AN AHP-BASED EVALUATION OF MAINTENANCE EXCELLENCE CIRTERIA

T.G. Tendayi[1*] and C.J. Fourie[2]
[1,2]Department of Industrial Engineering
Stellenbosch University, South Africa
[1]ttendayi@sun.ac.za
[2]cjf@sun.ac.za

ABSTRACT

A state of Maintenance Excellence is when an organisation has achieved best maintenance practice standards and has reached the benchmark for the performance of maintenance operations. Various models exist in literature that highlight what elements need to be present in an organization in order to achieve maintenance excellence standards. However, these standards have to be prioritised according to the current state of the organisation's operations. The Analytic Hierarchy Process (AHP) is a technique that is useful in establishing the priority and importance of individual decision-making alternatives through pairwise comparisons. In this study, the AHP process is used to evaluate a set of organisation-specific maintenance excellence criteria. A railway rolling stock maintenance organisation in the Western Cape region of South Africa is used as a case study for this exercise. By applying AHP to the results obtained from a survey conducted at the case study, some inconsistencies were found in the judgments made by the respondents. AHP was then used again to revise these judgments to make them more consistent. The end result of the study was a set of weighted and prioritized maintenance excellence criteria which will be useful in the organization's endeavors to attain maintenance excellence.

[*] Corresponding Author

1 INTRODUCTION

The concept of Maintenance Excellence is gaining wide acceptance as maintenance organisations look for ways to set objectives that will help them to meet their goals. However, identifying which goals are important is one thing, but prioritising them according the needs of the organisation is another. A technique is then required which can give the decision-maker an opportunity to make an informed choice on which objectives to prioritize. The Analytic Hierarchy Process (AHP) is one such technique which is designed to help the decision-maker perform this function, given a set of decision variables. AHP is a tried and tested decision-making tool that has been used to enhance the effectiveness of decision-making processes and to deal with the sometimes subjective linguistic judgments that arise when expressing relationships and correlations. The objective of the work presented here is to broaden the use of this approach by applying it in evaluating the importance of a set of Maintenance Excellence criteria. A survey, carried out at a maintenance organisation in the railway industry, acts as the foundation of this study. The structure of the paper is as follows; there is a brief discussion on the body of knowledge regarding maintenance excellence and the maintenance excellence criteria. A literature review of the AHP method is also done including the steps taken in order to execute it. A brief overview of the case study used in this research is then given. The section following that focuses on the steps taken to execute the AHP-based maintenance excellence criteria evaluation. Concluding remarks on the work carried out in the paper will then be done in the last section.

2 LITERATURE REVIEW

2.1 The Maintenance Excellence Criteria

According to Smith & Hawkins [1], Maintenance Excellence is when an organization has achieved best maintenance practice standards, which are essentially a benchmark for the performance of industrial maintenance. According to them, an organization that has adopted the principles of maintenance excellence will most likely achieve 30-50% reduction in maintenance spending within 3-5 years and also realize production volume increases. It can also be referred to as asset management excellence which is when a plant performs up to its design standards and equipment operates smoothly when needed [2]. Given in Figure 1 are some factors to consider for achieving a state of maintenance excellence.

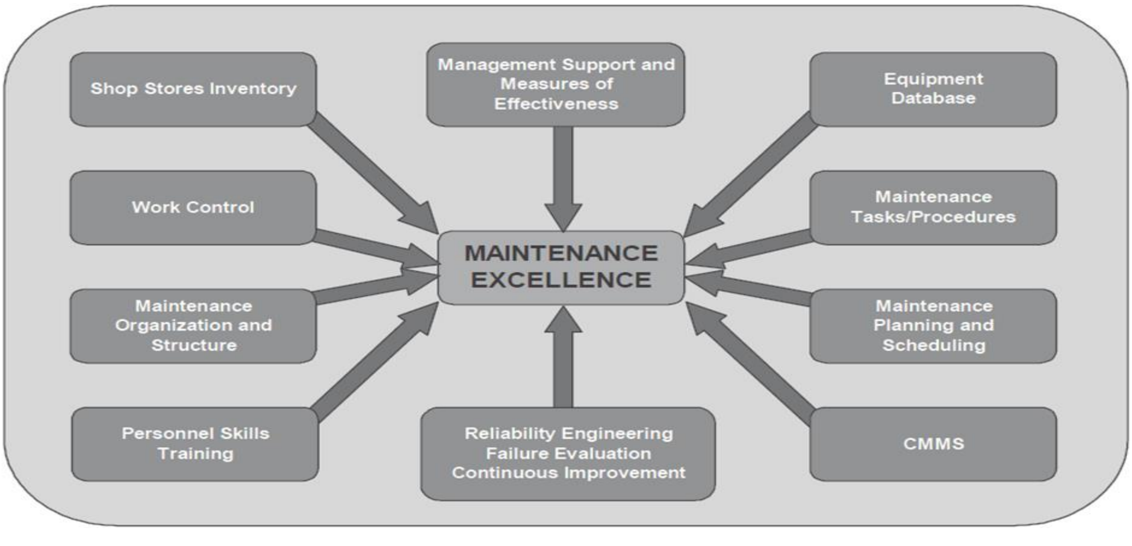

Figure 1: Factors to consider for Maintenance Excellence [1]

Lazreg & Gien [3] give an alternative maintenance excellence model with ten distinct areas, each representing a different aspect of the organization as shown in Figure 2. The purpose of the model is to determine where the maintenance organization’s strengths are so as to make improvements and identify areas of opportunity. The ten areas are subdivided into those concerned with *what* results need to be achieved (Results) and areas concerned with *how to achieve* these results (Enablers).

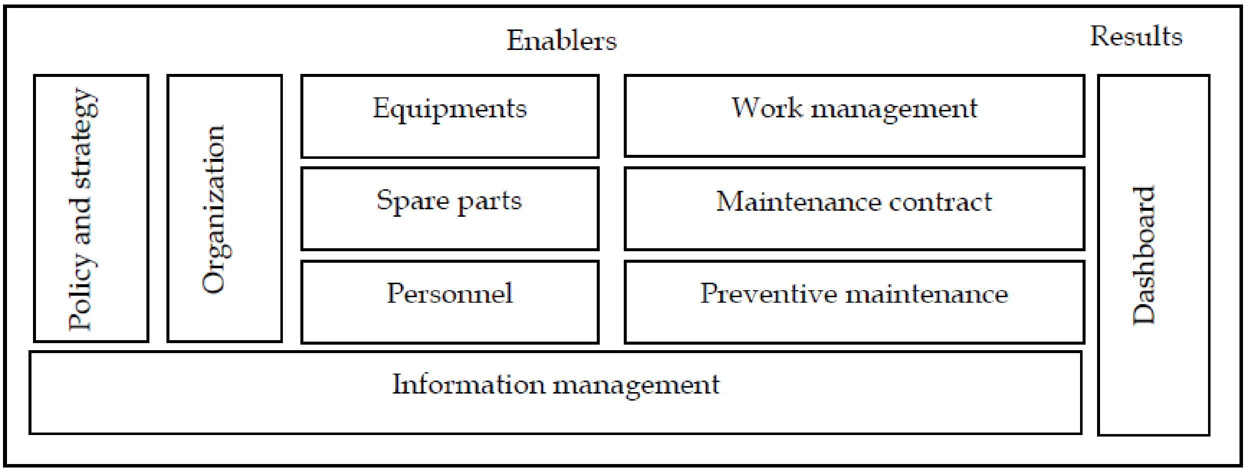

Figure 2: The Maintenance Excellence Model [3]

A maintenance excellence pyramid discussed by Campbell [4] is illustrated in Figure 3. The pyramid acts as an overall strategy or roadmap that can be used to guide choices on how maintenance is managed and what level the organization is. This pyramid stresses the need of having the right solid foundation, starting with the right management and strategy, before any other steps can be taken on the road to achieving maintenance excellence.

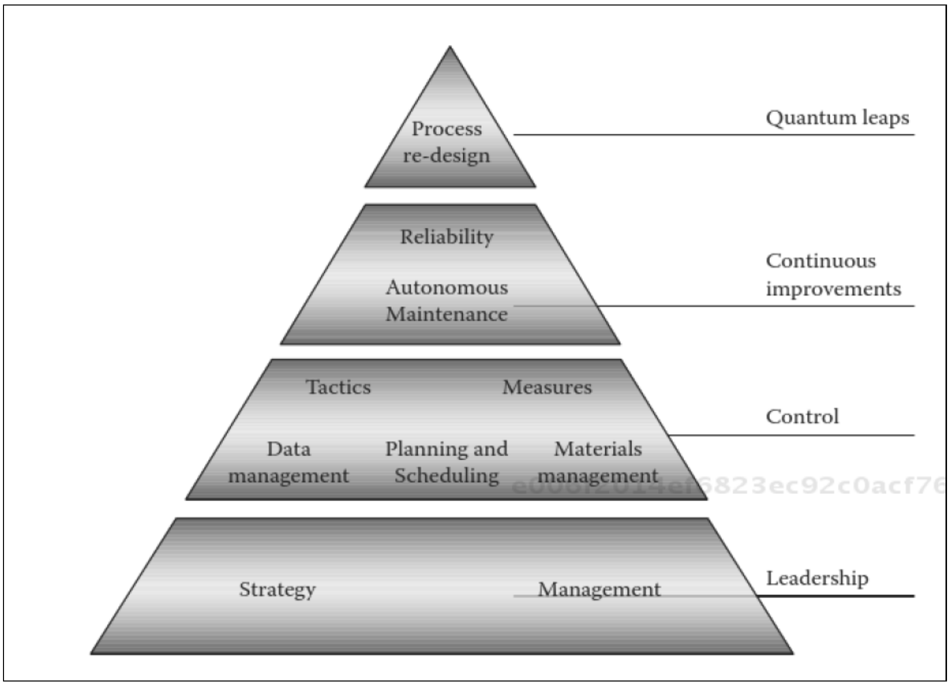

Figure 3: A maintenance excellence pyramid [4]

2.2 The Analytic Hierarchy Process Method

The Analytic Hierarchy Process (AHP) is a systematic decision-making approach that was developed in 1971 by Thomas L Saaty. A very detailed literature review of the many applications of AHP is given by Vaida & Kumar [6] who highlight just how broadly the process has been used. According to the study, AHP has been used in education, engineering, government, industry, management, manufacturing, finance sector and so forth. The reason why it has been so widely used is because of its simplicity, ease of use and flexibility [7].

The process does however have its critics with the earliest being Belton and Gear [8], who state that they discovered many instances where the addition of an alternative causes a change in the relative importance of criteria and thus overall preferences order. They recommend that the pairwise comparison questions be more specific than those advocated in the original method. This view is supported by other studies such as one carried out by Aiqin [9] who propose a new method of rank preservation based on what they call the judgement matrix consistency.

The technique can be summarised in the following steps [5]:

1. Break down the decision-making problem into a hierarchy which is a particular type of system based on the assumption that the entities which are identified, can be grouped into disjoint sets with the entities of one group influencing the entities of only one other group. Figure 4 shows a breakdown into three levels with the potential to have many more levels.

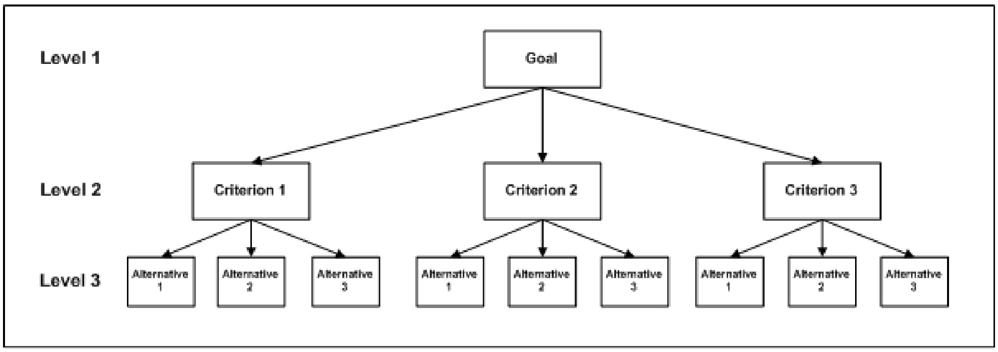

Figure 4: Analytic Hierarchy Process Levels

2. Make pairwise comparisons and establish priorities among the elements in the hierarchy. This helps to determine the strengths or priorities of the elements in one level relative to their importance for an element in the next level. The procedure for doing this is as follows :

Complete a pairwise comparison matrix A for m objectives,

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \tag{1}$$

Where, a_{ij} indicates how much more important the ith element is than the jth element for constructing the column vector of importance weightings. For all i it is necessary that a_{ii}=1 and $a_{ij} = 1/a_{ji}$. The possible assessment value of a_{ij} with the corresponding interpretation is shown in Table 1.

Table 1: Assessment of a_{ij}

Value of a_{ij}	Interpretation
1	Objective i and j are of equal importance.
3	Objective i is weakly more important than objective j.
5	Objective i is strongly more important than objective j.
7	Objective i is very strongly more important than objective j
9	Objective i is absolutely more important than objective j
2,4,6,8	Intermediate values

3. Normalise the resulting matrix. This is done by dividing each entry in column i of A by the sum of the entries in column I. This yields a new matrix A_w, in which the sum of the entries in each column is 1, as shown below.

$$A_w = \begin{bmatrix} \frac{a_{11}}{\sum_{i=1}^{m} a_{i1}} & \frac{a_{11}}{\sum_{i=1}^{m} a_{i2}} & \cdots & \cdots & \frac{a_{1m}}{\sum_{i=1}^{m} a_{im}} \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \vdots & \vdots & \ddots & & \\ \vdots & \vdots & & \ddots & \vdots \\ \frac{a_{m1}}{\sum_{i=1}^{m} a_{i1}} & \frac{a_{m2}}{\sum_{i=1}^{m} a_{i2}} & \cdots & \cdots & \frac{a_{mm}}{\sum_{i=1}^{m} a_{im}} \end{bmatrix} \tag{2}$$

4. Compute c_i as the average of the entries in row i of A_w to yield column vector C

$$C = \begin{bmatrix} c_1 \\ \vdots \\ \vdots \\ c_m \end{bmatrix} = \begin{bmatrix} \frac{\frac{a_{11}}{\sum_{i=1}^{m} a_{i1}} + \frac{a_{12}}{\sum_{i=1}^{m} a_{i2}} + \cdots + \frac{a_{1m}}{\sum_{i=1}^{m} a_{im}}}{m} \\ \vdots \\ \frac{\frac{a_{m1}}{\sum_{i=1}^{m} a_{i1}} + \frac{a_{m2}}{\sum_{i=1}^{m} a_{i2}} + \cdots + \frac{a_{mm}}{\sum_{i=1}^{m} a_{im}}}{m} \end{bmatrix} \tag{3}$$

   Where c_i represents the relative degree of importance for the ith criteria in the column vector of importance weightings.
5. Calculate and check the consistency of the pairwise comparison in the following manner:
   i. Compute $A \cdot C$:
   ii. Compute δ which is called the maximum or principal eigenvalue:

$$A \cdot C = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} \tag{4}$$

   The closer δ is to m, the more consistent is the result.
   iii. Compute the consistency index (CI) as follows:

$$CI = \frac{\delta - m}{m - 1} \tag{5}$$

   iv. Compare CI to the random index (RI) for the appropriate value of m to determine if the degree of consistency is satisfactory. After conducting some experiments at Oak Ridge National Laboratory [5], an average RI for matrices of the order 1-15 using a sample size of 100 was generated and is shown below.

m	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

If CI is sufficiently small, the decision-maker's comparisons are probably consistent enough to give useful estimates of the weights for the objective function. If the consistency ratio, given by CI/RI is less than 0.10, the degree of consistency is satisfactory, but if it is greater than 0.10, serious inconsistences may exist, and the AHP may not yield meaningful results. In situations where that happens, it is necessary to revise judgements and in order to help that revision there are three methods that have been shown to work [5].

Method 1: Form a matrix of priority ratios w_i/w_j and consider the matrix of absolute differences $[|a_{ij} - (w_i/w_j)|]$ and attempt to revise the judgement on the element(s) or row sums with the largest such difference.

Method 2: Form the root mean square deviation using the rows of (a_{ij}) and (w_i/w_j) and revise the judgements for the row with the largest value. The procedure can then be repeated to note improvement.

Method 3: The procedure consists of replacing all a_{ij} in the row in question by the corresponding w_i/w_j and recalculating the priority vector. Repetition of this process has been noted to produce convergence to the consistent case.

3 CASE STUDY

The case study chosen for this research is a railway rolling stock maintenance organisation based in the Western Cape region of South Africa. The main activity that takes place there is the maintenance, repair and overhaul of train sets and their various subcomponents. Figure 5 shows the current management structure at the case study in question. It should be mentioned that this structure is still going through changes as the organisation restructures its operations. According to a recent study carried out by Rommelspacher [11] at the case study, the current overall maintenance policy is shared between time directed maintenance (TDM) and run to failure (RTF). According to Wessels [12], TDM is a maintenance policy that uses the hazard function of part failure to determine when a part is replaced based on the organisation's definition of allowable risk. RTF is generally known as a maintenance policy that allows a machine to run until it breaks down before repairing it. There is currently a shift within the organisation to move from TDM and RTF to Condition Directed maintenance/Predictive maintenance which is a more tactical maintenance policy. Such tactical maintenance policies are good enablers for Maintenance Excellence as demonstrated in the models discussed earlier in section 2.1.

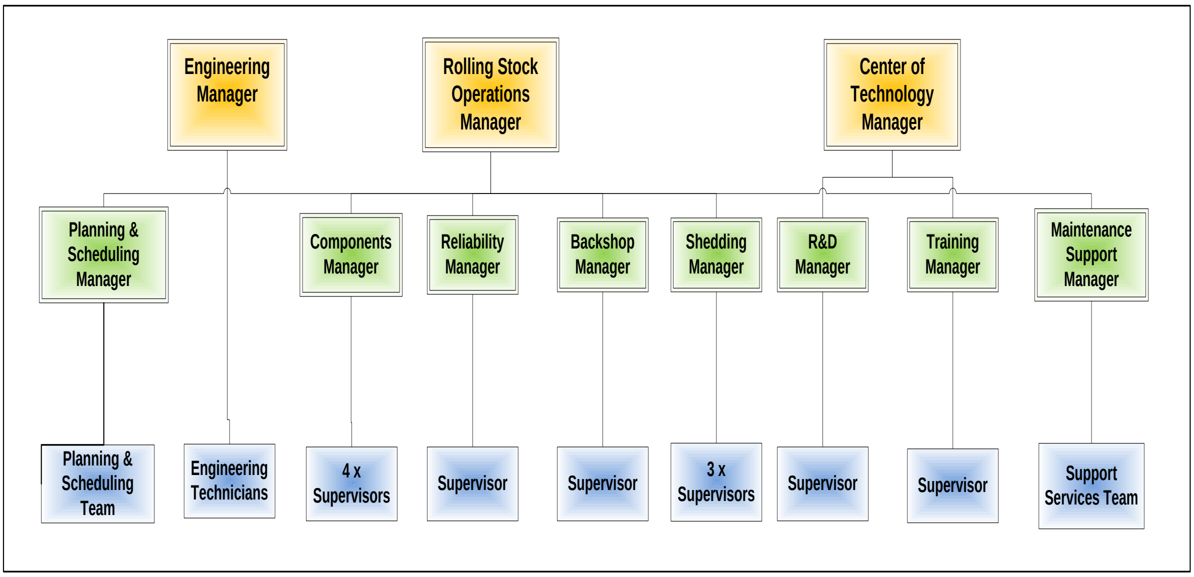

Figure 5: Rolling Stock Organogram of Case Study

4 AHP EVALUATION

A Maintenance Excellence survey was carried out in order to obtain the data necessary for the study. The survey constituted of a set of questions derived from maintenance excellence criteria in literature, as discussed in section 2.1, which are relevant to rolling stock maintenance.. Ad-hoc interviews with key personnel were also carried out and from them, the author gained an understanding of the critical areas that affect the performance of the maintenance function of the organisation (e.g. use of FMMS/SAP). These critical areas were included in the maintenance excellence survey. Management and supervisors of the relevant sections, as shown in the organogram in Figure 5, were asked to fill out the questionnaires giving an indication of where they perceived the organisation to be; in as far as each maintenance excellence criteria is concerned. Table 2 shows the results of the survey conducted at the case study with Table 3 showing the sample of respondents together with their respective sections. The Priority Scores were obtained by first assigning weights of 1, 2, 3, 4, and 5 for the reactions "Excellent", "Good", "Average", "Poor" and "Bad" respectively. The rationale of this weighting is that the more a particular ME practice is viewed as lacking in the organisation, the higher the weight and subsequently the higher the priority it will receive. These weightings were then multiplied by the number of responses and then added together to give the final score. An example of such a calculation is given below for the weighting of "Spare Parts and Material Availability" (SP):

$$\text{"Excellent"} \times 1 + \text{"Good"} \times 2 + \text{"Average"} \times 3 + \text{"Poor"} \times 4 + \text{"Bad"} \times 5$$

$$= 0 \times 1 + 1 \times 2 + 2 \times 3 + 10 \times 4 + 4 \times 5$$

$$\underline{\mathbf{= 68}}$$

Table 2: Respondents' Results and Weighting

Number of Responses								
Serial Number	ME Practice	Excellent	Good	Average	Poor	Bad	Priority Scores	Rank
1	**CI**		6	8	3		48	**11**
2	**FMMS**	1	1	5	8	2	60	**2**
3	**SC**	3	9	4	1		37	**15**
4	**DOP**	3	6	7	1		40	**14**
5	**MGT**		5	8	4		50	**9**
6	**SP**		1	2	10	4	68	**1**
7	**WO**		2	10	4		50	**9**
8	**MAINT**		5	8	5		54	**6**
9	**SKILLS**		4	10	1	1	47	**13**
10	**POL**		2	10	5		54	**6**
11	**CONTR 1**		3	13	3		57	**4**
12	**CONTR 2**	1	6	7	5		54	**6**
13	**KPI**		3	4	9	1	59	**3**
14	**WI**		2	8	5		48	**11**
15	**QUAL**		6	8	3		48	**11**

Table 3: Survey Sample Profile

Section	Respondents
Components Shop	1 Manager & 2 Supervisors
Reliability Shop	1 Manager & 2 Supervisors
Engineering	1 Manager
Support Services	1 Manager & 2 Supervisors
Research & Development	1 Manager & 2 Supervisors
Lifting Shop	1 Manager & 2 Supervisors
Training	1 Manager

In order to determine the consistency of the results of the survey, a Pairwise comparison based on the Priority Scores was made using the Analytic Hierarchy Process (AHP). Figure 6 shows a pairwise comparison matrix constructed according to Eqn. (1) for these scores.

	CI	FMMS	SC	DOP	MGT	SP	WO	MAINT	SKILLS	POL	CONTR 1	CONTR 2	KPI	WI	QUAL
CI	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1
FMMS	7	1	9	7	5	1/5	5	5	7	5	3	5	3	7	7
SC	1/7	1/9	1	1/3	1/7	1/9	1/7	1/7	1/5	1/7	1/7	1/7	1/9	1/7	1/7
DOP	1/5	1/7	3	1	1/5	1/9	1/5	1/7	1/5	1/7	1/7	1/7	1/7	1/5	1/5
MGT	3	1/5	7	5	1	1/7	1	1/3	3	1/3	1/5	1/3	1/5	3	3
SP	7	5	9	9	7	1	7	7	9	7	7	7	5	7	7
WO	3	1/5	7	5	1	1/7	1	1/3	3	1/3	1/5	1/3	1/5	3	3
MAINT	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
SKILLS	1/3	1/7	5	5	1/3	1/9	1/3	1/5	1	1/5	1/5	1/5	1/7	1/3	1/3
POL	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
CONTR 1	5	1/3	7	7	5	1/7	5	3	5	3	1	3	1/3	5	5
CONTR 2	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
KPI	7	1/3	9	7	5	1/5	5	3	7	3	3	3	1	7	7
WI	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1
QUAL	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1

KEY:

CI	Continuous Improvement Efforts
FMMS	Use of FMMS/SAP
SC	Schedule compliance
DOP	Detailed Operating Procedures
MGT	Management support
SP	Spare parts and material availability
WO	Work orders/Job cards
MAINT	Maintenance Organisation and structure
SKILLS	Personnel Skills training
POL	Maintenance Policy & Strategy
CONTR 1	Maintenance Contracting 1
CONTR 2	Maintenance Contracting 2
KPI	Key Performance Indicators
WI	Workforce Involvement
QUAL	Conformance Quality

Figure 6: ME Pairwise Comparison Matrix

This matrix is then normalised and gives the new Matrix according to Eqn. (2) as shown in Figure 7.

	CI	FMMS	SC	DOP	MGT	SP	WO	MAINT	SKILLS	POL	CONTR 1	CONTR 2	KPI	WI	QUAL
CI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FMMS	1/7	1/8	0	0	1/7	0	1/7	2/9	1/8	2/9	1/5	2/9	1/4	1/7	1/7
SC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DOP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SP	1/7	3/5	0	1/9	1/5	1/3	1/5	1/3	1/7	1/3	3/7	1/3	3/7	1/7	1/7
WO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAINT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SKILLS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
POL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CONTR 1	0	0	0	0	1/7	0	1/7	1/8	0	1/8	0	1/8	0	0	0
CONTR 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KPI	1/7	0	0	0	1/7	0	1/7	1/8	1/8	1/8	1/5	1/8	0	1/7	1/7
WI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
QUAL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7: Normalised ME Comparison Matrix

The importance weighting of each ME criterion is then derived from this matrix according to Eqn. (3) and the consistency measures according to Eqn. (4). These are displayed in Table 5 where they are ranked from the one with the highest ranking to the one with the lowest.

The Consistency Index is calculated from Eqn. (5) where δ is given by Eqn. (4) and is equal to 17.45 and $m = 15$, thus giving:

$$\boldsymbol{CI} = \frac{17.45 - 15}{15 - 1}$$

$$= \mathbf{0.175}$$

Table 5: Importance Weighting of ME Criterion

ME Criterion	Importance Weighting	Consistency Measure	Rank
Spare Parts and Material Availability	0.26	19.33	**1**
Use of FMMS/SAP	0.15	19.54	**2**
Key Performance Indicators	0.12	19.12	**3**
Maintenance Contracting 1	0.09	19.01	**4**
Maintenance Organisation & Structure	0.06	18.00	**6**
Policy and Strategy	0.06	18.00	**6**
Maintenance Contracting 2	0.06	18.00	**6**
Management Support	0.04	17.06	**9**
Comprehensive Work Orders	0.04	17.06	**9**
Continuous Improvement Efforts	0.03	15.89	**11**
Workforce Involvement	0.03	15.89	**11**
Conformance Quality	0.03	15.89	**11**
Personnel Skills Training	0.02	15.85	**13**
Detailed Operating Procedures	0.01	16.29	**14**
Schedule Compliance	0.01	16.85	**15**

For m = 15, we have $\boldsymbol{RI}$ given by 1.59. This gives a Consistency Ratio of:

$$\frac{0.18}{1.59}$$
$$\underline{= \mathbf{0.11}}$$

The value of 0.11 is just outside the scope of the acceptable threshold value of 0.10. There is therefore a need to revise the judgements made so that they fall within the acceptable limits and to do that, Method 3 from is used. This yields the results shown in Table 6.

Table 6: Revised ME Importance Weightings

ME Criterion	Importance Weighting	Consistency Measure	Rank
Spare Parts and Material Availability	0.17	16.96	**1**
Key Performance Indicators	0.15	18.05	**2**
Maintenance Contracting 1	0.12	18.06	**3**
Use of FMMS/SAP	0.11	17.30	**4**
Maintenance Organisation & Structure	0.08	17.33	**5**
Policy and Strategy	0.08	17.33	**6**
Maintenance Contracting 2	0.08	17.33	**7**
Comprehensive Work Orders	0.06	15.19	**8**
Management Support	0.04	16.47	**9**
Continuous Improvement Efforts	0.03	15.77	**10**
Workforce Involvement	0.03	15.77	**11**
Conformance Quality	0.03	15.77	**12**
Personnel Skills Training	0.02	15.88	**13**
Detailed Operating Procedures	0.01	15.09	**14**
Schedule Compliance	0.01	14.73	**15**

Figure 8 shows the difference between the values of the original importance weightings and the revised ones.

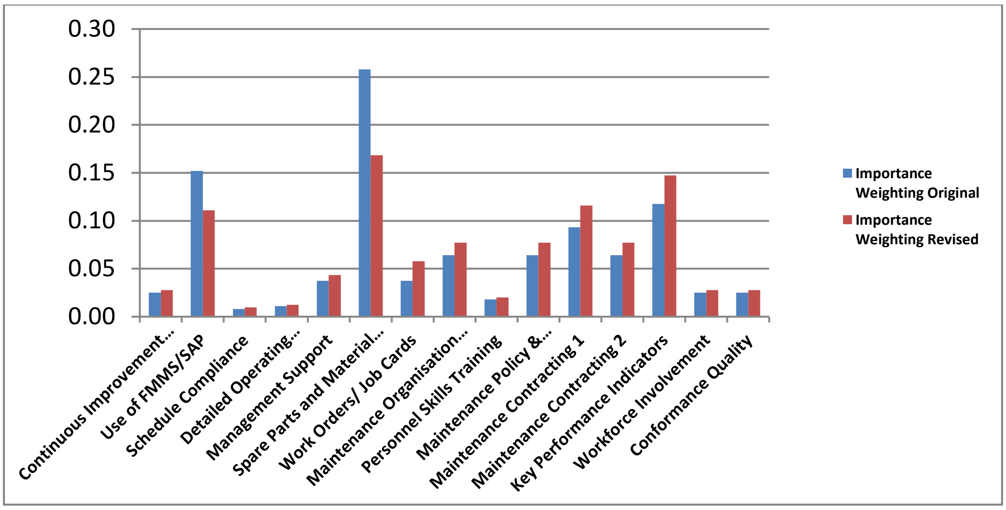

Figure 8: Revised vs. Original Importance Weightings

The Consistency Index is calculated from Eqn. (5) where δ is given by Eqn. (4) and is equal to 16.47 and $m = 15$, thus giving:

$$\boldsymbol{CI} = \frac{16.47 - 15}{15 - 1}$$
$$= \mathbf{0.105}$$

For m = 15, we have $\boldsymbol{RI}$ given by 1.59. This gives a Consistency Ratio of:

$$\frac{0.105}{1.59}$$
$$\underline{= \mathbf{0.07}}$$

The new value for the consistency ratio is below the threshold of 0.10 hence giving acceptability to our pairwise comparison.

5 CONCLUDING REMARKS

In this study, the evaluation of a set of maintenance excellence criteria using the Analytic Hierarchy Process has been highlighted. The set of criteria was obtained from a maintenance excellence survey conducted at a rail maintenance organisation aiming to achieve maintenance excellence but facing the problem of how to prioritise the different set of goals. The AHP approach was then used to evaluate the judgements from the survey in order to first determine their consistency and then secondly to give each of the criteria an importance weighting. Inconsistences in the results of the survey were found, showing a consistency ratio out of the acceptable threshold of 0.10. This anomaly was rectified using prescribed AHP methods in order to give more consistent judgements and hence producing what should be more accurate importance weightings of the various maintenance excellence criteria. Future work might involve going back to the case study to find out what initially caused the inconsistencies picked up by the AHP method. This will help give an even more accurate picture of the rankings and importance of each of the maintenance excellence criteria. The main contribution of this paper has been in using the AHP method in a unique setting in the rolling stock maintenance environment in order to find the best way of achieving maintenance excellence.

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