, \delta_2)$;

$X_1 = (\beta_1 - \alpha_1) * (\beta_2 - \alpha_2)$;

$X_2 = \alpha_2 * (\beta_1 - \alpha_1) + \alpha_1 * (\beta_2 - \alpha_2)$;

$Y_1 = (\delta_1 - \gamma_1) * (\delta_2 - \gamma_2)$;

$Y_2 = -[\delta_2 * (\delta_1 - \gamma_1) + \delta_1 * (\delta_2 - \gamma_2)]$

Thus, the fuzzy utility functions for the first pavement section (A1) are listed in Table 7.10. The interpretation of the entities of $w_1 S_{11}$ is summarized in Table 7.11.

**Table 7.10. Fuzzy utility functions for pavement section A1**

| j | $w_jS_{1j}$ |
|---|---|
| $w_1S_{11}$ | {0.1251 [0.0062,0.0558], 0.1870, 0.3062, 0.4461 [0.0130, -0.1529]} |
| $w_2S_{12}$ | {0.00628 [0.00023,0.00241], 0.00891, 0.01655, 0.02419 [0.00069, -0.00833]} |
| $w_3S_{13}$ | {0.01113 [0.00017,0.00334], 0.01465, 0.02874, 0.03797 [0.00046,-0.00970]} |
| $w_4S_{14}$ | {0.06902 [0.00103,0.02006], 0.09011, 0.15987, 0.21319 [0.00271,-0.05603]} |

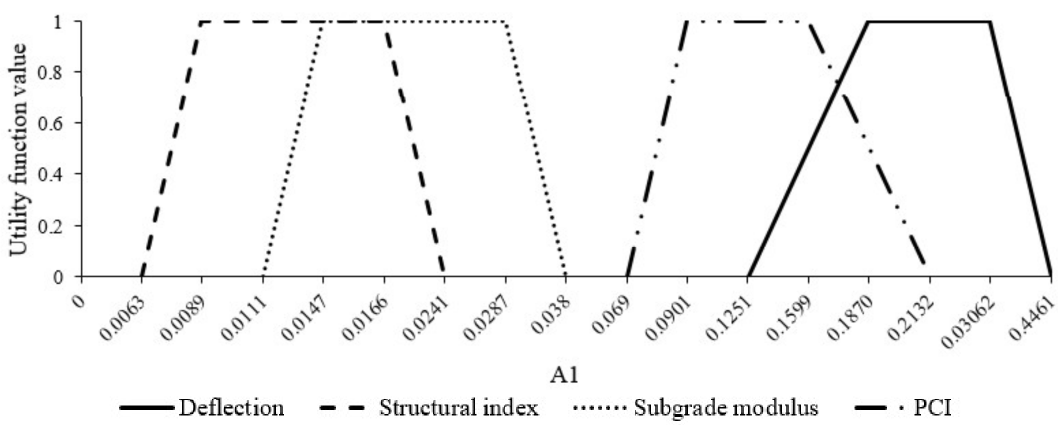
**Table 7.11. Interpretation of utility function value for $w_1S_{11}$**

| x | Function value |
|---|---|
| $\leq 0.1251$ | 0 |
| $\geq 0.4461$ | 0 |
| $0.1870 \leq x \leq 0.3062$ | 1 |
| $0.1251 \leq x \leq 0.1870$ | [0,1] |
| $0.3062 \leq x \leq 0.4461$ | [0,1] |

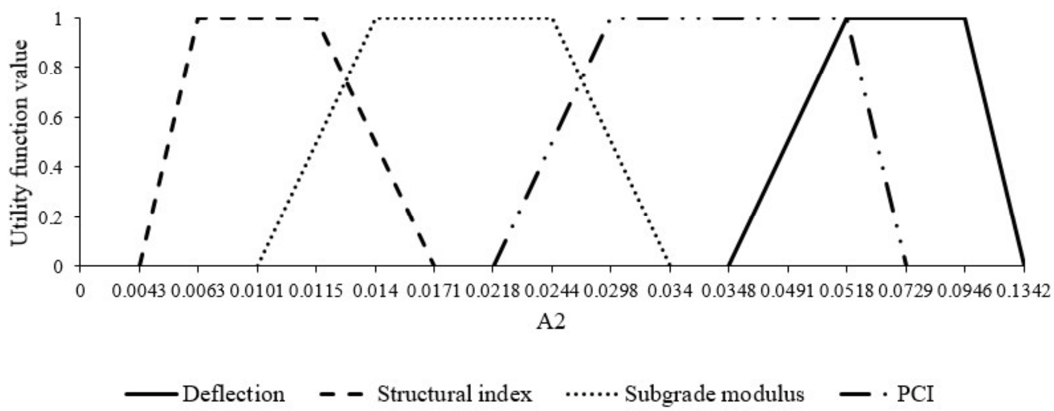
When $x \in [0.1251, 0.1870]$, it can be defined as: $x = (0.0062)*a^2 + 0.0558*a + 0.1251$

When $x \in [0.3062, 0.4461]$, it can be defined as: $x = (0.0130)*a^2 + (-0.1529)*a + 0.4461$

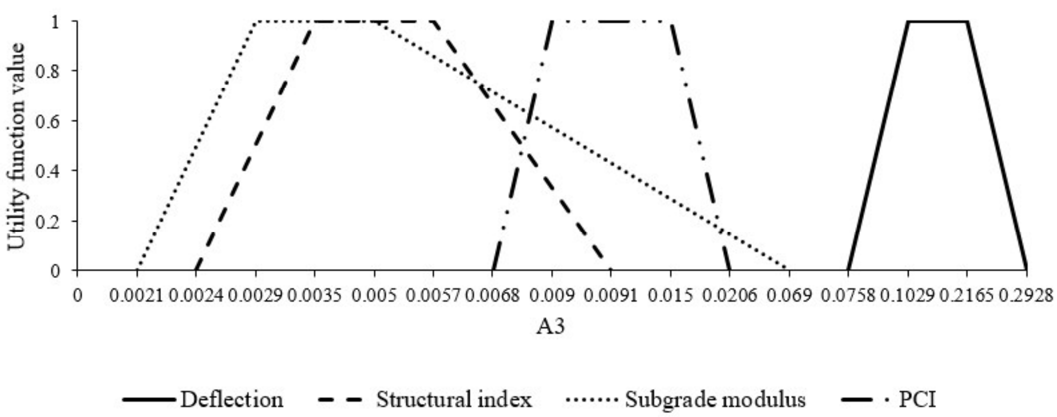
The plots of fuzzy utility functions of the pavement sections are illustrated in Figure 7.4.



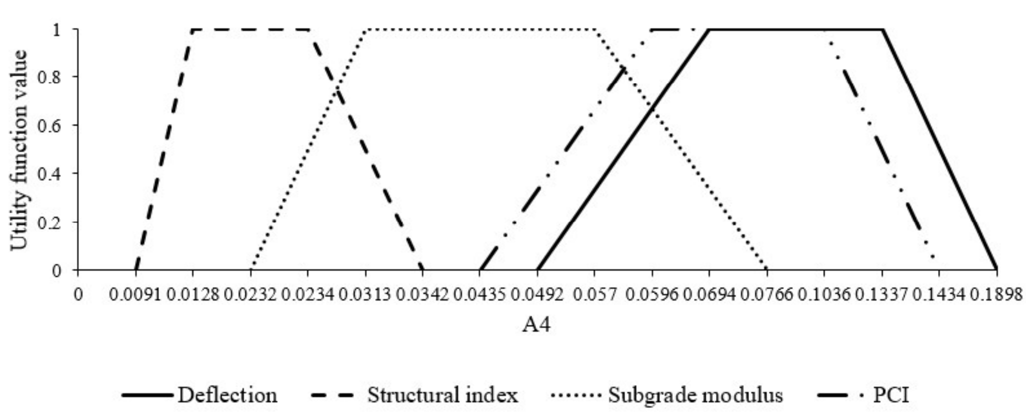

**(a) Utility function values for A1**



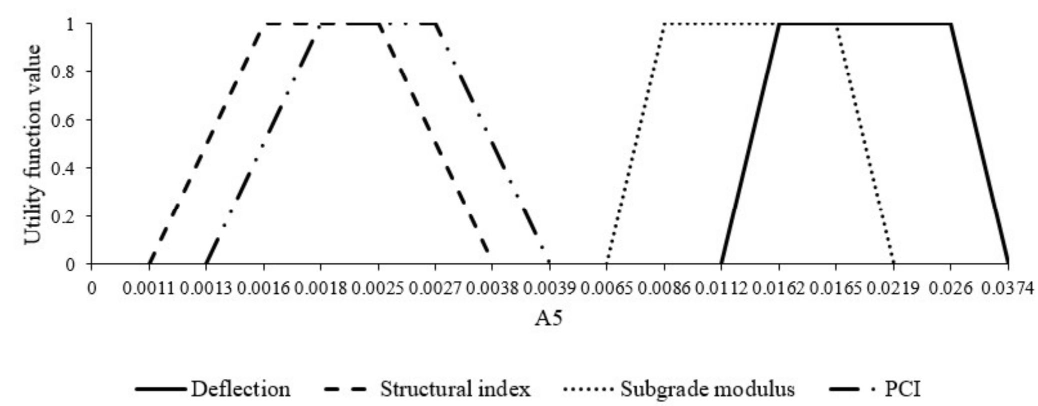

**(b) Utility function values for A2**



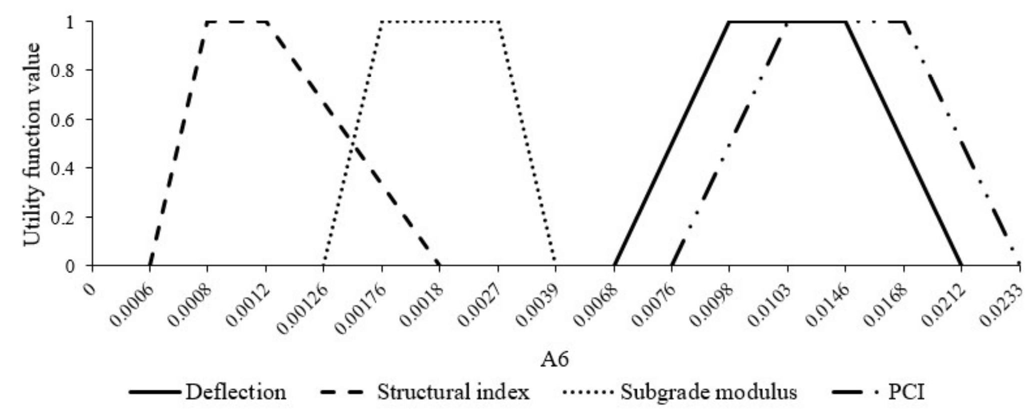

**(c) Utility function values for A3**




**(d) Utility function values for A4**




**(e) Utility function values for A5**




**(f) Utility function values for A6**

**Figure 7.4. Utility function values for runway pavement sections**

Finally, the normalized scores and ranking for all the pavement sections have been obtained after the process of defuzzification using mean of maximum method, as shown in Table 7.12.

**Table 7.12. Scores and ranking of runway pavement sections obtained using Buckley's FAHP**

| Pavement section | Normalized scores | Rank |
|---|---|---|
| A1 | 0.392 | 1 |
| A2 | 0.133 | 4 |
| A3 | 0.174 | 3 |
| A4 | 0.237 | 2 |
| A5 | 0.037 | 5 |
| A6 | 0.028 | 6 |

As postulated that the condition of pavement at any time is a consequence of the integrated impact of various attributes, it can be clearly observed from the plots of utility functions that they overlap each other. The plots show the variation and extent of impact of each attribute on every section of the runway pavement. The scores are used to prioritize the pavement sections for undergoing repair and maintenance. The higher scores indicate that these sections are in relatively good condition whereas the sections with lower scores are in poor state. As seen from Table 7.12, section A6 has obtained the lowest score and is concluded to be heavily deteriorated, followed by section A5. It can be inferred that section A6 can be treated first, or A6 and A5 can be treated together to prevent their further deterioration, since their scores do not differ much. Later, M&R on sections A2, A3, A4 and A1 can be implemented. The results are found to be consistent with earlier findings.

## 7.5. Cheng's entropy-based FAHP

Entropy approach of FAHP has been applied to address various problems such as evaluation of missile systems (Cheng, 1996), treatment technology for the drinking water supply (Chowdhury & Husain, 2006), and fuzzy eutrophication index model (Taheriyoun et al., 2010). In this study, application of entropy approach has been explored for pavement prioritization problems.

For in-depth analysis, the same runway section has been divided into sections of 250 m each, resulting in twelve sections (S1, S2,…, S12) to be prioritized, on the basis of five judgement criteria namely, pavement thickness, deflection, structural index, subgrade modulus, and PCI. The pavement condition evaluation model based on Cheng's (1996) method can be summarized stepwise (A to D) as:

(A) create a hierarchy structure for the decision problem;

(B) formulate membership functions of the judgement criteria;

(C) compute the performance scores;

(D) calculate aggregate weights by utilizing the FAHP method and entropy concepts.

In this work, the computations are based on triangular fuzzy numbers; the conversion of crisp to fuzzy numbers has been done, as defined in Table 7.13.

**Table 7.13. Fuzzy conversion scale**

| Crisp number | Corresponding fuzzy number |
|---|---|
| 1 | (1,1,2) |
| 2 | (1,2,3) |
| 3 | (2,3,4) |
| 4 | (3,4,5) |
| 5 | (4,5,6) |
| 6 | (5,6,7) |
| 7 | (6,7,8) |
| 8 | (7,8,9) |
| 9 | (8,9,9) |

A. The hierarchy structure for the decision problem is as presented in Figure 7.5.

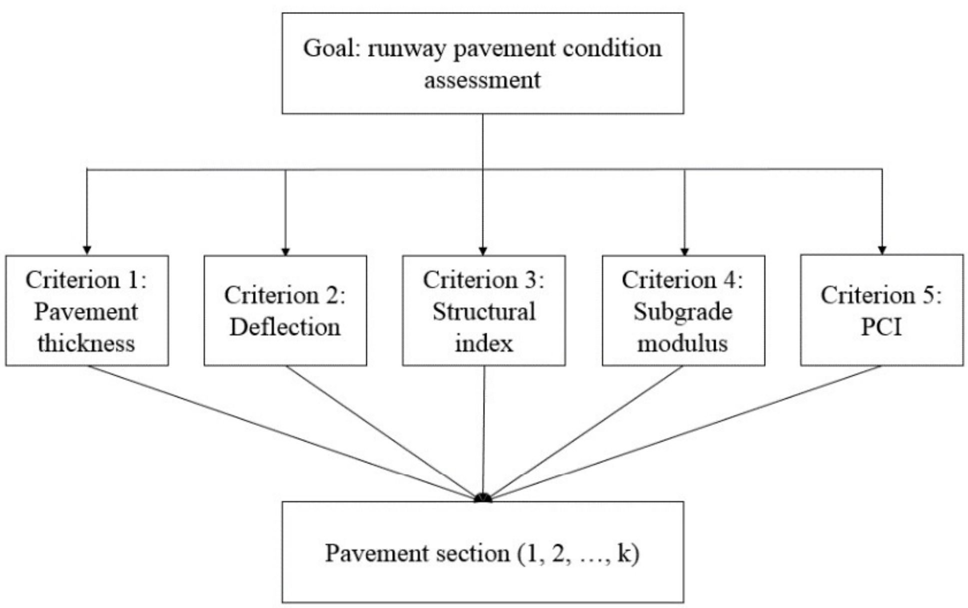



**Figure 7.5. Hierarchy of the decision problem**

B. In the next step, the membership functions of judgement criteria have been built using triangular, trapezoidal or exponential membership functions since they have been stated to be appropriate for demonstrating the ratings of pavement performance indicators (Singh et al., 2018; Zimmermann, 2011). The respective membership functions and their suitable coefficients are derived based on the opinion of ten field experts. Table 7.14 shows the corresponding membership functions of the judgement criteria.

**Table 7.14. Membership functions for the decision criteria**

| S. No. | Criterion | Membership function |
|---|---|---|
| 1. | Pavement thickness | $\mu_t = \begin{cases} 0, & x \leq 300 \\ 0.00571x - 1.714, & 300 < x < 475 \\ 1, & x \geq 475 \end{cases}$ |
| 2. | Deflection | $\mu_d = e^{(-\frac{x}{1764})}, \quad x \geq 0$ |
| 3. | Structural index (ACN/PCN) | $\mu_{\frac{ACN}{PCN}} = \begin{cases} 0, & x > 1.4 \\ 4.663 - 3.333x, & 1.1 \leq x \leq 1.4 \\ 1, & x < 1.1 \end{cases}$ |
| 4. | Subgrade modulus | $\mu_s = \begin{cases} 0, & x \leq 40 \\ 0.011x - 0.444, & 40 < x < 130 \\ 1, & x \geq 130 \end{cases}$ |
| 5. | PCI | $\mu_{PCI} = \begin{cases} 0, & x \leq 10 \\ 0.013x - 0.133, & 10 < x < 85 \\ 1, & x \geq 85 \end{cases}$ |

C. Next step is to compute the performance scores from pavement condition tests data and fuzzy membership functions as defined in Table 7.14, using symmetric triangular fuzzy numbers (refer Table 7.13) to indicate the relative strength of the elements in the judgement matrix.

D. Once the performance scores are computed, the total fuzzy judgement matrix $\tilde{T}$ containing *n* number of rows and *n* number of columns, given in Eq. (7.4) is established by multiplying fuzzy subjective weight vector $\widetilde{W}$ (Eq. (7.5)) with the corresponding column of fuzzy judgement matrix $\tilde{A}$, as given by Eq. (7.6).

$$\widetilde{T} = \begin{bmatrix} \widetilde{a_{11}} \otimes \widetilde{w_1} & \widetilde{a_{12}} \otimes \widetilde{w_2} & \dots & \widetilde{a_{1n}} \otimes \widetilde{w_n} \\ \widetilde{a_{21}} \otimes \widetilde{w_1} & \widetilde{a_{22}} \otimes \widetilde{w_2} & \dots & \widetilde{a_{2n}} \otimes \widetilde{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a_{n1}} \otimes \widetilde{w_1} & \widetilde{a_{n2}} \otimes \widetilde{w_2} & \dots & \widetilde{a_{nn}} \otimes \widetilde{w_n} \end{bmatrix} \quad (7.4)$$

$$\widetilde{W} = [\widetilde{w_1} \quad \widetilde{w_2} \quad \dots \quad \widetilde{w_n}] \quad (7.5)$$

$$\widetilde{A} = \begin{bmatrix} \widetilde{a_{11}} & \widetilde{a_{12}} & \dots & \widetilde{a_{1n}} \\ \widetilde{a_{21}} & \widetilde{a_{22}} & \dots & \widetilde{a_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a_{n1}} & \widetilde{a_{n2}} & \dots & \widetilde{a_{nn}} \end{bmatrix} \quad (7.6)$$

Multiplication operation of two fuzzy numbers say $\tilde{X}_\alpha = [x_L^\alpha, x_R^\alpha]$ and $\tilde{Y}_\alpha = [y_L^\alpha, y_R^\alpha]$ denoted by the operator $\otimes$ and described by interval of confidence $\alpha$, is performed as given in Eq. (7.7).

$$\tilde{X} \otimes \tilde{Y} = [x_L^\alpha y_L^\alpha, x_R^\alpha y_R^\alpha] \quad (7.7)$$

Fuzzy number additions and multiplications are then performed using the interval arithmetic and $\alpha$-cuts to get $\tilde{T}_\alpha$ defined in Eq. (7.8), where $\alpha$ is defined as the level of the interval of confidence of the decision expert.

$$\tilde{T}_\alpha = \begin{bmatrix} [t_{11p}^\alpha, t_{11q}^\alpha] & \dots & [t_{1np}^\alpha, t_{1nq}^\alpha] \\ \vdots & \ddots & \vdots \\ [t_{n1p}^\alpha, t_{n1q}^\alpha] & \dots & [t_{nnp}^\alpha, t_{nnq}^\alpha] \end{bmatrix} \quad (7.8)$$

where, $t_{ijp}^\alpha = w_i^\alpha a_{ijq}^\alpha$, $t_{ijq}^\alpha = w_i^\alpha a_{ijq}^\alpha$ , for $0 < \alpha \leq 1$ and for all i, j.

Keeping $\alpha$ fixed, the index of optimism ($\lambda$) is set, which is a measure of the amount of optimism of a decision expert. A higher degree of optimism is set by a larger $\lambda$. The optimism index is defined by Eq. (7.9).

$$\hat{t}_{ij}^\alpha = (1 - \lambda) t_{ijp}^\alpha + \lambda t_{ijq}^\alpha, \forall \lambda \in [0, 1] \quad (7.9)$$

Further, the degree of satisfaction of the judgement $\hat{T}$ is estimated, as shown in Eq. (7.10).

$$\hat{T} = \begin{bmatrix} \hat{t}_{11}^{\alpha} & \hat{t}_{12}^{\alpha} & \cdots & \hat{t}_{1n}^{\alpha} \\ \hat{t}_{21}^{\alpha} & \hat{t}_{22}^{\alpha} & \cdots & \hat{t}_{2n}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{t}_{n1}^{\alpha} & \hat{t}_{n2}^{\alpha} & \cdots & \hat{t}_{nn}^{\alpha} \end{bmatrix} \tag{7.10}$$

where, $\hat{T}$ is a precise judgement matrix.

Finally, in order to compute entropy, Eq. (7.11) is used first to calculate relative frequency, and then entropy formula of Eq. (7.12) is applied (Klir & Yuan, 1995).

$$\begin{bmatrix} \frac{t_{11}}{z_1} & \frac{t_{12}}{z_1} & \cdots & \frac{t_{1n}}{z_1} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{t_{n1}}{z_n} & \frac{t_{n2}}{z_n} & \cdots & \frac{t_{nn}}{z_n} \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{7.11}$$

where, $z_k = \sum_{j=1}^{n} a_{kj}$

$$E_n = -\sum_{j=1}^{n} (r_{nj}) \log_2(r_{nj}) \tag{7.12}$$

The entropy weights are calculated using Eq. (7.13) where $E_i$ is the $i^{th}$ entropy value.

$$E_i = \frac{E_i}{\sum_{j=1}^{n} E_j}, \qquad i=1, 2,\ldots,n \tag{7.13}$$

### 7.5.1. Illustration of Cheng's entropy-based FAHP

The evaluation of pavement sections based on their condition is performed in this section using entropy weights of FAHP method, as linguistically described in step D mentioned above. Using the field-collected data set of each criterion and fuzzy membership functions as defined in Table 7.14, the performance scores are obtained, which are then used to compute fuzzy judgement matrix as presented in Table 7.15.

**Table 7.15. Fuzzy judgement matrix of the alternatives**

| Pavement sections | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| S1 | (8,9,9) | (4,5,6) | (8,9,9) | (1,2,3) | (4,5,6) |
| S2 | (8,9,9) | (5,6,7) | (8,9,9) | (8,9,9) | (7,8,9) |
| S3 | (8,9,9) | (4,5,6) | (8,9,9) | (1,1,2) | (5,6,7) |
| S4 | (8,9,9) | (4,5,6) | (8,9,9) | (6,7,8) | (3,4,5) |
| S5 | (8,9,9) | (5,6,7) | (8,9,9) | (8,9,9) | (1,2,3) |
| S6 | (8,9,9) | (4,5,6) | (8,9,9) | (2,3,4) | (3,4,5) |
| S7 | (5,6,7) | (4,5,6) | (8,9,9) | (3,4,5) | (3,4,5) |
| S8 | (7,8,9) | (4,5,6) | (8,9,9) | (8,9,9) | (7,8,9) |
| S9 | (8,9,9) | (3,4,5) | (5,6,7) | (1,1,2) | (2,3,4) |
| S10 | (8,9,9) | (3,4,5) | (3,4,5) | (4,5,6) | (1,2,3) |
| S11 | (8,9,9) | (3,4,5) | (4,5,6) | (3,4,5) | (1,2,3) |
| S12 | (8,9,9) | (3,4,5) | (1,1,2) | (1,1,2) | (3,4,5) |

After interacting with the field experts, the weight vector for criteria are obtained (Table 7.16).

**Table 7.16. Fuzzy weight vector for each criterion**

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| $\tilde{W}$ | (7,8,9) | (6,7,8) | (4,5,6) | (5,6,7) | (7,8,9) |

The total fuzzy judgement matrix $\tilde{T}$, is obtained by multiplying values of fuzzy judgement matrix (Table 7.15) with the corresponding elements of the fuzzy subjective weight vector $\tilde{W}$ (Table 7.16), as shown in Table 7.17.

**Table 7.17. Total fuzzy judgement matrix of the alternatives**

$\tilde{T} =$

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| S1 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(4,5,6) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(1,2,3) | (7,8,9)⊗(4,5,6) |
| S2 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(5,6,7) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(8,9,9) | (7,8,9)⊗(7,8,9) |
| S3 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(4,5,6) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(1,1,2) | (7,8,9)⊗(5,6,7) |
| S4 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(4,5,6) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(6,7,8) | (7,8,9)⊗(3,4,5) |
| S5 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(5,6,7) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(8,8,9) | (7,8,9)⊗(1,2,3) |
| S6 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(4,5,6) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(2,3,4) | (7,8,9)⊗(3,4,5) |
| S7 | (7,8,9)⊗(5,6,7) | (6,7,8)⊗(4,5,6) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(3,4,5) | (7,8,9)⊗(3,4,5) |
| S8 | (7,8,9)⊗(7,8,9) | (6,7,8)⊗(4,5,6) | (4,5,6)⊗(8,9,9) | (5,6,7)⊗(8,9,9) | (7,8,9)⊗(7,8,9) |
| S9 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(3,4,5) | (4,5,6)⊗(5,6,7) | (5,6,7)⊗(1,1,2) | (7,8,9)⊗(2,3,4) |
| S10 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(3,4,5) | (4,5,6)⊗(3,4,5) | (5,6,7)⊗(4,5,6) | (7,8,9)⊗(1,2,3) |
| S11 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(3,4,5) | (4,5,6)⊗(4,5,6) | (5,6,7)⊗(3,4,5) | (7,8,9)⊗(1,2,3) |
| S12 | (7,8,9)⊗(8,9,9) | (6,7,8)⊗(3,4,5) | (4,5,6)⊗(1,1,2) | (5,6,7)⊗(1,1,2) | (7,8,9)⊗(3,4,5) |

In this study, three types of decision-makers are considered, and accordingly, value for $\lambda$ is fixed. For the nominal decision-maker, $\lambda = 0.5$ and $\alpha = 0.8$, the fuzzy number triplet i.e., $(t_1,t_2,t_3)$ is represented by its corresponding left and right side representation as $[t_L^\alpha, \quad t_R^\alpha]$ using Eq. (7.14).

$$\forall_\alpha \in [0,1], \qquad \tilde{T}_\alpha = [t_L^\alpha, \quad t_R^\alpha] = [(t_2 - t_1)\alpha + t_1, \quad -(t_3 - t_2)\alpha + t_3] \qquad (7.14)$$

For example, the first element of the matrix $\tilde{T}$ reduces to the following form:

$$[t_{11p}^{\alpha=0.8}, t_{11q}^{\alpha=0.8}] = [(8-7)\times0.8+7, (9-8)\times0.8+9] \otimes [(9-8)\times0.8+8, (9-9)\times0.8+9] = [68.64, 73.80]$$

In a similar manner, all other elements of the matrix are calculated and matrix $\tilde{T}_{\alpha=0.8}$ is obtained as given in Table 7.18.

**Table 7.18. Total fuzzy judgement matrix for $\alpha$ = 0.80**

| $\tilde{T}_{\alpha}=$ | | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|---|
| | S1 | [68.64, 73.80] | [32.64, 37.44] | [42.24, 46.80] | [10.44, 13.64] | [37.44, 42.64] |
| | S2 | [68.64, 73.80] | [39.44, 44.64] | [42.24, 46.80] | [51.04, 55.80] | [60.84, 67.24] |
| | S3 | [68.64, 73.80] | [32.64, 37.44] | [42.24, 46.80] | [5.80, 7.44] | [45.24, 50.84] |
| | S4 | [68.64, 73.80] | [32.64, 37.44] | [42.24, 46.80] | [39.44, 44.64] | [29.64, 34.44] |
| | S5 | [68.64, 73.80] | [39.44, 44.64] | [42.24, 46.80] | [51.04, 55.80] | [14.04, 18.04] |
| | S6 | [68.64, 73.80] | [32.64, 37.44] | [42.24, 46.80] | [16.24, 19.84] | [29.64, 34.44] |
| | S7 | [45.24, 50.84] | [32.64, 37.44] | [42.24, 46.80] | [22.04, 26.04] | [29.64, 34.44] |
| | S8 | [60.84, 67.24] | [32.64, 37.44] | [42.24, 46.80] | [51.04, 55.80] | [60.84, 67.24] |
| | S9 | [68.64, 73.80] | [25.84, 30.24] | [27.84, 32.24] | [5.80, 7.44] | [21.84, 26.24] |
| | S10 | [68.64, 73.80] | [25.84, 30.24] | [18.24, 21.84] | [27.84, 32.24] | [14.04, 18.04] |
| | S11 | [68.64, 73.80] | [25.84, 30.24] | [23.04, 27.04] | [22.04, 26.04] | [14.04, 18.04] |
| | S12 | [68.64, 73.80] | [25.84, 30.24] | [4.80, 6.24] | [5.80, 7.44] | [29.64, 34.44] |

The optimism index as defined in Eq. (7.9) is now used to generate elements of the precise judgement matrix $\hat{T}$. For example, again consider the first element of the matrix $\tilde{T}_{\alpha}$:

$$\hat{t}_{11}^{\alpha=0.8} = (1 - 0.5) \times 68.64 + 0.5 \times 73.80 = 71.22$$

Similarly, all other elements are calculated and matrix $\hat{T}$ is obtained as shown in Table 7.19.

**Table 7.19. Precise judgement matrix of the alternatives**

$\hat{T} =$

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| S1 | 71.22 | 35.04 | 44.52 | 12.04 | 40.04 |
| S2 | 71.22 | 42.04 | 44.52 | 53.42 | 64.04 |
| S3 | 71.22 | 35.04 | 44.52 | 6.62 | 48.04 |
| S4 | 71.22 | 35.04 | 44.52 | 42.04 | 32.04 |
| S5 | 71.22 | 42.04 | 44.52 | 53.42 | 16.04 |
| S6 | 71.22 | 35.04 | 44.52 | 18.04 | 32.04 |
| S7 | 48.04 | 35.04 | 44.52 | 24.04 | 32.04 |
| S8 | 64.04 | 35.04 | 44.52 | 53.42 | 64.04 |
| S9 | 71.22 | 28.04 | 30.04 | 6.62 | 24.04 |
| S10 | 71.22 | 28.04 | 20.04 | 30.04 | 16.04 |
| S11 | 71.22 | 28.04 | 25.04 | 24.04 | 16.04 |
| S12 | 71.22 | 28.04 | 5.52 | 6.62 | 32.04 |

Furthermore, Eq. (7.11) is utilized to determine the relative frequencies of all elements of the matrix $\hat{T}$ as presented in Table 7.20.

**Table 7.20. Relative frequency matrix of the alternatives**

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| S1 | 0.351 | 0.173 | 0.219 | 0.059 | 0.197 |
| S2 | 0.259 | 0.153 | 0.162 | 0.194 | 0.233 |
| S3 | 0.347 | 0.171 | 0.217 | 0.032 | 0.234 |
| S4 | 0.317 | 0.156 | 0.198 | 0.187 | 0.142 |
| S5 | 0.313 | 0.185 | 0.196 | 0.235 | 0.071 |
| S6 | 0.355 | 0.174 | 0.222 | 0.090 | 0.160 |
| S7 | 0.262 | 0.191 | 0.242 | 0.131 | 0.174 |
| S8 | 0.245 | 0.134 | 0.171 | 0.205 | 0.245 |
| S9 | 0.445 | 0.175 | 0.188 | 0.041 | 0.150 |
| S10 | 0.431 | 0.170 | 0.121 | 0.182 | 0.097 |
| S11 | 0.433 | 0.171 | 0.152 | 0.146 | 0.098 |
| S12 | 0.497 | 0.195 | 0.038 | 0.046 | 0.223 |

Lastly, entropy values are estimated using Eq. (7.12), and entropy weights are determined by normalizing entropy values as depicted in Eq. (7.13). Table 7.21 shows the final entropy values, entropy weights, and rankings of all the alternatives for $\alpha$ = 0.80 and $\lambda$ = 0.50.

**Table 7.21. Final entropy weights and rankings of the alternatives for $\alpha$ =0.80 and $\lambda$=0.50**

| Pavement sections | Entropy values | Entropy weights | Rank |
|---|---|---|---|
| S1 | 2.1518 | 0.0834 | 7 |
| S2 | 2.2923 | 0.0889 | 1 |
| S3 | 2.0931 | 0.0811 | 10 |
| S4 | 2.2587 | 0.0876 | 4 |
| S5 | 2.1967 | 0.0852 | 5 |
| S6 | 2.1863 | 0.0848 | 6 |
| S7 | 2.2810 | 0.0884 | 3 |
| S8 | 2.2871 | 0.0887 | 2 |
| S9 | 2.0143 | 0.0781 | 11 |
| S10 | 2.0999 | 0.0814 | 9 |
| S11 | 2.1048 | 0.0816 | 8 |
| S12 | 1.8306 | 0.0710 | 12 |

The obtained entropy weights serve as a good estimator of the level of deterioration of pavement sections. The sections with higher entropy values are in better condition, and ranks are given accordingly. It can be observed that the last section, i.e., S12, is in poorer state as compared to all the other sections. In addition to this, the entire one km of runway pavement from section S9 to S12 is heavily distressed. This is apparent from the lower entropy weights and consecutive low ranking of these four sections. Pavement section S2 has been found to be in the best condition. Thus, by making inferences from the entropy weights, the planners and engineers may adopt suitable M&R measures for section S12 with priority, followed by S9, S10, and S11. However, it would be desirable to adopt preventive M&R for the entire stretch (S9 to S12), so as to avoid further deterioration. Since the weights do not differ much, the minor repair and maintenance should be sufficient for the sections as per their current state, and rehabilitation or reconstruction is not required. The results are found to be consistent with the other approaches discussed in this chapter.

### 7.5.2. Sensitivity analysis

The sensitivity analysis demonstrates the feasibility and robustness of the model with change in time. This has been performed by considering different types of decision-makers: pessimistic, nominal, and optimistic, thereby varying the values of $\lambda$ as 0.25, 0.50, and 0.75 to obtain corresponding entropy weights. Table 7.22 summarizes the entropy weights and ranking for different values of $\lambda$, taking two values for the level of confidence (80% and 95%). The results for $\alpha$ = 0.80 and $\lambda$ = 0.50 are already presented in Table 7.21. The results show that for each of the level of confidence, the ranking obtained is almost the same, except for a few minor variations. It can be seen that the entropy weights of alternatives with higher and lower ranks are more sensitive as they vary substantially with change in the degree of optimism. On the other hand, intermediate alternatives, do not show considerable variation due to this change. This proves that the developed model is robust.

**Table 7.22. Final entropy weights and rankings of the alternatives for different values of confidence interval and index of optimism**

| Pavement sections | Entropy weights for $\alpha$ =0.80 | | | | Entropy weights for $\alpha$ =0.95 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\lambda$=0.25 | Rank | $\lambda$=0.75 | Rank | $\lambda$=0.25 | Rank | $\lambda$=0.50 | Rank | $\lambda$=0.75 | Rank |
| S1 | 0.08339 | 7 | 0.08349 | 7 | 0.0834 | 7 | 0.0835 | 7 | 0.0834 | 7 |
| S2 | 0.08911 | 1 | 0.08910 | 2 | 0.0884 | 1 | 0.0890 | 1 | 0.0874 | 2 |
| S3 | 0.08117 | 10 | 0.08081 | 10 | 0.0811 | 10 | 0.0810 | 10 | 0.0811 | 10 |
| S4 | 0.08771 | 4 | 0.08775 | 4 | 0.0873 | 4 | 0.0877 | 4 | 0.0867 | 4 |
| S5 | 0.08519 | 5 | 0.08564 | 5 | 0.0851 | 5 | 0.0853 | 5 | 0.0853 | 5 |
| S6 | 0.08478 | 6 | 0.08499 | 6 | 0.0847 | 6 | 0.0848 | 6 | 0.0847 | 6 |
| S7 | 0.08863 | 3 | 0.08930 | 1 | 0.0880 | 3 | 0.0886 | 3 | 0.0878 | 1 |
| S8 | 0.08891 | 2 | 0.08864 | 3 | 0.0881 | 2 | 0.0889 | 2 | 0.0867 | 3 |
| S9 | 0.07789 | 11 | 0.07760 | 11 | 0.0785 | 11 | 0.0778 | 11 | 0.0792 | 11 |
| S10 | 0.08120 | 9 | 0.08131 | 9 | 0.0817 | 9 | 0.0814 | 9 | 0.0821 | 9 |
| S11 | 0.08139 | 8 | 0.08154 | 8 | 0.0819 | 8 | 0.0816 | 8 | 0.0823 | 8 |
| S12 | 0.07062 | 12 | 0.06984 | 12 | 0.0718 | 12 | 0.0703 | 12 | 0.0733 | 12 |

## 7.6. Integrated SWOT-FAHP approach

### 7.6.1. Decision problem

Construction and M&R activities of pavements involve processes that emit harmful substances in the environment to different extents, and make pavement infrastructure development a destructive job, thereby seeking immediate attention. However, pavement M&R decision-making processes generally aim to address the immediate problem of enhancing pavement ride quality. Such an approach often ignores the consideration of sustainable prospects, which is the need of the hour. Therefore, a more holistic decision-making with long-term goals by considering the alarming aspects of environment and energy, would serve as an added advantage with its implication of a sustainable future, rather than merely satisfying the requirement of transporting goods and passengers. SWOT analysis is highly beneficial in such scenarios since it provides a broad vision of associated Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T), and derives hybrid mechanisms from various optimal perspectives even before performing any activity, thereby enabling the decision-makers to have an idea of its consequences beforehand. This indication offers great assistance in formulating defensive or aggressive strategies as per the need of project.

In this study, the SWOT analysis is performed for the runway pavement M&R practices and is demonstrated in subsequent subsections for its practical application using the case study of runway adopted in the earlier sections of this chapter. Selection of appropriate decision-makers is the preliminary step in formulating SWOT model. These decision-makers define internal factors (S, W) and external factors (O, T) for the SWOT matrix. The relevant decision criteria chosen by conducting the in-depth study are technical feasibility (C1), pavement durability (C2), financial viability (C3), and reliability (C4). These criteria form the basis upon which the hybridized SWOT matrix and appropriate strategic policies can be formulated.

### 7.6.2. Formulation of SWOT matrix

A total of 44 significant contributing factors have been obtained, which are classified using the SWOT matrix, as shown in Table 7.23. The ten strengths are obtained by virtue of the enhancement in the pavement quality after the execution of suitable maintenance. The nine weaknesses are derived due to mismanagement, poor administration, and deficient knowledge. Opportunities (21 factors) are predominantly related to the use of innovative material and technology for pavement maintenance and construction and increased transportation. Lastly, threats (4 factors) have resulted due to the environmental impacts on the pavement and lack of technological advancement. The mechanism and process of this modeling methodology for the runway of the international airport can be summed up as:

1. Appropriate decision criteria and governing factors are identified from the discussion and opinion of various stakeholders (field experts and engineers).
2. The most important factors (44 factors) are selected and classified into internal (19 factors) and external (25 factors) to develop the SWOT matrix (refer Table 7.23). The interrelationship between S, W, O, and T is examined to analyze the potential output of the M&R activity.
3. Hybridized matrix is formulated (5 hybrid mechanisms for the present case), and appropriate strategies are derived (8 strategies) based on the conclusions obtained from previous step. This is achieved by interlinking complementary internal and external factors for overcoming their negative traits by utilizing their positive ones (refer Table 7.24).
4. To quantify the decision criteria and strategies, Cheng's entropy-based FAHP is used, and their entropy weights are obtained and analyzed from different viewpoints of the decision experts.
5. Finally, the strategic alternatives are ranked based on the weights allotted by the experts to the decision criteria as per their judgement for the current case study.

### 7.6.3. Deriving strategic alternatives from hybridized SWOT matrix

The robustness of the SWOT model is used to address various issues related to pavement maintenance by connecting internal and external characteristics to devise feasible alternatives. The model has been comprehensively reviewed by the experts as per their perception and from the previous literature (Srinivas & Singh, 2017). The hybrid mechanisms developed from the SWOT model for this case study are briefly described as:

1. Strength-Opportunity (SO): Internal strengths are used to make use of external opportunities.
2. Weakness-Opportunity Mechanism (WO): External opportunities are used to eliminate internal weakness.
3. Opportunity-Threat Mechanism (OT): External opportunities are used to remove internal threats.
4. Opportunity-Threat-Weakness Mechanism (OTW): External opportunities are used to exterminate threats and weakness, which can trigger potential threats.
5. Strength-Opportunity-Weakness-Threat Mechanism (SOWT): Internal strengths and external opportunities are used to get rid of internal weakness and forthcoming potential threats.

These five scenarios are derived for this study specifically to demonstrate the methodology. However, the other combinations can be made to generate different scenarios as per the intended problem. Based on these hybrid mechanisms, a total of eight alternatives have been defined, as shown in Table 7.24. However, the relative importance and ranking of these alternatives are not possible through the SWOT model, even though it formulates appropriate strategic alternatives. The hybridized matrices are therefore integrated with Cheng's entropy-based fuzzy AHP. Each of these eight alternatives is now evaluated and prioritized on the basis of the four performance criteria using this approach. Nominal, optimistic, and pessimistic viewpoints of the decision-makers are also considered.

### 7.6.4. Inferences from integrated SWOT-FAHP approach

The weights and the final ranking of the eight alternatives obtained in the proposed approach are represented in Table 7.25. It shows that none of the entropy weight is drastically low to signify the need for reconstruction or a new runway. The allotment of weights and obtained ranking is logical in a way such that at the first step, improvement of the infrastructure is required for the runway to serve its primary purpose efficiently, only by routine or preventive maintenance. Eventually, the strategies incorporate the aspects of growing demand, technological advancements over conventional M&R, and at the same time saving energy and being environment-friendly. These are the best suited long-term goals for new construction and for sustainable growth.

In accordance with this, the strategy (A2) secures the first rank. This is in agreement with the requirements of the present time that a well-maintained runway would help in economic and faster transportation by saving energy and funds. The second rank is obtained by alternative (A1), which focuses on improvement in the infrastructure of nearby areas. A high-quality runway infrastructure could sustain more number of flights, thereby attracting more passengers. Due to this, the nearby area would also develop new facilities and generate economic and commercial potentials. The development of the surrounding road network would increase accessibility for local communities.

The other strategies are more preventive in nature and in tune with plans to optimize future investments by suggesting ways to enhance the durability of runways within the optimum budget and generate more source of income. Accordingly, alternative (A3) obtains the third rank, which focuses on planning a preventive maintenance program and exploring a less expensive M&R method to save future costs. The revenue generated by increased tourism would also help to overcome financial constraints. This is followed by alternative (A6), which involves more research to find ways protecting pavement surfaces from water, fuel spillage, and jet blasts, in order to have long-lasting pavement surfaces. The alternative (A7) aims at conducting training sessions to have more skilled laborers. This would help to successfully implement advanced and innovative maintenance techniques. The remaining strategies focus on long-term goals of sustainable development, are difficult to be adopted at an early stage but they would go well with new or reconstruction and expansion projects of the future. Therefore, the alternatives A8, A4, and A5 obtain lesser ranks as they do not excel in technical feasibility and financial viability criteria, presently. Consequently, policy (A8) deals with conservation of environment and protecting biodiversity by minimizing the need of new materials and promoting the use of environment-friendly ones. Strategy (A4) proposes for a holistic future planning of alternative runways so that M&R activities would not cause any interruption to aircraft operations. Additionally, it must also consider providing adequate room for future growth, such that significant construction activity could be delayed for longer durations. The policy (A5) related to harvesting solar energy collected by the asphalt pavements, obtains the least rank for this case study because the implementation of this strategy would require embedding pipes in the pavement, and it is a feasible option to incorporate in new constructions. In such a case, it has enormous potential to be explored by utilizing renewable sources and saving the non-renewable ones.

By taking advantage of the flexible nature of SWOT model and its derived hybrids, the developed integrated SWOT-FAHP approach can be used for other similar studies as well by customizing the weights or strategic alternatives appropriate for their intended problem. For example, if recycling procedure of M&R is required, the alternatives A8, and A5 would possibly secure higher ranks as per the weights allotted by the field experts, as these strategies are cost-efficient and yield sustainable pavement infrastructure.

### 7.6.5. Sensitivity analysis

The sensitivity analysis is performed in a similar way as presented in section 7.5.2, and is shown in Table 7.25. These results clearly reflect the robustness of the model since there is no change in the rankings even with variation in the scores. In general, it is found that as the value of $\lambda$ increases, the entropy weight decreases. The alternatives having higher and lower rankings are more sensitive to this change whereas, the intermediate ones are less sensitive. Hence, the model can be considered rigorous for decision-makers to address issues related to pavement M&R.

**Table 7.23. SWOT matrix developed based on the opinion of field experts**

| **Internal factors** | | | |
|---|---|---|---|
| **Strengths (S)** | | **Weakness (W)** | |
| S1 | Increased serviceability of pavements | W1 | Interference with normal aircraft operations; diversion of flights or routes during M&R activities |
| S2 | High pavement condition index | W2 | Not all M&R treatments can be carried out to the extent and at the time recommended due to financial constraints |
| S3 | Reduced risk of road accidents | W3 | Limitation of skilled laborers with expertise in different M&R technologies |
| S4 | High structural capacity of pavement structure | | |
| S5 | Extended pavement life due to a maintenance treatment | W4 | Improper and inadequate drainage of rainwater harm pavements, may create flash flood which can cause runway or taxiway closures |
| S6 | Rise in airport operations and number of flights | | |
| S7 | Attainment of desired pavement strength by using waste and recycled materials | | |
| | | W5 | Lack of interest and willingness of employees/workers/laborers to learn new technologies |
| S8 | Provision of comfortable riding surface | | |
| S9 | Reduced fuel consumption and vehicle operating costs | W6 | Lack of operational control |
| S10 | Increased rutting resistance of pavements, good skid resistance and no undue damage to aircraft tires | W7 | Lack of sustainability awareness throughout the organization and public |
| | | W8 | Lack of cooperation between various stakeholders and departments for implementing M&R strategies |

| | | | |
|---|---|---|---|
| | | W9 | Lack of integration and coordination of planning process |
| **External factors** | | | |
| **Opportunities (O)** | | **Threats (T)** | |
| O1 | Economic and faster transportation of passengers and commodities | T1 | Intrusion of water/moisture or snow into the pavement structure and its lower layers |
| O2 | Use of innovative materials for asphalt concrete overlays and reconstruction | | |
| O3 | Use of industrial by-products such as fly ash and blast furnace slag in high proportions with Portland cement construction | T2 | Adverse impacts on biodiversity (harm to wildlife) and environment. Particulate matter, nitrogen oxides, unburnt hydrocarbons, etc., pollute air quality; de-icing fluids used on runways and aircraft pollute groundwater |
| O4 | Reuse of deteriorated pavement materials, such as Reclaimed Asphalt Pavement (RAP), Reclaimed Concrete Aggregates (RCA), and Reclaimed Asphalt Shingles (RAS) into new pavement infrastructure construction | T3 | Limitations of robust airport pavement management software |
| | | T4 | Ambient temperature variations cause excessive asphalt softening and bleeding, thereby result in rutting and expansion of concrete slabs |
| O5 | Use of warm-mix asphalt concrete technology (rather than the traditional hot mix) | | |
| O6 | Potential for future cost savings if a new, less expensive M&R becomes available | | |
| O7 | Plan a preventive pavement maintenance program | | |
| O8 | Further research including making pavement preservation knowledge available to practitioners by organizing and synthesizing information and data in an interactive electronic format | | |
| O9 | Improvement of infrastructure in nearby areas particularly, road and transport facilities | | |

| | |
|---|---|
| O10 | Potential to explore advanced water-resistant seal coats |
| O11 | Measures to protect pavement surfaces from negative impacts of solvent (fuel and hydraulic fluids) spillage and jet blasts |
| O12 | Adopting measures to minimize impact on biodiversity and climate change |
| O13 | Utilization of economic and commercial potentials created by the project |
| O14 | Proposing more holistic planning in future for better and alternative runways with optimum infrastructure and scheduling of flights; flexibility for future expansion |
| O15 | Revenue generation from increased tourism |
| O16 | Procedures for estimating and comparing the costs of various strategies and alternatives |
| O17 | Harvesting solar energy collected by the asphalt pavements by embedding pipes that would contain water or another circulating fluid below the wearing course of pavements. The hot water can be used directly or help in electricity generation |
| O18 | Asphalt pavement solar collectors extend the pavement life by removing the heat from the pavement, since the pavement temperature drops and lessens the phenomenon of rutting |
| O19 | Use of buried semiconductors in the pavement structure to develop heat differential for generating electricity |
| O20 | Covering Jersey barriers or other road partitioning barriers by solar collectors to gain power for highway lightning |
| O21 | Potential to reduce the effect of concrete slab expansion by using serpentine pipes inside concrete pavements with solar concrete collectors for domestic water heating or other purposes |

**Table 7.24. Hybrid mechanisms from SWOT matrix and corresponding alternatives**

| | | |
|---|---|---|
| **Strength-Opportunity Mechanism (SO)** | | |
| A1 | S3+S4+S6+S8→O9+O13 | Airfield pavement M&R would result in increased structural capacity of pavements, less risk of accidents, increase in number of flights and passengers, and comfortable riding surface, thereby improving the infrastructure in nearby areas particularly, road and transport facilities and utilizing economic and commercial potentials created by the project. |
| A2 | S1+S2+S5+S9+S10→O1 | Pavement maintenance would yield increased serviceability, extended pavement life, improved pavement condition index, increased rutting resistance, good skid resistance, no undue damage to aircraft tires, less fuel consumption and vehicle operating costs which will help in economic and faster transportation of passengers and goods. |
| **Weakness-Opportunity Mechanism (WO)** | | |
| A3 | W2→O6+O7+O15+O16 | Limitation of implementing extensive M&R policies due to financial constraints can be addressed by planning a preventive maintenance program and exploring a less expensive rehabilitation method to save future costs. Also, there is revenue generation from increased tourism. There is enormous potential to estimate and compare the costs of various strategies and alternatives. |
| A4 | W1→O14 | More holistic planning in future for better and alternative runways with optimum infrastructure and scheduling of flights would help to carry out M&R activities without causing any interruption to aircraft operations. |

| | | |
|---|---|---|
| **Opportunity-Threat Mechanism (OT)** | | |
| A5 | O17+O18+O19+O20+O21→T4 | Harvesting of solar energy collected by the asphalt pavements by embedding pipes that would contain water or another circulating fluid below the wearing course of pavements. |
| **Opportunity-Threat-Weakness Mechanism (OTW)** | | |
| A6 | O10+O11→T1+W4 | Airports contain large paved surfaces. Limitation of poor and inadequate drainage conditions and risk of water retaining on pavements provides an opportunity to develop high water resistant pavement surfaces, improved drainage techniques and measures to protect pavement surfaces from negative impact of fuel spillage and jet blasts. |
| A7 | O8→T3+W3+W5+W6+W8+W9 | Limitation of skilled laborers with expertise in different M&R technologies and robust airport pavement management software can be addressed by conducting training programs and organizing research in synthesizing information and data in an interactive electronic format. This will integrate and coordinate planning process. |
| **Strength-Opportunity-Threats Mechanism (SOWT)** | | |
| A8 | S7+O2+O3+O4+O5+O12+W7→T2 | There is a large potential for use of industrial waste and by-products, warm-mix technology for asphalt concrete pavement construction, and recycling using RAP, RCA, and RAS into new construction. This will reduce risk of negative impact on biodiversity and environment without any reduction in pavement strength. |

**Table 7.25. Results of sensitivity analysis for the SWOT model**

| Alternatives | Entropy weights for $\alpha$=0.80 | | | Entropy weights for $\alpha$=0.95 | | | Ranking |
|---|---|---|---|---|---|---|---|
| | $\lambda$=0.25 | $\lambda$=0.50 | $\lambda$=0.75 | $\lambda$=0.25 | $\lambda$=0.50 | $\lambda$=0.75 | |
| A1 | 0.12599 | 0.12596 | 0.12593 | 0.12597 | 0.12596 | 0.12595 | 2 |
| A2 | 0.12628 | 0.12624 | 0.12620 | 0.12626 | 0.12625 | 0.12624 | 1 |
| A3 | 0.12592 | 0.12590 | 0.12588 | 0.12591 | 0.12591 | 0.12590 | 3 |
| A4 | 0.12476 | 0.12475 | 0.12475 | 0.12476 | 0.12476 | 0.12476 | 7 |
| A5 | 0.12126 | 0.12139 | 0.12151 | 0.12131 | 0.12134 | 0.12138 | 8 |
| A6 | 0.12541 | 0.12540 | 0.12538 | 0.12541 | 0.12541 | 0.12540 | 4 |
| A7 | 0.12527 | 0.12526 | 0.12524 | 0.12527 | 0.12526 | 0.12526 | 5 |
| A8 | 0.12510 | 0.12510 | 0.12510 | 0.12511 | 0.12511 | 0.12511 | 6 |

### 7.6.6. Practical significance of the SWOT-FAHP methodology

The model developed in this work incorporates a combination of pavement deterioration parameters not only from primary causes (loading, temperature, and moisture) but also secondary causes (subgrade soil conditions, pavement structure, and visual performance indicator). Individually assessing the pavement sections for all the above-mentioned performance parameters is a difficult task since the viewpoints of decision-makers may differ. Therefore, a composite index represented by entropy weight, proposed in this work assists in analyzing the severity of deterioration in an effort to prioritize sections. It marks an excellent advancement over the conventional assessment methods since the developed index is not merely a representative of all the major governing parameters but encompasses the diverse judgement of field experts. Moreover, the cost of deteriorating airfield is likely to be one of the most expensive operational expense. Therefore, prior to investing a reasonable amount of fund for M&R, thorough knowledge of the degree of deterioration is required, as indicated by the magnitude of the index. The next stage after condition assessment is the implementation of M&R strategies. SWOT analysis empowers the proposed methodology and provides a beforehand indication about the potential impacts such that the defensive strategies could be pre-planned against the negative ones, if any.

## 7.7. Concluding remarks

From the discussions presented herein, it is clear that pavement condition assessment and its M&R is a challenging task due to the involvement of a multitude of factors. The action of these numerous variables intricate the assessment of pavement condition and it becomes difficult to evaluate their impact collectively. In addition to this, the decision-making involved in prioritizing pavements, and justifying the M&R need requires the opinion of decision-makers to be free from any uncertainty, imprecision, approximation, and partial truth. In order to address these issues, the chapter presented a number of soft-computing approaches for pavement prioritization including AHP, FAHP, FIS, and also formulate a strategic framework for PMS using SWOT model and its hybridized forms. AHP is very easy to apply but the limitations of subjectivity involved with crisp data and 9-point scale, are overcome by objectivity of fuzzy-based techniques. Formulation of a number of inference rules in FIS and use of only trapezoidal fuzzy numbers in Buckley's FAHP, acts as their disadvantages. Cheng's entropy-based FAHP can be concluded to be more realistic since they incorporate two factors i.e., degree of optimism and confidence interval, which closely relates to human decisions.

The prioritization results obtained for the case study of runway pavement from different fuzzy techniques are broadly similar for the highest and lowest rank, with minor intermediate variations. This finding is in agreement with the observations from visual survey that due to the presence of touchdown zone and impact exerted on pavement due to major commercial aircraft in this section, last one km section is severely distressed. The scores developed in this work offer an objective approach to justify the requirement of M&R and obtain requisite amount of budget. The conversion of qualitative estimates to quantitative terms using the developed methodology greatly assists in decision-making processes.

The variables are selected keeping in view, the most important factors for runway pavement. The variables may be changed according to the study area by keeping the same approach. Numeric values of these decision variables itself gives an indication of deterioration, but their cumulative effect may greatly vary from the individual estimates, which can be effectively represented by scores obtained from different approaches. The feasibility and suitability of pavement M&R

treatments can also be decided as per the site conditions by utilizing these scores. For instance, a critically low score indicates that the governing criteria have exceeded their threshold limits, and thus the pavement may warrant rehabilitation or recycling since reconstruction is generally not recommended in order to preserve natural resources. In a similar manner, a moderate or high score may demand only minor/routine repair and maintenance. In this context, concerning the case study performed, it is important to note the insignificant difference among the scores of the sections, it is not critically low to demand rehabilitation, recycling, or reconstruction. Nevertheless, the final decision would depend on intellect and understanding of the respective site engineers and planners by considering site-specific conditions. Additionally, the final rehabilitation strategy would also depend on economic factors such as life-cycle costs and availability of budget, operational factors such as scope of work, and time of the project. The integration of analytical and practical approach provides a better significance to the work and increases its applicability.

The approaches discussed in this chapter are highly flexible, and provides a wide scope to the decision-makers to customize the alternatives according to their anticipated problem and data availability. Additionally, SWOT model assists in planning and decision-making processes by analyzing potential impacts of a project, in advance. Therefore, it is highly beneficial to conduct SWOT analysis, particularly for network level investigations. Nevertheless, it is worth mentioning that some of the assigned weights and pairwise comparison matrices need to be reformulated in accordance with the type of pavement and prevailing environmental conditions.