

FUZZY MULTI-ATTRIBUTE DECISION MAKING FOR THE SELECTION OF A SUITABLE RAILWAY TRACK MAINTENANCE PLAN: A CASE STUDY IN THAILAND

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ABSTRACT: Degradation of infrastructure has affected service quality; in other words, the rail freight transportation rate has been considerably low at only 2%. As a result, for the purposes of safety and high-reliability levels in infrastructure, several organizations have conducted serious research on the interesting topic of railway track degradation. As the focus of the present study was degradation factors, the Fuzzy Multi-Attribute Decision Making Method (FMADM) was used to analyze railway track defects and degradation and to select a maintenance plan schedule. Related research and literature were reviewed, and a questionnaire was designed to collect opinions from experts working for the State Railway of Thailand (SRT). The experts prioritized risk levels likely to result in the worst breaks or damage, using UIC defect codes. These consisted of transverse break defects without apparent origin (code 200) with the highest level of impact and relative weight of 0.396, followed by star-cracking of fish bolt holes (code 135) with a relative weight of 0.276 and transverse cracking of profile thermite welding (code 421) with a weight of 0.187. The least severe impact was said to come from horizontal cracking at web-head (code 1321) with a relative weight of 0.142. Analysis results based on FMADM indicated that the railway track structure replacement plan, as considered by the experts, was better than the railway track rehabilitation plan, as shown by their importance weights of 0.575 and 0.425, respectively.

Keywords: Fuzzy multi-attribute decision making (FMADM), Maintenance, Rehabilitation, Decision support system (DSS)

1. INTRODUCTION

1.1 Background

Railway network in Thailand includes one-meter railway track size (meter gauge) with a total distance of 4,033 kilometers covering 47 provinces. Most of the railway tracks are single tracks, totaling a length of 3,569 kilometers or 88.5% of Thailand's railway network, while the rest of the network is either double tracks or three-way tracks, totaling a length of 464 kilometers or 11.5% of Thailand's railway network. Overall, 62% of the tracks have been used for more than 30 years and 1,509 kilometers, or 35% of the tracks still have wooden rail sleepers, making them incapable of efficiently supporting increased train speed and weight [1].

According to the International Institution for Management (IMD), World Competitiveness Yearbook 2014, rail transportation development in Thailand ranked 43rd among 60 countries in Asia and had a track network density of 0.009 km/sq.km. Service quality and safety were also reported as unsatisfactory, with train operation lacking punctuality and with a low train speed of only 54 km/hr. for passenger trains and 26 km/hr. for freight

trains. Moreover, information quality of tracks in Thailand (72nd among 148 countries) as per the World Economic Forum Report 2013-2014 ranked much worse than Singapore (10th) and Malaysia (18th) [1]. While railway tracks consist of different components with different characteristics serving different purposes and while each component is designed to support different forces and with different life spans, each component is designed with the same objectives of ensuring safety, convenience, and reasonable maintenance costs. Therefore, laying out a plan for monitoring and maintenance is very important. In general, inspection and maintenance plans for a railway track structure depend on considerations made by the infrastructure managers or service providers that have received government concessions. Maintenance process heart and the primary capital in achieving the highest efficiency in railway track management consist of the following steps (as shown in figure 1): 1) receiving policies from basic infrastructure administration, 2) conducting planning, 3) conducting inspections of the three physical factors including geometry, vibration, and component conditions, 4) conducting analysis, and 5) applying analysis results to further maintenance

planning. The inspection and maintenance are done in cycles. The frequency of the cycles depends on the characteristics of each component on the track. The main factors in determining cycle frequency are the policies of the administrative team and budgeting controls set on the project. Maintenance plan implementation must take into consideration the data on the management of the basic structure of the mega-size railway track system, which relies on continuous data collection and results in analysis, in order to decipher the frequency of the maintenance cycle that will be used to ensure safety and meet standards. However, the Railway Authority of Thailand has its own maintenance measures based on the different types of tracks in its maintenance manual for permanent tracks, including specific maintenance directions for each type of track. This manual is a compilation of other countries' different cycles of inspection and maintenance, with conclusions on important aspects to be considered by the Railway Authority of Thailand.

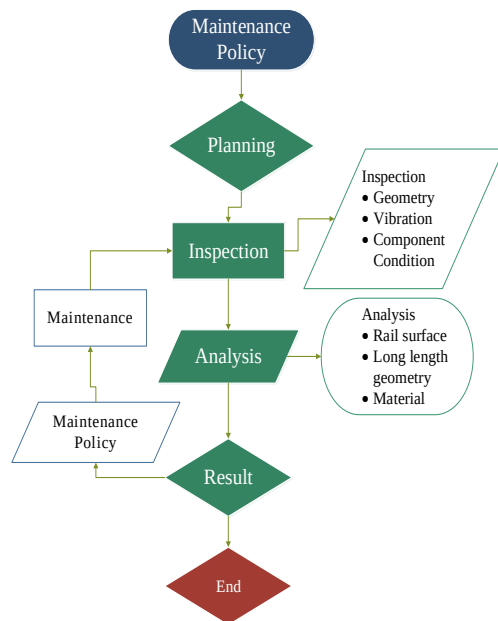


Fig. 1 Procedures for monitoring, and maintenance

The time period for inspection and maintenance needs to be clearly specified due to its importance in improving the efficiency of appropriate maintenance. A delay in increasing the lifetime of any of the components or a delay in maintenance implementation can result in unsafe conditions. Consequently, the older the railway track is and the longer it has been used, the higher maintenance costs will be. Therefore, reducing costs, in addition to implementing appropriate maintenance methods, will help increase the efficiency of the railway tracks. The basic structure of modern railway transportation must include certain inspection methods, for instance, the condition-based approach and crisis and urgency analysis of the key overall

basic structure. The Railway Authority of Thailand has been successful in the maintenance and improvement of the railway track by finding the fitness value between maintenance and improvement [4]. In addition, the fitness value for spatial and temporal coherence is also calculated due to degradation, which is one of the most important aspects of this study. It is important to understand the complexity of degradation mechanisms, the likelihood of occurrence, and contributing factors. Awareness of any changes that will happen to the railway track based on time or impacts from maintaining the track contributes to estimating the residual lifetime of the track, its full life cycle, and all maintenance that will be needed throughout its lifetime. The Railway Authority of Thailand has the capacity to systematically reduce steps and maintenance costs without affecting traffic safety.

1.2 Problem Statement

The behavior of the railway track system and other related systems under inefficient maintenance and increasing freight weight is unique compared to other engineering phenomena, especially as effects from inefficient maintenance of the railway track that may remain unseen for a relatively long period of time. Effects due to inefficient maintenance can include unreliability of the basic structure, rapid loss of quality and increased difficulty in restoration, and more frequent halts of trains if the basic structure is not fixed or maintained. Frequent stops of trains will affect service capacity and quality. Therefore, engineering problems related to maintenance of the railway track will be reconsidered in this study by examining the implementation of maintenance in terms of better supporting service capacity and quality. For the Railway of Thailand, the study found the problems with maintenance as follows:

- A lack of supporting information for decision-making surrounding important maintenance or improvement of basic structures based on current conditions.
- A lack of planning based on modeling and tools to find the fitness value in making decisions related to budget distribution for maintenance, which should also consider the shutting down some of the routes.
- A lack of quantitative methods applied in prioritizing maintenance in terms of effects on service capacity and quality.

2. OBJECTIVES

The goal of this study is to apply FMADM for analyzing railway track defects and degradation and for selecting a maintenance plan for a railway case study in Thailand.

3. LITERATURE REVIEW

3.1 Railway Track System

A railway track can be generally divided into two parts, namely the superstructure and substructure. The superstructure normally consists of the rails, sleepers, rail pads and fastening, while the substructure comprises the ballasts, sub-ballast and subgrade layers as shown in figure 2 [9].

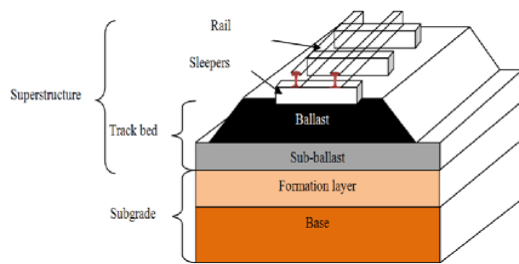


Fig. 2 Cross-Section for a Typical Rail Track System [9]

3.2 Track Degradation

It has been observed that the condition of a railway track rapidly degrades over a period. Having knowledge of the degradation process will aid to estimate the future state of a track condition and in the mitigation of the problems associated with operational safety. The following section presents the theoretical framework and the current practices related to railway track degradation.

3.3 The Quality of Railway Track Structure

Track degradation is a complex process. The mechanism involves many influencing parameters such as axle load, traffic speed, climate, track characteristics, and topography (Fig.3) . Today, research efforts have been carried out not only to address the degradation problems but also to determine the contribution of each parameter to the entire process.

Ferreira & Murray (1997) have investigated the physical factors that may have an impact on track deterioration. According to the results, the authors argue that the declination in the track quality is mainly driven by three parameters, i.e. dynamic forces, axle load, and train speed. Speed contributes to the deterioration process by increasing the dynamic forces at high speeds and decreasing those at low speeds. Load contributes to increased rail wear and fatigue, wheel wear, and strains in rails and sleepers. As a consequence, cracks in the rail

and sleepers will occur, the railhead will be worn out, the rail fastening will be loosening, and the ballast load will thus be redistributed. These situations will reduce travel safety and comfort and increase track components deterioration and delays.

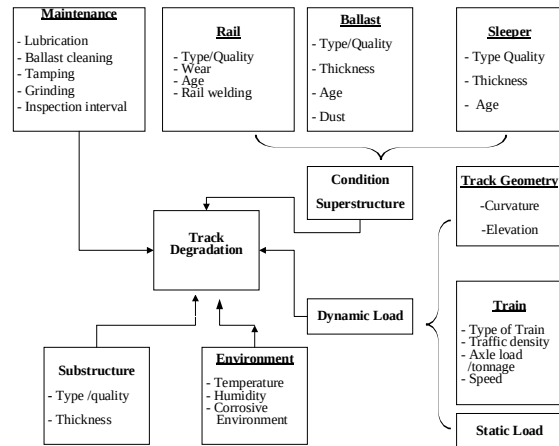


Fig.3 Parameters of Track Degradation [Ferreira & Murray, 1997]

3.4 Investigation of Railway Track Structure

The objectives of railway track maintenance are to constantly maintain the tracks' condition and to fix the tracks for the quality of the tracks and their components to meet standards throughout their service life. Holistic data is required to accompany decision-making surrounding the implementation of efficient track maintenance. Two parameters can be used to investigate the condition of the tracks: track measurement and ride quality. According to UIC Standards, investigations should be conducted in the following manner:

1. Track measurement should obtain the following values:
 - Track geometry, consisting of the elevation of the track on both the right and left sides, the diversion rate of the track on the left/right, curvature, track gauge, elevated curvature, and the diagonal difference between two points 5 meters apart.
 - Rail profile, including horizontal corrosion, vertical corrosion, and corrosion at the 45-degree angle.
 - Corrugation, which takes into account flatness of tracks between 20-3,000 millimeters.
 - Surface defects, including broken railway, deterioration of slipping, rail flaking (plates), flaws, corrugation, welding defects, and rail defects from ballast sprinkling, broken fasteners, and broken sleepers.
2. Ride Quality is a measure of track structure quality which is used to examine the force between the wheels and the tracks and the acceleration rate that occurs during what is called an "on track test."

This is used to measure the level of safety and comfort provided by the service.

3.5 Measurements for Maintenance Implementation

The international measurement principle for implementing maintenance depends on the index value of the track structure's quality and the service time for each of the track components [5]. Due to the fact that train tracks degrade and decrease in quality according to their service time and usage, maintenance is imperative in order to restore the quality of the tracks until it is time for them to be replaced. Track maintenance under the Railway Authority of Thailand is determined through "track control," that is, by comparing each section of the track and their usage quality. This is achieved by comparing the track irregularity index, or P, when measuring static values and by using the Track Quality Index, or QI, when measuring dynamic values, determining the higher and lower values. The inconsistency value of the tracks is sent to superior officers to report the condition of the tracks, and the quality of maintenance for each kilometer is evaluated on whether it meets standards by either the Railway Authority of Thailand or through private contractors [5]. Conditions are divided into 5 categories, with each category having its own error values, as follows:

Table 1 Track quality index tolerance [2]

Track Quality Condition	Track Quality Tolerance (%)					P or TQI value (%)
	Grade	Profile	Cross Level	Alignment	Twist	
Very Good	A	0-13	0-5	0-9	0-14	0-10
Good	B	14-20	6-13	10-20	15-27	11-20
Fair	C	21-30	14-22	21-31	28-36	21-30
Below Fair	D	31-40	23-31	32-41	37-46	31-40
Not Acceptance	E	>41	>32	>42	>47	>41

3.6 Track Inspection Car (TIC)

In Thailand, prior to the maintenance works, the measurement of the track geometry parameters is normally carried out within a specific time interval. The results are recorded as numerical values, which can be used to indicate the level of track quality. Track condition monitoring is performed by the Track inspection car EM120N (Fig.4).



Fig.4 Proposed Track Inspection Car EM120N [4]

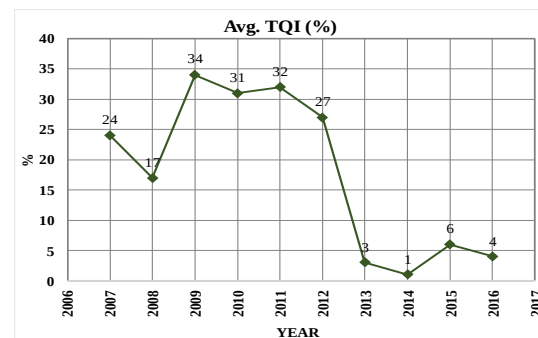


Fig.5 Graph of TQI Values for NE Line [4]

4. STUDY AREA

The area of line chosen for this study was Thailand's Northeastern line from Thanon Chira junction to Nong Khai station comprising 320.900 km. and 35 stations, as shown in figure 6.



Fig.6 Proposed study area location, NE Line

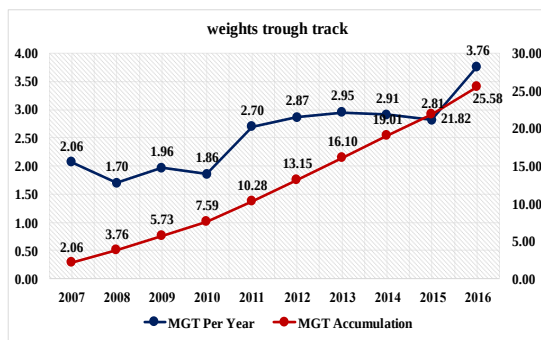


Fig.7 Weight through the track of NE Line [2]

5. METHODOLOGY

The flow chart of the methodology is presented in figure 8.

5.1 DATA COLLECTION

In this study, a thorough selection of the experts was important in order to achieve a high-quality decision support system (DSS) on track Maintenance and Rehabilitation (M&R). The survey experts were carefully selected to guarantee that they acquired the capability needed for the objectives of the study. The survey experts were selected from the State Railway of Thailand (SRT); general directorate, regions, divisions, and subdivisions. The participants were a mixed group of engineers and technicians working at the SRT track department. Their specialist areas were rails, sleepers, ballast, earthworks, track geometry, measuring systems, and engineering structures. Briefly, the experts were selected based on the following criteria: 1) survey experts were engineers and technicians, 2) survey experts were selected by the head of each organization (SRT General Directorate, regions, divisions, and subdivisions), and 3) survey experts had at least 15 years of work experience. Preparation of questionnaire from information maintenance experts of Northeastern Line Maintenance of the State Railway of Thailand was conducted primarily from identifying factors that affect the quality of the way to assess the risk level of the conditions and the M&R plan. The questionnaire consists of the type of fault code, according to the UIC (International Union of Railways) obtained from the query from the reference document. Questionnaire shows a broken or cracked track of the defect code 1321, 135, 200 and 421 as shown in figure 10. The parameters given in figure 10 defined by the expert opinions were used to develop the M&R rules for each type

of M&R operation. The developed DSS is used to calculate some of the parameters based on the FMADM analytical.

5.2 DATA ANALYSIS

5.2.1 Evaluation Criteria

The score of each factor was considered to meet low, moderate, or high-level criteria, and fuzzy data were changed into scores using the Fuzzy Scoring Method (FSM). The AHP procedure is presented in figure 9.

5.2.2 Decomposition

Decision elements used in a hierarchy structure determined by a decision maker are important in terms of demonstrating the consistency of all decision elements, from the highest to the lowest points in the hierarchy, as presented in figure 9.

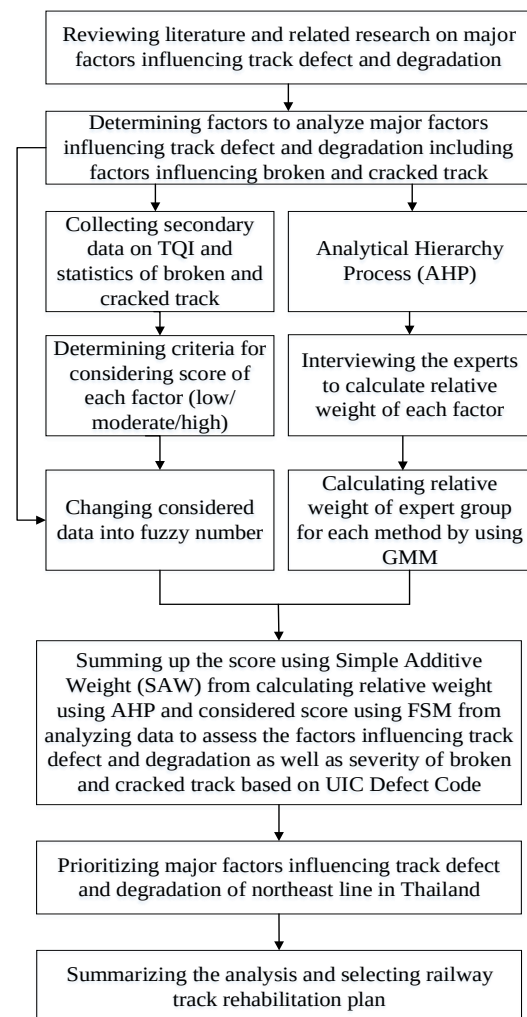


Fig.8 Methodology Flowchart

5.2.3 Fuzzy Multi-Attribute Decision Making

Fuzzy multi-criteria decision making is a method that is developed to support the making of complex decisions. It includes many related factors, for example, in the case of railway maintenance, including a degradation due to maintenance, a status of the superstructure, a status of sub-structure, degradation due to the environment, and degradation due to dynamic Load. These factors are detailed in figure 3. The fuzzy logic is not any less accurate than any other form of logic. It is a mathematical method to handle inherently imprecise concepts (Negnevitsky, 2002).

FMADM was developed based on the basic concepts of fuzzy set theory together with Multi-Attribute Decision Making (MADM). Chen and Hwang (1992) hypothesize that FMADM may consist of fuzzy data (words) and numeric data, and fuzzy data can be represented by fuzzy numbers.

5.2.4 Prioritization

Scores from 1 to 9 are used for pairwise comparison, where 1 indicates that both factors have equal relative weight and 9 indicates that one factor has an extremely high weight relative to the other. Pairwise comparison for decision factors that are on the same hierarchy structure is useful for calculating the relative weights of decision elements for each factor. Necessary data are measurements used in decision making with pairwise comparison are presented in table 2. The decision-making matrix obtained from the pairwise comparison is a pair of decision factors in the same hierarchy level, which corresponds to other factors on the hierarchy level just above. The square matrix has values as shown in equation (1), where w_i and w_j represent the relative weights of factors i and j , respectively.

$$AW = \begin{pmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = n \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = nw \quad (1)$$

According to the theory of square matrix A , consistency can be found when all elements of comparison are in the form of $a_{ik} = a_{ij} \times a_{jk}$, $k = 1, 2, \dots, n$ and principle right eigenvector for A is equal to n (matrix sequence A). It is very difficult for matrix A to be completely consistent. In equation (1), Eigenvalue for A is not equal to n . Normally, the right eigenvector (W) is represented by the largest right eigenvalue ($\lambda_{\max}$) of matrix A , as shown in equation (2).

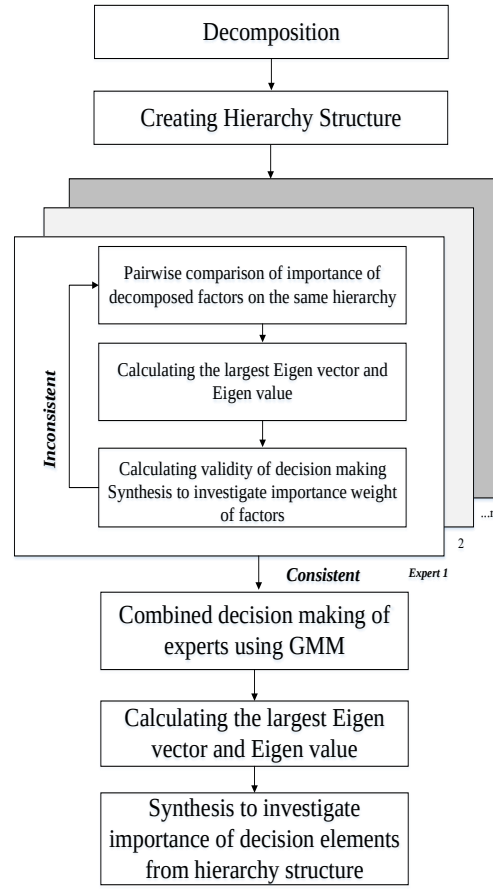


Fig. 9 Proposed Procedure of AHP [10]

$$AW = \lambda_{\max} W \quad (2)$$

The value of $\lambda_{\max}$ is greater than or equal to n when $\lambda_{\max}$ is similar to n . As matrix A is consistent and reliable, $\lambda_{\max}$ can be used as an indicator to express the validity of judgments from matrix A , as presented in equation (3). A consistency index (CI) is developed from random square matrix tests (500 samples), which is known as a random consistency index (RCI) [10], as presented in table 3 [10]. The ratio between the CI and the RCI is called the consistency ratio (CR). The CR is allowable when it is under 0.10, a value indicating consistency in decision-making judgments, as shown in equation (4).

$$C.I. = \frac{(\lambda_{\max} - n)}{n - 1} \quad (3)$$

$$CR = \frac{CI}{RCI} \quad (4)$$

$$w_i = \left(\prod_{j=1}^n a_{ij} \right)^{1/n} / \sum_{k=1}^n \left(\prod_{j=1}^n a_{kj} \right)^{1/n} \quad (5)$$

There are many methods for calculating principle right eigenvector (W) and largest eigenvalue ($\lambda_{\max}$) for square A. This research used normalization of the geometric mean of the row (NGM) [12] as indicated in equations (5) and (6) to estimate principle right eigenvector (W), as it is easy to calculate and understand the largest eigenvalue ($\lambda_{\max}$) of square matrix A. The importance weight of each factor was used to calculate global relative

Table 2 Pairwise Comparison Values [10]

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one activity over another.
5	Strong importance	Experience and judgment strongly favor one activity over another.
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between adjacent scale values	
Reciprocals of above		If activity i has one of the above nonzero numbers assigned to it when compared with activity j, j has the reciprocal value

importance, which could be used for selecting an optimal alternative on the lowest position of the hierarchy structure chart, as shown in equation (7), where C [1, k] = global importance of elements for decision making on hierarchy K, which is consistent with decision making on the upper hierarchy.

$$\lambda_{\max} = \sum_{i=1}^n \left(\sum_{j=1}^n a_{ij} \times W_i \right) \quad (6)$$

Table 3 Sample Consistency Index [8]

Number of factors	1	2	3	4	5	6	7	8	9
RCI	0.00	0.00	0.52	0.90	1.12	1.24	1.32	2.41	1.45

5.2.5 Synthesis

After obtaining the importance weight of each factor on each hierarchy structure, decision-making process using AHP is generally applied to the “principle of hierarchy composition” [10]. Calculated from the importance weight of each factor value, global relative importance that can be used for selecting an optimal alternative is on the lowest position of the hierarchy structure chart as equation (7)

$$C [1, k] = \prod_{i=2}^k B_i \quad (7)$$

where C [1, k] = global importance of elements for decision making on hierarchy K which is consistent with decision making on upper hierarchy.

$B_i = n_i - 1$ Matrix of n_i Matrix of the row that is contained for calculation.

n_i = numbers of factors used for decision making on hierarchy structure i.

Diagnosis of the weight of the cause of the defect in accordance with the fault code (UIC) by the maintenance specialist of the State Railway of Thailand when bringing the weight of experts to perform the average weight analyze to assess the risk of the cause by using decision tree as shown in figure 10, which takes the weight value of the probability of the impact of the defect code, multiplied by the weight value, the cause of the defect to find the risk score and prioritize the cause.

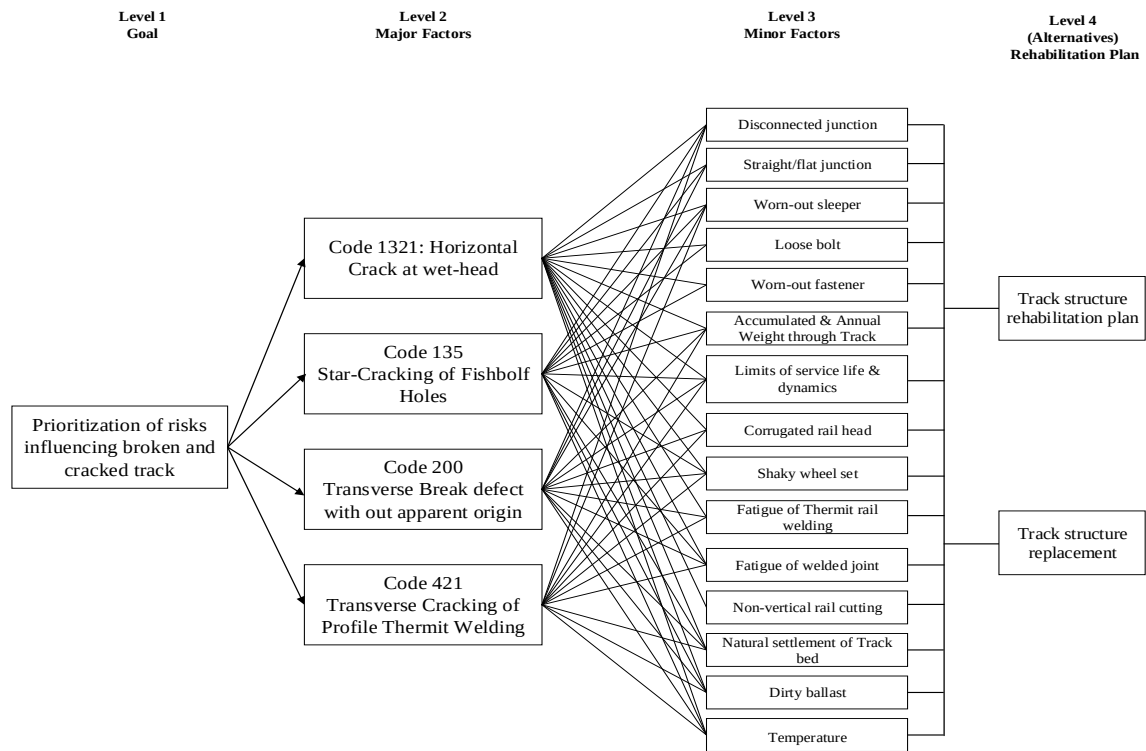


Fig.10 Proposed Fuzzy Composite Structure

Table 4 Results of the Analysis

1. Risk-Causing Defects				2. Causal Factors		
Level	Defect Code	Definition	Weight	Level	Causal Factor	Weight
1	200	Transverse break	0.396	1	Limits on service life & dynamic load	0.200
2	135	Star cracking	0.276	2	Worn-out sleeper	0.150
3	421	Transverse cracking of profile thermite weight	0.187	3	Straight/flat junction	0.120
4	1321	Horizontal cracking	0.142	4	Disconnected junction	0.110
3. The Weight of Criteria for Decision Making in Plan Selection				5	Shaky wheel set	0.083
Criterion	Track Structure Rehabilitation	Track Structure Replacement	Weight	6	Fatigue of thermite rail welding	0.075
1. Quality	0.38	0.62	0.434	7	Fatigue of welded joint	0.066
2. Risk Reduction	0.32	0.68	0.263	8	Corrugated rail head	0.056
3. Return on Investment	0.58	0.42	0.303	9	Accumulated & annual weight through track	0.052
4. Total wt.	0.425	0.575		10	Loose bolt	0.045
				11	Worn-out sleeper	0.033
				12	Non-vertical rail cutting	0.004
				13	Temperature	0.003
				14	Natural settlement of track bed	0.002
				15	Dirty ballast	0.001

6. RESULTS AND DISCUSSIONS

These findings are presented in part 1 of table 4. The experts specified the severity of code 200: a transverse break defect without apparent origin. Its level of severity is the highest with a relative weight of 0.396. This was followed by code 135: star-cracking of fish bolt holes, with a relative weight of 0.276, and code 421: transverse cracking of profile thermite welding with a relative weight of 0.187. The least severe was code 1321: horizontal cracking at web-head, with a relative weight of 0.142.

In addition, according to part 3 of table 4, FMADM analysis results indicate that the railway track structure replacement plan, as considered by the experts, is better than the railway track rehabilitation plan, as shown by their importance weights of 0.575 and 0.425, respectively.

7. CONCLUSIONS AND RECOMMENDATIONS

According to the analysis of factors influencing track quality, particularly track degradation, rail should be considered the most significant element of the track structure, as it withstands the highest stress relative to other elements; in other words, it directly connects to the train's wheels.

According to expert interviews, the northeastern line has encountered the problem of broken and cracked track caused by degradation, which exposes trains to a high risk of derailment, impacted by the usability factor. Data collected from an SRT report with a track quality index showing degradation from 2007-2016 reveal that track defects contributing to breaks or damage can be divided based on the International Union of Railways (UIC) codes using the pairwise comparison method. Each type of defect is different in its starting point and extension direction along the railway track, with a contingency index below 0.01.

8. ACKNOWLEDGMENTS

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