

A fuzzy-grey-weighted aggregate sum product assessment methodical approach for multi-criteria analysis of maintenance performance systems

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Abstract Diverse maintenance performance models have been previously proposed in literature. However, many of these frameworks perform inefficiently or are not applicable in real-world problems due to their over-simplified assumptions. Such models do not take into account peculiarities of the maintenance situation in which multiple factors need to be prioritised under uncertain conditions. Keeping the above issues in mind, this communication proposes a framework for ranking maintenance performance systems using integrated fuzzy entropy weighting method, grey relational analysis (GRA) and weighted aggregate sum product assessment (WASPAS). The values of criteria weights were determined using fuzz entropy weighting method. Ranking was carried out using GRA and WASPAS methods. GRA ranking considered a criterion, while WASPAS method considered multi-criteria. It is the belief of the authors that merging these three mentioned tools generates synergy. The synergic advantage of the fusion is that these tools interact to create the combined results of ability to handle logic decisions, or partial information and choice among complex alternatives, demonstrated in this paper. The built-up frame-work was illustrated with practical data from five manufacturing companies operating in Nigeria with

information gathered through the questionnaire approach to show that the approach can be effectively implemented in practice. Based on the proposed framework's results, the highest ranked maintenance system belongs to companies 4 and 5, while the lowest ranked maintenance system belongs to company 5. TOPSIS method was used to determine the best performing maintenance function of the companies. It was observed that maintenance system of company 4 was the highest ranked system. The results from model testing confirmed that the presented scheme is feasibility in industrial settings, efficient and capable of revealing the best company in performance according to certain six input criteria. The novelty of this approach is its uniqueness of the combined frameworks' structures in achieving the highest accuracy of estimation, introduced for the first time in maintenance performance assessment in a multi-criteria framework.

Keywords WASPAS · Fuzzy logic · Grey relational analysis · Maintenance · Performance · Multi-criteria

1 Introduction

Nowadays, the subject of performance measurement in both production and service concerns is of relevance and interest (Liyana and Kumar 2003; Zhou et al. 2014; Sari et al. 2015a, b) and provides insights into an arena that is not currently fully understood. With the diversities of manufactured products by companies, expanding asset base, increase in sophistication of technology of production, the issue of how to maintain emerging organisations is central in the agenda of companies, and maintenance performance measurement (Chopu-inwai et al. 2013), monitoring and control have therefore been taken very seriously

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by organisations (Liyanage and Kumar 2001a, b; Azadeh et al. 2014a, b). The information that is generated from maintenance performance measurements is used during decision-making process.

In the maintenance arena, decision making is very complex and difficult to track with respect to reporting and controlling the outcomes of the maintenance function in quantifiable measures. The traditional-problem solving approach in maintenance performance evaluation has sometimes performed woefully, inefficiently or is not applicable in many cases. This then leads to over-simplification of assumptions being made by maintenance performance modellers and analysts to solve problems. Obviously, to overcome this literature deficiency, multi-criteria decision making methods are necessary. Multi-criteria decision-making methods have attracted a wide range of attention in the scientific field in recent times (Khanlari et al. 2008; Wang et al. 2008; Lu et al. 2009; Bashiri et al. 2011; Duran 2011; Kumar and Maiti 2012; Zavadskas et al. 2014). Different multi-criteria decision-making schemes appear to have been successfully contributed in obtaining solutions for complex real-world problems. Frequently used multi-criteria decision-making methods are TOPSIS (technique for order preference by similarity to ideal solution) (Kabir and Hasin, 2012), WASPAS (weighted aggregate sum product assessment), promethee (preference ranking organization method for enrichment evaluation) as well as ELECTRE (elimination et choix traduisant le realite).

Unfortunately, the applications of the above mentioned multi-criteria decision-making methods are sparsely implemented in maintenance performance measurement (Parida and Kumar 2009). To the best of our knowledge, only a case with detailed analysis, using multi-criteria methods has been reported in literature for the maintenance systems (Parida and Chattopadhyay 2007). The current study extends the work Parida and Chattopadhyay (2007) from a number of viewpoints. First, the application of linguistic terms in describing maintenance performance measurement is considered. A second perspective is the introduction of a weighting framework for maintenance performance measurement criteria. Another extension is the use of grey relational analysis (GRA) to aggregate maintenance performance measurement factors into a criterion. Last, ranking of maintenance systems performance using multi-criteria tools is also an extension of the work of Parida and Chattopadhyay (2007).

The goal of the present study is the advancement of a ranking framework for maintenance systems performance. The proposed framework is based on fuzzy-grey-based WASPAS methodology. In the framework, WASPAS method was used to aggregate the fuzzy entropy weighting method (FEWM) and GRA results. The applicability of the proposed framework was verified using information

obtained from five manufacturing system based on six maintenance performance criteria.

The novelty of this study is that it considered multi-criteria analysis in analysing maintenance performance based on linguistic terms. Another novelty of the current study is the application of FEWM for maintenance performance measurement criteria weights determination. In addition, the employment of GRA to aggregate maintenance performance measurement criterion factors and ranking of maintenance systems are also novelties of this study. Finally, the application of WASPAS and TOPSIS methods for ranking of maintenance systems performance are among novelties of this study.

2 Literature review

In the maintenance performance arena, a growing number of excellent reviews have been documented by researchers and prominently by Kumar's research group in Sweden (Parida and Kumar 2006). Knowledge in this area has been updated by the same research group in classic reviews (Kumar et al. 2013; Parida et al. 2015). Another review was recently carried out by Sari et al. (2015a, b). Consequently, the reviews presented in this paper are only some key related contributions to the current work.

De Groote (1995) demonstrated the used of quantifiable performance indicators in analysing maintenance performance systems with the aid of quality audit. De Groote justified his approach using cost-benefit concepts based on information on 10 performance indicators among three organisations. His study revealed that priority setting and information analysis in maintenance performance systems are pivotal to successful operation of maintenance performance systems. Arts et al. (1998) adopted a method in industrial engineering to explain the required information system for inferential verdict on the process industry's operational maintenance performance. A determination of the pointers to locating the largely expensive equipment from the maintenance perspective was made. The current maintenance perception cost as well as the main constituents of maintenance cost should also be focused on. Furthermore, the application of balanced scorecard in tracking maintenance action plan effectiveness was reported by Tsang (1998). In Tsang's (1998) study, the use of balanced scorecard as a medium for enlightening maintenance personnel on organisation's maintenance strategy was mentioned.

Among the many maintenance performance measures proposed by several authors in literature, the ones by Oke and Oluleye (2005) as well as Kumar and Parida (2006) are relevant to this study. Oke and Oluleye (2005) tracked maintenance performance to avoid cyclic occurrence when

using a number of standard performance indices utilised in industries. The study consists of interesting and useful set of factors in many practical situations. In addition, the simplicity of composing the performance measures in practice are key motivations for maintenance administrators for the potential use the tool for maintenance performance in companies in Nigeria.

However, the approach by Oke and Oluleye (2005) did not model consider fuzzy logic application. The contribution of Kumar and Parida (2006) is also internationally relevant. Unfortunately, Kumar et al.'s methodology did not also account for linguistic terms application. Also, prioritisation concept was not considered in their study. Alsyouf (2006) built up a system of planned maintenance performance measurement using a balanced scorecard structure to weigh up the contributions of base functions. A report was given on the possibility to enhance company's return-on-investment up to 9%. Parida and Chattopadhyay (2007) built up a multi-criteria framework for the measurement of maintenance performance. It was reported that the gauges at the echelons of sub-system/component, plant and corporate were associated to the MPis for the purpose of organisational goals and strategy.

Muchiria et al. (2011) built up a performance notional representation for the maintenance function in which alignment of maintenance goals through manufacturing and corporate goals was sought, providing an association among maintenance goals, maintenance process/endeavour as well as maintenance outcomes.

The use of cost of poor maintenance as it affects maintenance performance was investigated by Salonen and Deleryd (2011). In their study, they pointed out that their approach had the potential of recognising performance deficiencies in maintenance performance systems. The novelty of their approach is its ability to justify investment in maintenance activities while recognising areas where cost of maintenance is poorly managed established from the standpoint of performance of the maintenance systems.

Maletic et al. (2012) investigated the impact of continuous improvement in maintenance activities on maintenance performance. The results of their study indicated that positive relationships exist between continuous improvement in maintenance activities and maintenance performance. Also, the need for inclusion of quality in maintenance activities was advocated in their study. The issue of how quality in maintenance engineering based on improvement in maintenance system reliability, sustainability and productivity was examined by Narayan (2012). The work noted that continuous improvement in business performance is achievable by establishing a balance among human and non-human variables in business processes. Their study showed that this is possible through joint analysis of keys business parameters such as maintenance,

profitability, process safety, technology and reliability. Gustafson et al. (2013) assessed and analysed a load haul dump's maintenance performance as well as its production using key performance indicators (KPIs) for a mine setup in Sweden. A common observation was that close to a third of the data entered manually was not regular when compared with the production times that were recorded automatically. In addition, the authors ascertained the existence of comparability in the operation as well as loading rate but dissimilarities in the manufactured tonnes/machinery hour connecting the two machineries.

Soderholm and Norrbin (2013) introduced how risk-oriented dependability method employable in the linkage of maintenance performance appraisal as well as management to the general aims within the organisation. The study focused on an instance of the Swedish transport management. It was reported that the risk-based dependability approach critical availability indicators was employed to check the influence of dependability management actions aimed at different indenture ranks of the infrastructure and connected to the task of various hierarchical ranks of the organisation. It was added that the approach effectively strengthened the internal control of the organisation. Chopu-inwai et al. (2013) developed a maintenance performance measurement model with reference to the price-tag of deprived maintenance; the national quality award tagged "Malcom Baldrige" as well as the perspective-input-procedure-product evaluation. A total of 105 factors were considered using questionnaire. It was concluded that the study results helped in improving the maintenance performance system. Juuso and Lahdelma (2013) developed a comprehensive approach to efficiently integrate maintenance and operations by combining process and condition monitoring data with performance measures. It was reported that through data-driven analysis methodology it could be demonstrated that management-oriented indicators can be presented in the same scale as intelligent condition and stress indices.

van Horenbeek and Pintelon (2014) built up a maintenance performance management structure, which aligns the objectives of maintenance on top of all management ranks through the pertinent management performance indices. The authors concluded that the framework was applicable and capable to assist maintenance managers to define and select maintenance performance indicators (MPis) in line with the objectives and strategies of the company. Stefanovic et al. (2015) assessed and ranked the indicators due to maintenance process, maintenance cost and equipment employing fuzzy set method and genetic algorithm. The framework was based on weights of indicators classified employing decision makers' experience from examined small and medium enterprises. The calculation was done using fuzzy set approach. The authors concluded that the

tool presented is valuable in the identification of strengths and weaknesses, and learning from organisations and improving maintenance performance. Sari et al. (2015a, b) developed an original structure for evaluating sustainable maintenance performance with 15 quantities at the group echelon and 20 quantities at the strategic echelon as well as 43 quantities at the operative echelon with the use of survey in the Malaysian automotive companies. Very recently, Famurewa et al. (2015a, b), in two notable contributions advanced the literature by analysing the railway infrastructure performance measurement.

Despite these notably contributions in literature, there is still much information absent, especially on the aspect of multi-criteria analysis for the assessment of maintenance performance. The problem of sparse information on maintenance performance measurement multi-criteria analysis is due to the challenge of analysing linguistic terms for criteria. More recently, fuzzy logic has been applied to address this difficulty.

3 Methodology

The proposed framework that is presented in this study is oriented around a multi-criteria multi-factor concept. Based on the work of Parida et al. (2003), the criteria and factors for maintenance system performance evaluation are selected (Table 1). The weights for the criteria are determined based

Table 1 Criteria and factors for maintenance system performance evaluation

Criteria	Factors
Equipment or process related (y_1)	Overall equipment effectiveness (f_{11})
	Product quality (f_{12})
	Frequency of equipment stoppage (f_{13})
	Production rate (f_{14})
Cost or finance related (y_2)	Production cost (f_{21})
	Maintenance cost (f_{22})
Maintenance task related (y_3)	Quality of maintenance work (f_{31})
	Change over time (f_{32})
	Unplanned maintenance work (f_{33})
	Planned maintenance work (f_{34})
Customers satisfaction (y_4)	Quality return (f_{41})
	Number of new customers (f_{42})
	Customers' satisfactions (f_{43})
	Customers' complaints (f_{44})
Health safety and environment (y_5)	Number of accidents (f_{51})
	Compensation cost (f_{52})
Employee satisfaction (y_6)	Technicians complaint (f_{61})
	Technicians turnover rate (f_{62})

on FEWM. Aggregation of factors for a criterion is carried out using GRA. The aggregation of criteria and their weights for the ranking purpose is based on the concept of WASPAS method (Fig. 1). The proposed framework deals with the aggregation of FEWM, GRA and WASPAS results as a basis for ranking maintenance performance system. The data for implementing the proposed framework is in form of linguistic variables. The variables are obtained using a questionnaire. The questionnaire is designed to capture the various factors which are presented in Table 1. The first section of the questionnaire deals with the evaluation of the importance of the criteria in Table 1. The second section of the questionnaire considered the impacts of maintenance activities with respects to the factors in Table 1. For all the questionnaires administered in the companies, it was ensured that three respondents filled them and those who filled them are responsible for unit functions.

3.1 Fuzzy entropy method

FEWM is a tool which uses subjective judgements to determine the weights of criteria. Subjective judgements are expressed in linguistic terms in order to aid mathematical analysis. The linguistic terms are first of all converted into fuzzy numbers (Table 2). The conversion of linguistic terms into crisp values is usually done using fuzzy numbers. There are several fuzzy numbers which can be used for conversion of linguistic terms into crisp values in literature. Fuzzy triangular and trapezoidal numbers are the two widely used fuzzy numbers in literature (Shemshadi et al. 2011; Sun and Ouyang 2015). The current study uses triangular fuzzy numbers in converting linguistic terms into crisp values (Fig. 2). In Fig. 2, the first fuzzy triangular fuzzy number is (q_{11}, q_{12}, q_{13}) , while the second fuzzy triangular fuzzy number is (q_{21}, q_{22}, q_{23}) .

The determination of criteria weights using FEWM starts with the design of a decision matrix expressing the criteria weights in linguistic terms. This is then preceded with the conversions of linguistic terms into fuzzy numbers and crisp values. The conversion of fuzzy numbers into crisp values is known as defuzzification (Chen and Hsieh 2000).

$$z_i = \frac{q_{1i} + 4q_{2i} + q_{3i}}{6}. \quad (1)$$

The crisp values are then normalised (Eq. 2) in order to generate the entropy values for each criterion (Eq. 3).

$$p_{kj} = \frac{z_{kj}}{\sqrt{\sum_k^K z_{kj}^2}} \quad (2)$$

$$e_j = \frac{1}{\ln(K)} \sum_{k=1}^K P_{kj} \ln(P_{kj}) \quad (3)$$

Fig. 1 Methodological framework

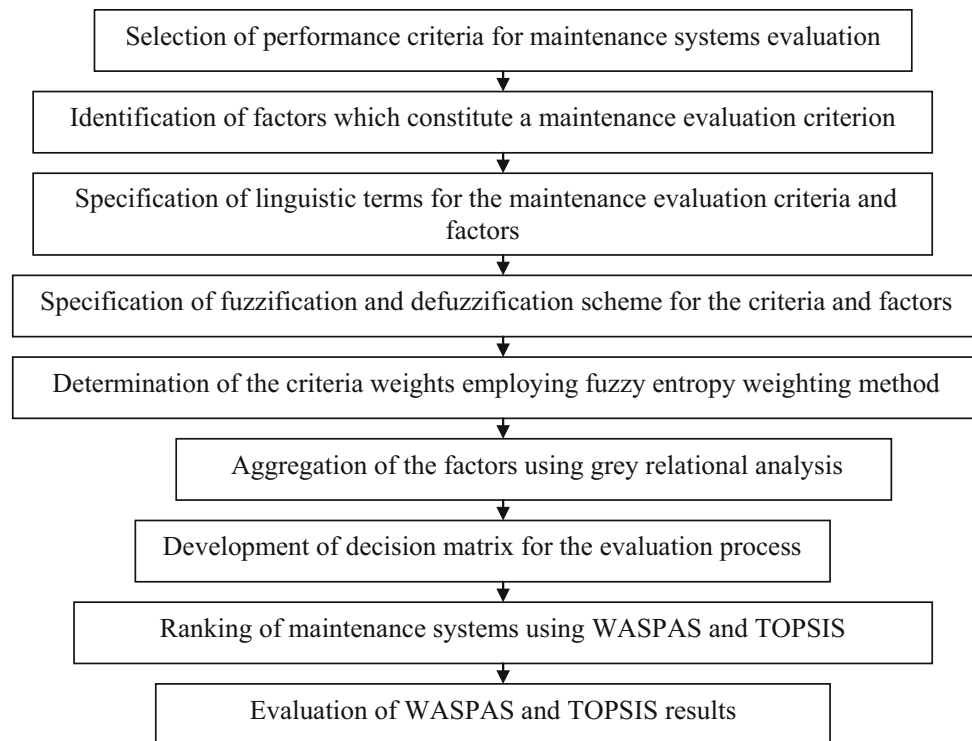


Table 2 Triangular fuzzy numbers for importance of criteria

Linguistic terms	Symbols	Triangular fuzzy numbers
Very low	VL	0, 1, 2
Low	L	1.5, 2.5, 3.5
Normal	N	3, 4, 5
High	H	4.5, 6, 7.5
Very high	VH	7, 8, 9

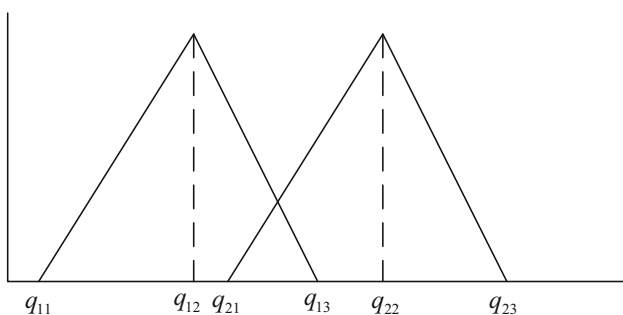


Fig. 2 Triangular fuzzy numbers

where p_{kj} represents the normalised value of criterion j in relation to decision-maker k , z_{kj} represents the actual value of criterion j in relation to decision-maker k , and K represents the total number of decision-makers.

The inherent contrast intensity of the criteria (Eq. 4) is used to determine the weight of each criterion (Eq. 5).

$$d_j = 1 - e_j \tag{4}$$

$$w_j = \frac{d_j}{\sum_{j=1}^n d_j} \tag{5}$$

3.2 Grey relational analysis

To apply GRA, the responses from each maintenance system are obtained using linguistic terms. The linguistic terms that are used for the GRA are divided into five classes (Fig. 3; Table 3). The maximum value of μ in Fig. 2 is 1, while the minimum value is 0.

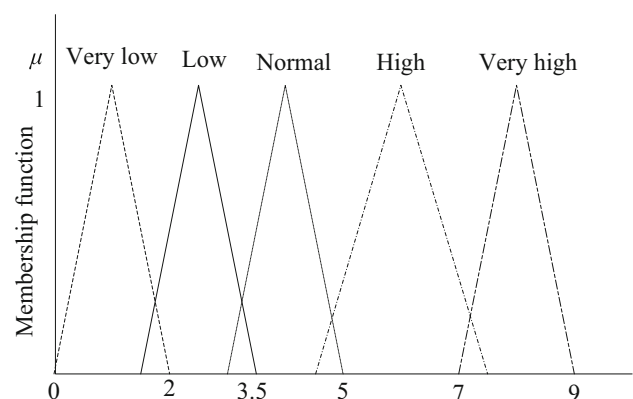


Fig. 3 Membership function for maintenance systems performance responses

Table 3 Triangular fuzzy numbers for impact of maintenance

Linguistic terms	Symbols	TFN
Very poor	V	(1, 1, 3)
Fairly poor	F	(1, 3, 5)
Poor	P	(3, 5, 7)
Good	G	(5, 7, 9)
Very good	VG	(7, 9, 9)

By using GRA, the various inputs are combined into single output values for the different criteria. A brief description of GRA is presented as follows:

The first step in GRA involves normalisation of each input. This entails the consideration of the desired direction of the inputs as either maximum or minimum functions. Normalisation expression for inputs that their maximum values are desired is given as Eq. (6). The normalisation scheme of inputs that their minimum values are desired is expressed as Eq. (7).

$$x_{ij}^* = \frac{x_{ij}^o - \min_j x_{ij}^o}{\max_j x_{ij}^o - \min_j x_{ij}^o} \quad (6)$$

$$x_{ij}^* = \frac{\min_j x_{ij}^o - x_{ij}^o}{\max_j x_{ij}^o - \min_j x_{ij}^o} \quad (7)$$

where x_{ij}^o depicts the initial value of factor i in relation to criterion j , x_{ij}^* represents normalised value of factor i in relation to criterion j , $\min_j x_{ij}^o$ represents the minimum value of factor i in relation to criterion j , and $\max_j x_{ij}^o$ reveals the value of maximum threshold of factor i in relation to criterion j .

The second step of GRA application involves the determination of grey relation coefficient for the inputs (Hasani et al. 2012). The value of grey relational coefficient is expressed as Eq. (8).

$$\zeta_i(j) = \frac{\Delta \min + \zeta \Delta \max}{\Delta_{o,i}(j) + \zeta \Delta \max} \quad (8)$$

$$\Delta \min = \min_{\forall j \in i \forall k} \|x_o^*(j) - x_i^*(j)\| \quad (9)$$

$$\Delta \max = \max_{\forall j} \|x_o^*(j) - x_i^*(j)\| \quad (10)$$

where ζ represents called identification coefficient and its values lie between 0 and 1.

The determination of the grey relational grade (GRG) represents the last step of GRA application (Hasani et al. 2012). This step involves the estimation of the average values of all the grey relational co-efficient (Eq. 11). The

output from GRA method serves as input for the WASPAS method.

$$\gamma_k = \frac{1}{n} \sum_{i=1}^n \zeta_i(j). \quad (11)$$

3.3 WASPAS methodology

WASPAS methodology combines weighted sum and weighted product models in ranking criteria or alternatives. Several studies have applied WASPAS as a ranking tool. For instance, Lashgari et al. (2014) reported the successful applications of WASPAS as well as Zavadskas et al. (2012). The works of Zavadskas et al. (2013), Staniunas et al. (2013) and Lashgari et al. (2014) are other application of WASPAS method. WASPAS ranking ability is better than those of weighted sum and weighted product models, which constitute WASPAS method (Zavadskas et al. 2012). The application of WASPAS involves four steps (Hashemkhani et al. 2013; Gecevska et al. 2014).

Step 1 Formulation of decision matrix

In this study, the decision matrix is generated using the values from GRG results.

Step 2 Data normalisation

This step entails the conversion of the GRG values for each alternative into normalised values. The expression for normalising minimisation and maximisation criteria are given as Eqs. (12) and (13), respectively.

$$\bar{x}_{ij} = \max_i x_{ij} / x_{ij} \quad (12)$$

$$\bar{x}_{ij} = x_{ij} / \max_i x_{ij} \quad (13)$$

where x_{ij} is the assessment value of alternative i in relation to criterion j .

Step 3 Determination of the relative importance of alternatives

The relative importance of each of alternative is determined using weighted sum (Eq. 14) and weighted product methods (Eq. 15). The weights in Eqs. (14) and (15) are obtained from Eq. (5).

$$Q_i^{(1)} = \sum_{j=1}^n \bar{x}_{ij} w_j \quad (14)$$

$$Q_i^{(2)} = \prod_{j=1}^n \bar{x}_{ij}^{w_j}. \quad (15)$$

Step 4 Ranking of alternatives

This step entails the combination of weight sum method and weighted product method outputs additively (Eq. 16) using a constant parameter (λ).

$$Q_i = \lambda Q_i^1 + (1 - \lambda) Q_i^2 \quad (16)$$

where, $\lambda = 0, 0.1 \dots 1$.

3.4 TOPSIS

TOPSIS is a ranking tool which considers the values of positive and negative ideal solutions (Hwang and Yoon 1981). Since its introduction, it has enjoyed wide acceptance from researchers and industrial practitioners across the globe. Some areas of its applications are health-care service (Afkhama et al. 2012), product design (Lin et al. 2008), firm performance evaluation (Ertugrul and Karakasoglu 2009) and investment boards selection (Madi and Tap 2011).

The achievement of TOPSIS is due to its ease of application using five basic steps. The steps that are required for TOPSIS application are outlined as follows (Afkhama et al. 2012; Ertugrul and Karakasoglu 2009; Madi and Tap 2011):

Step 1 Normalisation of decision matrix

The expressions in Eqs. (6) and (7) have the setback of generating normalised values of zero when all the parameters are the same values. Whenever this problem occurs, Eq. (2) can be considered as a normalisation scheme (Afkhama et al. 2012).

Step 2 Building-up of weighted normalised decision matrix

The values of alternatives in a weighted decision matrix are obtained using the values of each criterion weight and its normalised value (Equation).

$$y_{ij} = w_j x_{ij}. \quad (17)$$

Step 3 Computation of proportional distances

The values of the positive (Eq. 18) and negative (Eq. 19) ideal solutions of each criterion are used to compute the value of the positive and negative proportional distances. The value of positive proportional distance is evaluated using Eq. (20), while the negative ideal solution value is expressed as Eq. (21).

$$y_j^+ = \max_j(y_{ij}) \quad (18)$$

$$y_j^- = \min_j(y_{ij}) \quad (19)$$

$$D_j^+ = \sqrt{\sum_{i=1}^m (y_{ij} - y_j^+)^2} \quad (20)$$

$$D_j^- = \sqrt{\sum_{i=1}^m (y_{ij} - y_j^-)^2} \quad (21)$$

where y_j^- is the negative ideal solution of criterion i , and y_j^+ is the positive ideal solution of criterion i .

Step 4 Establishment of closeness coefficients

The value of an alternative closeness coefficient is based on its proportional distance from the positive and negative ideal solutions (Eq. 22).

$$C_j = \frac{D_j^-}{D_j^+ + D_j^-}. \quad (22)$$

Step 5 Ranking of alternatives

The closeness coefficient values of the alternatives are used for the ranking process. The alternative with the highest closeness coefficient value is ranked the best alternative. The least ranked alternative is the alternative with the lowest closeness coefficient value.

4 Model application

The questionnaire of this research is designed based on the information in Table 1. The first section of the questionnaire consists of six questionnaires, while the second section consists of eighteen questions. A copy of the questionnaire was given to different maintenance managers in five different companies. The responses of from each company were based on the information that was presented in (Tables 2, 3). In terms of company based responses for the criteria in Table 1, none of the criterion had the same importance (Table 4) Table 5.

Based on the information in Table 2 and Eq. (1), the triangular fuzzy numbers for the various criteria (Table 3) were used to determine the crisp values of the relative maintenance of the criteria (Table 6).

The weights for the criteria were determined based on the information in Table (6). First, the relative importance of the criteria were normalised using Eq. (2). The normalised values that were obtained were used to determine the entropy values for the criteria based on Eq. (3). The inherent contrast intensities of the criteria were determined using Eq. (4). The criteria weights (Table 7) which is the final output from FEWM were obtained based on Eq. (5).

The linguistic values for the various factors in Table 2 from the different companies were obtained based on the

Table 4 Linguistic importance of the criteria

Criteria	Company 1	Company2	Company 3	Company 4	Company 5
y_1	G	G	VG	G	G
y_2	G	G	VG	G	G
y_3	G	G	G	VG	G
y_4	G	G	VG	G	G
y_5	F	G	G	F	F
y_6	VG	F	VG	F	VG

Table 5 Triangular fuzzy numbers for relative importance of the criteria

Criteria	Company 1	Company2	Company 3	Company 4	Company 5
y_1	(5, 7, 9)	(5, 7, 9)	(7, 9, 9)	(5, 7, 9)	(5, 7, 9)
y_2	(5, 7, 9)	(5, 7, 9)	(7, 9, 9)	(5, 7, 9)	(5, 7, 9)
y_3	(5, 7, 9)	(5, 7, 9)	(5, 7, 9)	(5, 7, 9)	(5, 7, 9)
y_4	(5, 7, 9)	(5, 7, 9)	(7, 9, 9)	(5, 7, 9)	(5, 7, 9)
y_5	(1, 3, 5)	(5, 7, 9)	(5, 7, 9)	(1, 3, 5)	(1, 3, 5)
y_6	(7, 9, 9)	(1, 3, 5)	(7, 9, 9)	(1, 3, 5)	(7, 9, 9)

Table 6 Crisp values for relative importance of the criteria

Criteria	Company 1	Company2	Company 3	Company 4	Company 5
y_1	7.000	7.000	8.667	7.000	7.000
y_2	7.000	7.000	8.667	7.000	7.000
y_3	7.000	7.000	7.000	7.000	7.000
y_4	7.000	7.000	8.667	7.000	7.000
y_5	3.000	7.000	7.000	3.000	3.000
y_6	8.667	3.000	8.667	3.000	8.667

Table 7 Entropy-based weights for the criteria

Criteria	e_j	d_j	w_j
y_1	0.967	0.033	0.060
y_2	0.967	0.033	0.060
y_3	0.950	0.051	0.093
y_4	0.967	0.033	0.060
y_5	0.743	0.257	0.472
y_6	0.862	0.139	0.254

linguistic terms (Table 3). Based on the information that was obtained from the different companies, impact of maintenance activities on the select factors were not the same for all the companies except for f_{14} , f_{33} and f_{51} (Table 8). In order to determine the crisp values of the information in Table 8, the triangular fuzzy numbers in Table 3 were considered (Table 9).

The normalisation of the information in Table 9 was done using Eq. (2). By considering Eq. (2) instead of Eqs. (6) and (7), the problem of losing of the attributes in Table 9 was avoided. Based on the information in Table 10, the grey relational grades (Table 11) for the various criteria were obtained using Eqs. (8) to (11).

In terms y_1 , Company 5 had the highest grey relational grade, while the value of y_1 for Company 3 was the lowest. The Company 2 had least grey relational grade for y_2 and y_3 when compared with the other companies. The highest grey relational grade for y_2 was obtained from Company 4, while Company 1 had the highest grey relational grade for y_3 . Company 2 grey relational grade for y_4 was the highest, the grey relational grade of y_4 for Company 4 was the lowest, while its grey relational grade for y_5 was the highest. The grey relational grade for y_5 and y_6 from Company 1 were the lowest among the companies. Company 2 had the highest grey relational grade for y_6 (Table 12).

Based on the information in Table 11, there is the need for Company 3 to improve the equipment or process related factors in order to compete favourably with other company's maintenance systems. The cost and maintenance task related factors for Company 2 need to be improved upon. The maintenance manager in Company 1 needs to suggest ways to improve the health safety and environment factors.

Since the highest and lowest values for the criteria alternate among the various companies, to make an

Table 8 Linguistic variables for the impact of maintenance

Criteria	Factors	Company 1	Company2	Company 3	Company 4	Company 5
y1	f ₁₁	H	H	VH	H	L
	f ₁₂	H	VH	VH	H	VL
	f ₁₃	L	L	H	H	L
	f ₁₄	L	L	L	L	L
y2	f ₂₁	H	VL	L	H	L
	f ₂₂	H	L	VL	H	L
y3	f ₃₁	H	H	VH	H	L
	f ₃₂	L	L	H	H	L
	f ₃₃	L	L	L	L	L
	f ₃₄	H	L	N	N	H
y4	f ₄₁	H	L	H	L	H
	f ₄₂	L	L	H	L	VL
	f ₄₃	L	VL	VL	VL	H
	f ₄₄	H	H	H	N	L
y5	f ₅₁	VL	VL	VL	VL	VL
	f ₅₂	H	H	VH	VH	H
y6	f ₆₁	VL	L	VL	VL	L
	f ₆₂	H	H	VH	VH	H

Table 9 Crisp values of the impact of maintenance activities

Criteria	Factors	Company 1	Company2	Company 3	Company 4	Company 5
y1	f ₁₁	6.000	6.000	8.000	6.000	2.500
	f ₁₂	6.000	8.000	8.000	6.000	1.000
	f ₁₃	2.500	2.500	6.000	6.000	2.500
	f ₁₄	2.500	2.500	2.500	2.500	2.500
y2	f ₂₁	6.000	1.000	2.500	6.000	2.500
	f ₂₂	6.000	2.500	1.000	6.000	2.500
y3	f ₃₁	6.000	8.000	8.000	6.000	2.500
	f ₃₂	2.500	2.500	6.000	6.000	2.500
	f ₃₃	2.500	2.500	2.500	2.500	2.500
	f ₃₄	6.000	2.500	4.000	4.000	6.000
y4	f ₄₁	6.000	6.000	6.000	2.500	6.000
	f ₄₂	2.500	6.000	6.000	2.500	1.000
	f ₄₃	2.500	1.000	1.000	1.000	6.000
	f ₄₄	6.000	6.000	6.000	4.000	2.500
y5	f ₅₁	1.000	1.000	1.000	1.000	1.000
	f ₅₂	6.000	6.000	8.000	8.000	6.000
y6	f ₆₁	1.000	2.500	1.000	1.000	2.500
	f ₆₂	6.000	6.000	8.000	8.000	6.000

informed decision, the need for a ranking tool (WASPAS method) is justified. Based on the information in Table 11 and Eq. (12), the normalised values for the values criteria were determined (Table 13).

The determination of the ranks of the companies was based on the aggregation of the weights in Table 7 and the normalised values of the grey relational grades for the criteria (Table 12). This entails the evaluation of the criteria weighted sum (Eq. 14) and weighted product (Eq. 15)

values (Table 13). The WASPAS values for the companies were examined based on different values of λ (Fig. 4).

When the value of λ was less than 0.4, the highest ranked maintenance system was Company 5. When the value of $\lambda = 0.5$, Companies 4 and 5 were ranked equal. The WASPAS results showed that Company 4 was the highest ranked system when $\lambda > 0.5$. When $\lambda = 0.4$ or 0.5, the lowest ranked maintenance system was for Company 2. For other values of λ , Company 1 was the lowest

Table 10 Normalised crisp values of the impact of maintenance activities

Criteria	Factors	Company 1	Company2	Company 3	Company 4	Company 5
y ₁	f ₁₁	0.449	0.449	0.599	0.449	0.187
	f ₁₂	0.423	0.564	0.564	0.423	0.071
	f ₁₃	0.262	0.262	0.630	0.630	0.262
	f ₁₄	0.447	0.447	0.447	0.447	0.447
y ₂	f ₂₁	0.649	0.108	0.270	0.649	0.270
	f ₂₂	0.649	0.270	0.108	0.649	0.270
y ₃	f ₃₁	0.418	0.557	0.557	0.418	0.174
	f ₃₂	0.262	0.262	0.630	0.630	0.262
	f ₃₃	0.447	0.447	0.447	0.447	0.447
	f ₃₄	0.571	0.238	0.381	0.381	0.571
y ₄	f ₄₁	0.490	0.489	0.489	0.204	0.489
	f ₄₂	0.270	0.649	0.649	0.270	0.108
	f ₄₃	0.372	0.149	0.149	0.149	0.892
	f ₄₄	0.526	0.526	0.526	0.350	0.219
y ₅	f ₅₁	0.447	0.447	0.447	0.447	0.447
	f ₅₂	0.391	0.391	0.521	0.521	0.391
y ₆	f ₆₁	0.254	0.635	0.254	0.254	0.635
	f ₆₂	0.391	0.391	0.521	0.521	0.391

Table 11 Criteria grey relational grades for the companies

Companies	y ₁	y ₂	y ₃	y ₄	y ₅	y ₆
Company 1	0.396	0.431	0.560	0.487	0.242	0.396
Company 2	0.431	0.189	0.189	0.649	0.270	0.649
Company 3	0.189	0.376	0.504	0.469	0.364	0.425
Company 4	0.376	0.453	0.453	0.243	0.427	0.414
Company 5	0.453	0.419	0.484	0.484	0.419	0.419

Table 12 Normalised values of the grey relational grades for the criteria

Companies	y ₁	y ₂	y ₃	y ₄	y ₅	y ₆
Company 1	0.706	0.769	1.000	0.870	0.432	0.706
Company 2	0.769	0.292	0.292	1.000	0.417	1.000
Company 3	0.292	0.747	1.000	0.931	0.722	0.843
Company 4	0.747	1.000	1.000	0.537	0.943	0.914
Company 5	1.000	0.865	1.000	1.000	0.865	0.866

Table 13 Weighted sum and product assessment values of the criteria

Companies	Q _i ⁽¹⁾	Q _i ⁽²⁾
Company 1	0.617	0.505
Company 2	0.602	0.572
Company 3	0.767	0.705
Company 4	0.908	0.884
Company 5	0.894	0.900

ranked system. In other to improve the quality of decision from the proposed framework, the results from TOPSIS method is presented.

Based on the information in Tables 7 and 12, the weighted normalised values for the grey relational grades were determined using Eq. (17). By using the weighted normalised values (Table 14), the positive and negation ideal solutions were determined based on Eqs. (18) and (19) for each criterion (Table 15). Equations (20) and (21) were used to determine the proportional distances of companies (Table 16).

The coefficient closeness for each company was determined using the information in Table 15 and Eq. (22). The reason why the coefficient closeness of Company 4 was 1 was because its D_j^+ was zero (Table 16). The TOPSIS results showed that the highest ranked maintenance system was of that Company 4 (Table 17).

Most applications of WASPAS method make decision based on a λ value of 0.5 (Chakraborty and Zavadskas 2014; Zavadskas et al. 2016). Based on the average ranks for the companies, the highest ranked maintenance system was that of company 4 (Table 17). Based on the WASPAS results, the cause of ranking Company 1 as the lowest ranked system can be attributed to the values of health, safety and environment as well as employee satisfaction. By improving the values of these criteria, Company 1 ranking will also increase. For the TOPSIS results, Company 5 was ranked lowest because of the values of the criteria were fall from the positive and negative ideal solutions (Table 16). The final average rank showed that

Fig. 4 WASPAS results for different values of λ

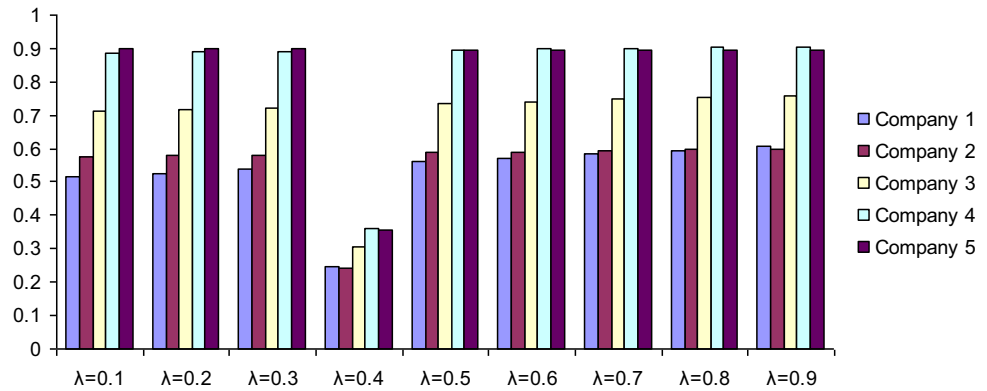


Table 14 Weighted normalised of the grey relational grades for the criteria

Companies	y_1	y_2	y_3	y_4	y_5	y_6
Company 1	0.043	0.046	0.093	0.053	0.204	0.179
Company 2	0.046	0.018	0.027	0.060	0.197	0.254
Company 3	0.018	0.045	0.093	0.056	0.341	0.214
Company 4	0.045	0.060	0.093	0.032	0.445	0.232
Company 5	0.060	0.052	0.093	0.060	0.409	0.220

Table 15 Positive and negative ideal solutions

Ideal solutions	y_1	y_2	y_3	y_4	y_5	y_6
Positive ideal solutions	0.060	0.060	0.093	0.060	0.445	0.060
Negative ideal solutions	0.018	0.018	0.027	0.032	0.197	0.018

Table 16 Analysis of TOPSIS parameters

Companies	D_j^+	D_j^-	C_j
Company 1	0.050	0.309	0.861
Company 2	0.047	0.305	0.866
Company 3	0.066	0.132	0.667
Company 4	0.000	0.051	1.000
Company 5	0.357	0.357	0.500

Table 17 Ranks for the companies using different methods

Companies	TOPSIS	WASPAS ($\lambda = 0.5$)	Average ranks
Company 1	2	5	3.5 (3*)
Company 2	3	4	3.5 (3*)
Company 3	4	3	3.5 (3*)
Company 4	1	1	1
Company 5	5	1	3 (2*)

* Final average rank

Company 1 is the highest ranked company, while Company 2 is the second ranked company (Table 17).

5 Conclusions

This study has presents a framework for ranking the performance of maintenance systems based on the concept of FEWM, GRA and WASPAS methods. An illustrative example using practical data collected from five different manufacturing systems was presented. Based on the manufacturing associated criteria of equipment/process, cost/finance and maintenance tasks as well as customers' and employee satisfaction, health, safety and environment as input criteria for the WASPAS method, the results obtained indicated that the best maintenance performance system was that of company 4. This result was compared with those of TOPSIS and it was observed that it was the same.

The proposed framework can be extended to incorporate maintenance system sustainability criteria. This could be considered as a further study. Other multi-criteria ranking tools such as VIKOR and PROMETHEE can be used to evaluate the performance of WASPAS. The idea of incorporating Kaizen criteria into the proposed framework can be seen as a further study.

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