AN INTEGRATED FUZZY ANALYTICAL HIERARCHICAL PROCESS AND FUZZY GREY RELATIONAL ANALYTICAL MODEL WITH VIKOR FOR MAINTENANCE SYSTEM APPRAISAL

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ABSTRACT

The motivation for this research lies in the understanding that the evaluation of a maintenance department for a manufacturing organization strongly depends on a wide range of uncertainties and vague parameters. Consequently, utilising intuition may not be technically correct and downplays on the supposed results for the right management decisions on maintenance. The need for a new method to correct this anomaly is very much pressing to enhance the performance of maintenance systems. In this paper, the fusion of fuzzy analytical hierarchy process with fuzzy grey relational analysis as well as VIKOR is presented. A measuring instrument, questionnaire, for evaluating the performance of maintenance systems was developed and administered in four companies. Using the pair-wise comparisons of criteria relevant to systems reliability, profitability, lead-time, system safety, production cost and manufacturing goals, the crisp values for the major components were generated. Computation of the grey relational grade, best and worst values, utility regret measure and VIKOR index, and finally the ranking of the maintenance system were made. The approach is feasible in maintenance system evaluation. The unique and innovative approach that established a link between maintenance system's goals and variables when dealing with maintenance system appraisal is the main novelty of the work. An additional novelty not reported earlier in literature is the consideration of human attributes and environments in an integrated manner. This study contributes a significant approach for correctly evaluating the technical aspects of the maintenance system.

KEYWORDS: *Maintenance performance criteria; Membership functions; Fuzzy grey relational analysis; VIKOR; Fuzzy analytical hierarchy process*

1.0 INTRODUCTION

The maintenance system in a manufacturing organisation is top among the value-adding units of the industrial enterprise. The function is responsible for making the repaired equipment and facilities safe and ensuring minimum breakdowns of the same. Over the past several years, the maintenance function has been evaluated for its quality of service in terms of its output and the progress of the function determined by comparing the

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outputs with the input measures of labour, material, equipment hours, capital and energy (Baluch et al., 2010). The traditional approach to evaluating maintenance department hugely leans on a variety of parameters but tracking the environmental, economic, financial, machine performance and human attribute consequences in analysing maintenance system is often a great challenge (Plantweb, 2003; Simoes *et al*., 2011; Muchiri *et al*., 2011). Yet maintenance practices cannot improve without the adequate coverage of these main parametric determinants. Novel and insightful theories and applications that would aid sound decision making in maintenance are a necessary requirement for progress. It is however unfortunate that through a detailed literature review and an understanding of the accomplishments of scholars in the maintenance performance appraisal area, no work seems to have engaged, in a very detailed manner, the engineering concepts as well as technology while also considering the managerial, economic and environmental perspectives in which the industry thrives. As a response to this literature gap and challenge, the present paper focuses on the analysis and modelling of the important maintenance parameters in the evaluation of the maintenance system in a manufacturing system. It is interesting to identify the engineering aspects of the system from perspectives of measures of availability, mean-time-to-failure, mean-time-to-restore, mean-downtime as well as the overall equipment effectiveness. So, the engineering aspects referred to as the machine performance indicators in this work have been taken as an important component in the modelling and analysis of maintenance performance. As advocated earlier, if we are to consider the technological aspect, then the examination of factors such as vibration control, temperature control and lighting are of principal importance. Recall that it was mentioned earlier that a good evaluation system must also contain the managerial factors. Such a consideration is expected to have factors reflecting labour-management relations, communication and cooperation among others. Economic aspects include costs of spare parts, training, bonuses, worker's salaries and compensation. The environmental perspective which reflects sustainable practices include noise control and cleanliness. From the above analysis, it has been established that practical and sound decision based on managerial, economic, engineering, technology, managerial and environmental perspectives is a must towards attaining a strong theoretical base that works in practice.The objective of the current paper is to propose a conceptual framework for maintenance systems appraisal based on maintenance environments (physical and organisational), machine performance indicator, maintenance cost and human attributes. The proposed framework is an integrated fuzzy analytical hierarchy process (FAHP), fuzzy grey relational analysis (FGRA) and VIKOR approach.

FAHP is employed to evaluate the weights for the above mentioned five maintenance criteria for the evaluation process based on manufacturing system's goals. Each criterion of the principal components is aggregated into a single performance index using the FGRA approach. The ranking of maintenance systems is based on the VIKOR technique. In the remaining parts of this paper, the literature review is elaborated in the second section. In the third section, the methodological aspect of the work is discussed. The fourth section showcases the application of the model, carried out in four companies. The first company produces sheets, coils and circles and it is known as a rolling mill. The second company manufactures agricultural sacks (sack manufacturing) while the third company produces household utensils (hollowware manufacturing). The fourth case study is engaged in the production of noodles (Food Company). This section also contains a discussion of research results while the fifth section presented the conclusion of the study.

2.0 LITERATURE REVIEW

Several theories have been advanced in literature to explain maintenance performance characteristics. Certainly, the literature has covered the different types of such theories; the review undertaken here will only focus on three main themes that repeatedly occur throughout the review literature. The themes are namely, the measurement of maintenance profitability, the improvement of maintenance profitability, the need to measure maintenance productivity and the importance of maintenance quality and its associated parameters. Although the literature explains the above themes in a diversity of contexts, the current research mainly direct attention to their applications in manufacturing systems. Furthermore, a wide range of authorities has contributed to the development of maintenance performance literature and the coverage of literature is intensive. However, the direction of focus of the current study shall be on those that consistently contribute to literature for the past several years. The review of literature in the current study is approached first by identifying the major theories in research on maintenance profitability, maintenance productivity, maintenance quality and generally on maintenance performance. The next stage of research brought out notable contributors in the field, who works were inspirational to the development of the field. Then the major theories in the field are reviewed. The final phase of the literature review identified the gaps in the literature relevant to maintenance performance.

In literature, a number of studies on the performance of maintenance systems have been made. These investigations are further broken down into more specific issues but treating the various criteria of performance as individual topics of interest. Recall that performance has been noted to contain criteria such as productivity, profitability, innovation, quality and quality of working life. Out of all these criteria, significant reporting could only be found for maintenance productivity, maintenance profitability and maintenance quality while reports on maintenance innovation and maintenance quality of working life are almost non-existent. In maintenance profitability, the common themes of research are that (i) profitability can be measured; and (ii) can be improved (Oke, 2005; Maletic et al. 2014). Oke (2005) contributed a mathematical approach to measuring maintenance profitability. The author proved the utility of the approach in a case study. It was argued that a change in the perception of the maintenance function from a cost centre to a profit centre, wherein profit could be made by the function was the arguement. Maletic et al. (2014) detailed out the function of maintenance with respect to enhancing company’s profitability using empirical data from a textile mill. It was concluded that practices in maintenance associated with condition-based maintenance method had the greatest potential for improvement. Oke et al. (2008) viewed maintenance from a value-adding perspective, using the concept of charging the services by maintenance to production in prices. A mathematical framework that describes maintenance profitability while considering inflation was contributed by the authors. From the three studies reviewed above, Oke (2005), Oke et al. (2008) and Maletic et al. (2014), the two themes of the drive for the measurement and improvement of performance were adopted in the current study.

A group of maintenance performance appraisal studies focused on maintenance productivity evaluation, wherein the output to input ratio from the conceptual perspective was taken into account. The main themes of the studies are that (i) maintenance productivity could be associated with safety, quality and reliability; (ii) maintenance productivity can be improved. Researchers strongly believed in the linkages of safety, productivity, maintenance, quality and reliability as evident in the study by Narayan (2012) in which the associations among safety, quality, reliability and productivity were established. The conclusion was that integrating the technological as well as the behavioural aspects of humans presents a holistic viewpoint of maintenance. Further in an associative effort, Khan and Darrab (2010) related productivity with quality as well as maintenance. It was concluded that the developed approach predicted the most acceptable productivity outcomes in association of maintenance with quality indices from practical data.

Elangovan et al. (2007) established a linkage between quality and productivity enhancement of maintenance executive decisions. The conclusion from the report was that it is feasible to link quality and productivity in maintenance using data collected from practical experience. This is however consistent in view with that of earlier researches on concept integration in maintenance.

Still on the association of maintenance with other concepts, Abdul-Raouf (2004) related productivity and safety maintenance, claiming that they enhance maintenance in terms of performance. They outlined the tasks that aided the elimination of accidents as well as removing potential interruption causes. Raouf's (1994) contribution is similar to the theme in current literature on profitability, whereby productivity was argued as a candidate for improvement. Now, drawing from the themes of researchers' arguments on productivity, we add the idea of integrating issues and not treating measures in compartments with each item being accounted for in stand-alone perspectives. Rather, a holistic approach has been adopted in the current paper. It is worth noting that majority of appraisal studies on maintenance are captioned under the general term of maintenance performance instead of maintenance productivity, maintenance profitability and maintenance quality investigations. So, the next set of review relates to maintenance performance appraisal studies (De Groote, 1995; Parida and Kumar, 2006).

In this literature review, the question answered here relates to what has been documented in the maintenance performance field. Drawing from the works of major authors that have contributed in a significant manner to developing the maintenance performance measurement field, Kumar and co-workers, Labib and co-researchers, Parida and co-workers as well as Pintellon and co-researchers may be mentioned. Most attention has been directed to strategic issues, tools, models and the diverse applications such as mining and railway infrastructure. Arising from the literature analysis is the gap that no reported studies have been documented in the Nigerian environment. There have not been comprehensive reports in any form, worldwide on the applications of maintenance performance to rolling mills. The cases of bag manufacturing, household utensils and food products are missing.

The springboard for the current research on maintenance performance is the performance measurement field, which majorly hinged on the criteria of productivity, profitability, innovation, quality and quality of working life. As interest in maintenance performance sprang up, researchers began to engage in the adoption of criteria to the maintenance field. The major theories in this area of research are related to productivity theory, theory concerning profitability and the quality theory. The general theory concerning performance is also well-documented in literature. Associated in the performance theories are the theories on indicators, multicriteria, measurement and performance (Parida and Kumar, 2004; Parida et al., 2005.; Kumar and Parida, 2006; Parida, 2007. Ahren and Parida, 2009; Parida and Uday, 2009). However, most of these theories have not matured to incorporate artificial intelligence models. In maintenance performance models, the use of AHP, fuzzy logic and grey relational analysis in an integrated form has not been reported.

Furthermore, Muchiri et al. (2011) developed a framework for evaluating the performance of a maintenance system. Their study reported that performance gaps in maintenance system could be identified based on information on maintenance cost and machine performance indicators. Apart from machines and maintenance work attributes, Sondalini (2016) suggested that human-factors should be considered when evaluating maintenance systems. They also reported that the desire of setting too high maintenance performance indicator should be avoided by decision makers. Wu et al. (2012) proposed the use of fuzzy multi-criteria decision-making process for maintenance workforce performance analysis. They considered professionalism, teamwork, discipline and innovation as criteria for workforce evaluation. A case study of the proposed approach which integrates fuzzy analysis hierarchy process and VIKOR was used to demonstrate the applicable of the approach in an aircraft maintenance system.

From the above highlighted issues, it becomes apparent that developing an appropriate maintenance system appraisal strongly hinges on the layout of a suitable measurement scheme, the development of a system with system enhancement in mind and a system that could be audited, taking into consideration system flexibility that permits quantifiable inputs and outputs of the system. In addition, despite the large volume of literature on maintenance performance evaluation (Muchiri et al., 2011), the use of fuzzy logic in capturing vagueness of maintenance parameters has been sparsely reported in literature. In addition, sparse information has been documented on VIKOR (Vlse Kriterijumska Optimizacija I Kompromisno Resenje) approach to maintenance system appraisal. The need to address this important knowledge gaps serves as the motivation for the current study. Addressing this gap has implications for management decision making as proper evaluation of system is made and actions carried out will have direct and long-lasting impact on organisational survival.

In view of the aforementioned issues, the maintenance system appraisal developed in this work has been made in the perspective of literature support, by considering all the issues raised as themes as well as appropriately filling the gap identified in the current paper. Thus, the work is strongly oriented at applying the integrated fuzzy analytical hierarchy process and fuzzy grey relational analytical scheme while solidifying the integration with the VIKOR concept. In verifying the feasibility of the developed model, a questionnaire-oriented feedback method was employed and analyzed in four companies operating in the Nigerian industrial environment.

In addition, based on the above related works, the issues of human-factors and the appreciation of vagueness in maintenance performance indicators have been downplayed by researchers and industrial practitioners. Also, most studies on the development maintenance performance framework do not consider the physical and organisational environments. Furthermore, the use of FGRA for maintenance performance indictors' aggregation has not been reported in literature to the best of our understanding. Consequently, the current study has considered these parameters in presenting the proposed framework.

3.0 METHODOLOGY

The identification of best practice in maintenance system provides means for performance gaps analysis. In order to identify performance gaps in a maintenance system, there is the need for maintenance system appraisal. Based on the information obtained from literature, this study proposes a conceptual framework for maintenance systems appraisal (Table 1). The framework is based on the integration of fuzzy logic, AHP, GRA and VIKOR (Figure 1). Brief descriptions on how each of the above mentioned tools in the proposed conceptual framework is presented as follows:

Table 1: Factors and criteria for maintenance system appraisal

Criteria	Principal components
Physical environment (C_1)	Noise control (x_{11}) Vibration control (x_{12}) Temperature control (x_{13}) Lighting (x_{14}) Cleanliness (x_{15})
Organisation's environment (C_2)	Cooperation (x_{21}) Communication (x_{22}) Labour-management relationships (x_{23}) Promotion rate (x_{24}) Retrenchment rate (x_{25})
Machine performance (C_3)	Overall equipment effectiveness (x_{31}) Mean-downtime (x_{32}) Mean-time-to-restore (x_{33}) Mean-time-to-failure (x_{34}) Availability (x_{35})
Human attributes (C_4)	Stress (x_{41}) Fatigue (x_{42}) Team work (x_{43}) Workers' agility (x_{44}) Turnover rate (x_{45}) Responsiveness (x_{46}) Work pressure (x_{47})
Maintenance cost (C_5)	Bonuses (x_{51}) Workers' salaries (x_{52}) Compensation (x_{53}) Training (x_{54}) Spare parts (x_{55})

In order to have a clear understanding of the methodology adopted in this paper, an outline for the proposed framework is presented as follows:

Step 0: Decision-makers size

Given that the proposed framework is a multi-decision making framework, the number of decision-makers makers for its implementation is first determined. This serves as the initialisation of the proposed framework.

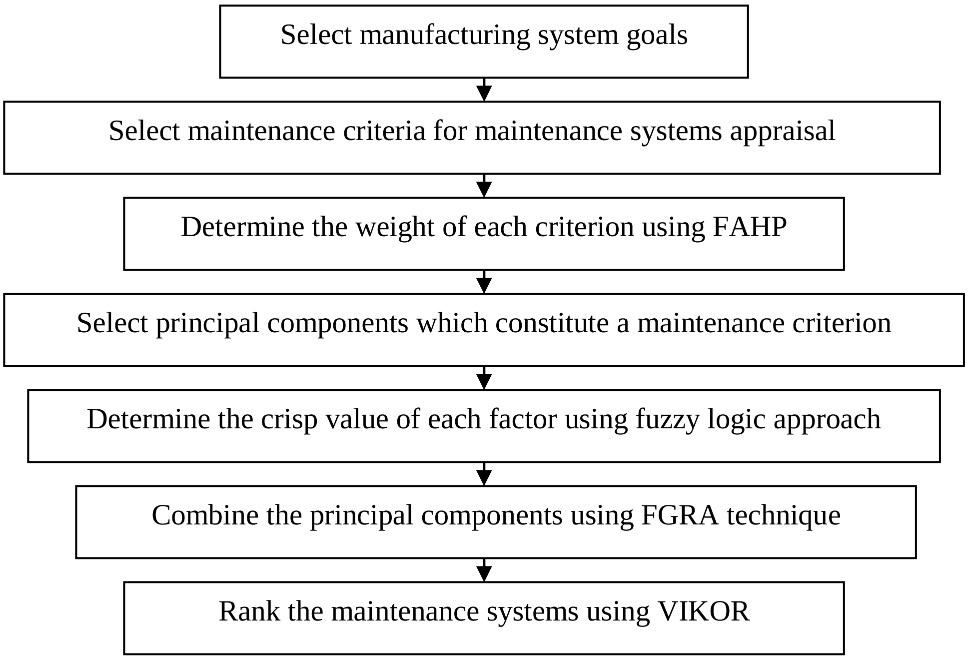

Figure 1. A conceptual framework for maintenance system appraisal

Step 1: Selection of manufacturing goals
Information on manufacturing goals may be different from one maintenance system to another. It is the responsibility of the decision-makers to select the most suitable manufacturing goals for their evaluation process.

Step 2: Selection of maintenance system appraisal criteria
The number of maintenance system appraisal criteria that will be used for maintenance system appraisal is dependent on the decision-makers. Also, the number of principal components for a selected maintenance system appraisal criterion is a function of the decision-makers judgements.

Step 3: Evaluation of maintenance system appraisal criteria weight
In order to make the proposed model an easy-to-apply tool, the evaluation of the maintenance system appraisal criteria weights are expressed using linguistic terms. The information obtained is processed using a FAHP.

Step 4: Evalution of the impact of principal components on maintenance system
Since some of the principal components values can only be expressed using linguistic terms, the impact of principal components on maintenance system are evaluated using linguistic terms.

Step 5: Aggregation of impact of principal components values
The aggregate of impact of principal components values is carried out using FGRA approach. This approach provides a means of using the desired direction of a principal component (cost-based or benefit-based criterion). The results from FRGA provide insights to the ranking of maintenance systems.

Step 6: Aggregation FRGA results
The results from FRGA are aggregated using VIKOR. The outputs from VIKOR are used to determine the best ranked maintenance system using three criteria (utility, regret measure and VIKOR index).

Brief descriptions on how each of the above mentioned tools in the proposed conceptual framework is presented as follows:

Fuzzy-AHP
Fuzzy-AHP is a modified version of AHP for systems where information is presented in linguistic terms (Saaty, 1990; Chang, 1996). The weights for maintenance criteria are evaluated with respect to five manufacturing system goals. The manufacturing system goals are system reliability (g_1), profitability (g_2), production lead-time (g_3), system safety (g_4) and production cost (g_5). The weights for the maintenance criteria determined based on a FAHP approach (Chang, 1996). In order to convert responses from decision makers into crisp values, triangular membership function is considered (Table 2).

Table 2. Linguistic variables and triangular membership fuzzy conversation scale

Linguistic variables	Triangular membership fuzzy conversation scale	Triangular membership fuzzy reciprocal scale
Just equal	(1,1,1)	(1,1,1)
Equally important	(1/2,1,3/2)	(2/3,1,2)
Weakly more important	(1,3/2,2)	(1/2,2/3,1)
Moderately more important	(3/2,2,5/2)	(2/5,1/2,2/3)
Strongly more important	(2,5/2,3)	(1/3,2/5,1/2)
Extremely more important	(5/2,3,7/2)	(2/7,1/3,2/5)

The conversion of the triangular membership functions in Table 2 for a multi-responses analysis into crisp values is achieved using Equations (1) and (2).

$$\left(a_1, a_2, a_3\right) = \frac{\sum_{k=1}^{K} a_{1k}, \sum_{k=1}^{K} a_{2k}, \sum_{k=1}^{K} a_{3k}}{k} \tag{1}$$

$$a = \frac{a_1 + 4a_2 + a_3}{6} \tag{2}$$

where k represents decision-maker.

After the conversion of the fuzzy values for the principal components, standard AHP approach of weights determination is then applied. Information on how to apply standard AHP is contained in Saaty (1980). Furthermore, the mathematics of AHP can be avoided using commercial software.

Fuzzy-GRA

GRA is a tool for aggregating the components of a factor into single value. This study considered FGRA as a means for aggregating the principal components that constitute a maintenance criterion into a single-index because the responses from decision-makers are in linguistic terms. The responses from decision-makers linguistic terms are analysed using trapezoidal membership functions (Equation 3, Figure 2 and Table 3). The aggregated value of trapezoidal membership function for multi-responses is obtained based on (Equations 4 to 7).

$$x_{ij} = \left\{ x_{ij1}, x_{ij2}, x_{ij3}, x_{ij4} \right\} \tag{3}$$

$$x_{ij1} = \min \left\{ x_{ijk1} \right\} \tag{4}$$

$$x_{ij2} = \frac{1}{K} \sum_{k=1}^{K} x_{ijk2} \tag{5}$$

$$x_{ij3} = \frac{1}{K} \sum_{k=1}^{K} x_{ijk3} \tag{6}$$

$$x_{ij4} = \min \left\{ x_{ijk4} \right\} \tag{7}$$

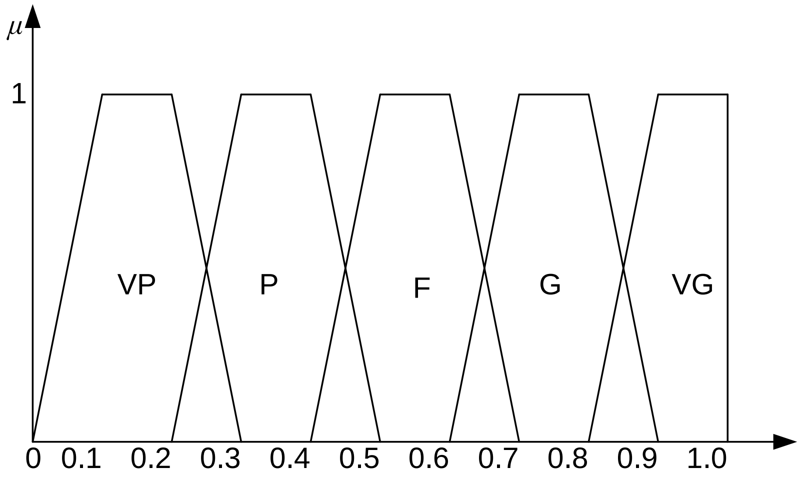

Figure 2. Membership functions for GRA analysis

Table 3. Linguistic variables and corresponding fuzzy number for GRA analysis

Linguistic variables	Abbreviations	Fuzzy number
Very poor or very low	VP	(0.0, 0.1, 0.2, 0.3)
Poor or low	P	(0.2, 0.3, 0.4, 0.5)
Fair or moderate	F	(0.4, 0.5, 0.6, 0.7)
Good or high	G	(0.6, 0.7, 0.8, 0.9)
Very good or very high	VG	(0.8, 0.9, 1.0, 1.0)

The normalisation of the principal components that are considered for the physical environment criterion is based on the higher-the-better criterion (Equation 8). During organisation criterion normalisation, cooperation, communication, labour-management relationships and promotion rate are normalised based on a higher-the-better criterion. A lower-the-better criterion is used for retrenchment rate normalisation (Equation 9). Apart from mean-time-to-restore and mean downtime which is normalised using lower-the-better criterion, other principal components for machine performance criterion are normalised based on higher-the-better criterion. Stress, fatigue, turnover rate and work pressure are normalised based on lower-the-better criterion. Higher-the-better criterion is used for responsiveness, workers' agility and teamwork normalisation. The normalisation scheme for maintenance cost factors is based on lower-the-better criterion.

$$\mu_{ij} = \left(\frac{x_{ij1}}{\hat{x}_{ij4}}, \frac{x_{ij2}}{\hat{x}_{ij4}}, \frac{x_{ij3}}{\hat{x}_{ij4}}, \frac{x_{ij4}}{\hat{x}_{ij4}} \right), c_i \in B \tag{8}$$

$$\mu_{ij} = \left(\frac{x_{ij1}}{\breve{x}_{ij1}}, \frac{x_{ij2}}{\breve{x}_{ij1}}, \frac{x_{ij3}}{\breve{x}_{ij1}}, \frac{x_{ij4}}{\breve{x}_{ij1}} \right), c_i \in C \tag{9}$$

where μ_{ij} is the normalised values for factor *i* belonging to criterion *j*, c_i represents factor *i*,

A centroid scheme defuzzification scheme is used in this study (Opricovic and Tzeng, 2004). In Girubha and Vinodh (2012) study, centroid scheme defuzzification was expressed as Equation (10).

$$X_{ij} = \frac{x_{ij4}x_{ij3} - x_{ij2}x_{ij1} + \frac{1}{3}\left(x_{ij4} - x_{ij3}\right)^2 - \frac{1}{3}\left(x_{ij2} - x_{ij1}\right)^2}{x_{ij4} + x_{ij3} - x_{ij2} - x_{ij1}} \tag{10}$$

where X_{ij} represents the crisp value of factor *i* for maintenance criterion *j*.

After the normalisation of the maintenance criteria, the next stage of FGRA implementation is the determination of grey relation coefficient (Hasani *et al.*, 2012). The grey relation coefficient for a maintenance criterion is obtained using Equation (11).

$$\zeta_i(k) = \frac{\Delta \min + \zeta \Delta \max}{\Delta_{o,i}(k) + \zeta \Delta \max} \tag{11}$$

$$\Delta \min = \min_{\forall j \in i} \min_{\forall k} \left\| x_o^* - x_i^* \right\| \tag{12}$$

$$\Delta \max = \max_{\forall j \in i} \max_{\forall k} \left\| x_o^* - x_i^* \right\| \tag{13}$$

where $x_o^*(k)$ represents the reference sequence, $x_i^*(k)$ represents the comparative sequence, and ζ is called identification coefficient and its values lies between (0,1).

The grey relational grade for each maintenance criterion for a maintenance system is obtained using Equation (14).

$$f_{sj} = \frac{1}{m} \sum_{i=1}^{m} \zeta_i(k) \tag{14}$$

4.0 VIKOR

VIKOR methodology is based on the analysis of alternatives with respect to measures of closeness-to-ideal alternative under conflicting criteria. The multi-criteria measure is used for compromised ranking (Opricovic and Tzeng, 2004). VIKOR is used to rank the different maintenance systems using the results obtained from the FGRA (Equation 14). The implementation of VIKOR involves five basic steps. These steps are discussed as follows (Opricovic and Tzeng, 2004; Wang and Pang, 2011):

Step 1: Evaluation of the worst and best maintenance criterion. The worst maintenance criterion is the minimum value maintenance criterion among the maintenance systems (Equation 15), while the best maintenance criterion is the best value maintenance criterion among the maintenance systems (Equation 16).

$$f_j^- = \min\left(f_{sj}\right) \tag{15}$$

$$f_j^* = \max\left(f_{sj}\right) \tag{16}$$

where f_{sj} represents the GRA value for criterion *j* obtained from maintenance system *s*, f_j^* represents maximum value for criterion *j*, and f_j^- represents minimum value for criterion *j*.

Step 2: Computation of utility (*S*) and regret measure (*R*) for each alternative. The value of *S* is expressed as Equation (17), while *R* value is expressed as Equation (18).

$$S_s = \sum_{j=1}^{n} \frac{w_j\left(f_j^* - f_{sj}\right)}{f_j^* - f_j^-} \tag{17}$$

$$R_j = \max_j \left(\frac{w_j \left(f_j^* - f_{sj} \right)}{f_j^* - f_j^-} \right) \tag{18}$$

Step 3: Determination of VIKOR index for each maintenance system. The value of VIKOR index for maintenance system is based on utility and regret measure values as well as weight (*v*). The VIKOR index for a maintenance system is expressed as Equation (19).

$$Q_s = \frac{v\left(S_s - S_s^-\right)}{S_s^* - S_s^-} + \frac{(1-v)\left(R_s - R_s^-\right)}{R_s^* - R_s^-} \tag{19}$$

where R_t^- represents min(R_s), R_t^* represents max(R_s), S_s^* represents max(S_s), and S_s^- represents min(S_s).

Step 4: Ranking and selection of the maintenance systems using the values obtained from Equations (17) to (19). The best maintenance system is the maintenance system with the lowest value for *S*, *R* and *Q*.

Step 5: Generation of compromise solution using the VIKOR indices that are obtained from Equation (20). The conditions for compromise solution generation are given as follows:

CC1: Acceptable advantage

$$Q\left(a''\right) - Q\left(a'\right) \geq \frac{1}{T-1} \tag{20}$$

where a'' represents the second-ranked alternative based on VIKOR indices.

CC2: Acceptable stability
The best alternative must also be the best alternative based on either utility or/and regret measure.

When any of the above conditions is violated, a compromise solution is generated as follows:

i. Alternative a' and a'' when the acceptable stability is violated.
ii. Alternative $a', a'' \ldots a^m$ when the acceptable advantage is violated. Alternative a^m is determined based on Equation (21).

$$Q\left(a^m\right) - Q\left(a'\right) \geq \frac{1}{T-1} \tag{21}$$

5.0 CASE STUDY AND DISCUSSION OF RESULTS

As earlier outlined in this work, a robust literature exists on performance appraisal concerning the maintenance system but the use of non-traditional optimization tools and methodologies involving the fusion of fuzzy logic with Saaty's AHP prioritization scheme as well as the fuzzfied GRA have not been experimented with industrial data. There have not been any robust efforts and results from individual application perspective, to validate its worthiness. Consequently, fuzzified AHP, fuzzified GRA and VIKOR were subjected to industrial and practical analysis using the developed framework and the outcome of this research exercise are reported in the current section.

The proposed conceptual framework was applied in four manufacturing systems. The first manufacturing system (S_1) specialised in the production of packaged fast foods, while the second (S_2) and third (S_3) manufacturing systems specialised in the production of metallic products for household utensils and industrial purposes. The last manufacturing system (S_4) specialises in the production of packaging materials for industrial and domestic purposes. Information used for the implementation of the proposed conceptual framework was obtained using questionnaires. Interviews were conducted with two main decision-makers in each of the maintenance systems. The participants were asked to give answers to five categories of questions. The categories were: (I) physical environment; (II) organisation's environment; (III) machine performance; (IV) human attributes; and (V) maintenance cost. For each maintenance system, three decision-makers from a maintenance department were considered as respondents (maintenance manager and supervisors).

During the computation of the importance of the maintenance criteria, it was observed that the importance of each of the maintenance criterion varies with respect to a selected manufacturing system goal (Table 4 to 9). For instance, the most important criterion with respect to any selected manufacturing system goal varies from goal to goal (Tables 4 to 9). In terms of system reliability, the most important criterion was human attributes. This was followed by machine performance criterion. The least important criterion under system reliability goal was organisational environment (Table 4).

Table 4. Pair-wise comparisons of maintenance criteria with respect to system reliability

Criteria	C_1	C_2	C_3	C_4	C_5	Priorities
C_1	1.0000	3.9028	1.5522	0.9446	1.4591	0.1160
C_2	1.1819	1.0000	1.4633	0.8155	1.0730	0.0044
C_3	2.9583	3.6042	1.0000	0.9954	4.1250	0.2550
C_4	4.5833	0.8155	4.6875	1.0000	1.0863	0.4403
C_5	3.4167	1.0730	1.4113	3.9583	1.0000	0.1843

During the consideration of profitability goal, maintenance cost was the most important criterion. The importance of maintenance cost was slightly greater than machine performance importance (Table 5). Furthermore, the physical environment of the manufacturing companies was the least important criterion under profitability goal. However, physical environment was identified as the most important criterion under production lead-time goal. This was followed by organisational environment criterion (Table 6). There was slight difference between maintenance cost and machine performance criteria under production lead-time goal. In addition, human attributes criterion was the least important criterion under production lead-time goal (Table 6).

Table 5. Pair-wise comparisons of maintenance criteria with respect to profitability

Criteria	C_1	C_2	C_3	C_4	C_5	Priorities
C_1	1.0000	3.7500	1.0099	0.9690	1.2383	0.0646
C_2	1.0583	1.0000	1.3163	4.2500	0.8446	0.1057
C_3	4.0833	4.3125	1.0000	4.3750	1.2571	0.3164
C_4	4.4583	1.1871	1.4321	1.0000	2.0161	0.1333
C_5	4.3125	4.6042	4.0625	3.3411	1.0000	0.3799

Table 6. Pair-wise comparisons of maintenance criteria with respect to production lead-time

Criteria	C_1	C_2	C_3	C_4	C_5	Priorities
C_1	1.0000	1.8722	1.7472	4.1119	4.0000	0.2618
C_2	3.7994	1.0000	3.7500	1.3472	3.3514	0.2489
C_3	3.7889	1.2792	1.0000	3.7264	1.9716	0.1937
C_4	1.5813	3.7889	1.6452	1.0000	0.6369	0.1024
C_5	1.3472	1.6792	3.5494	3.9583	1.0000	0.1932

The results for the importance of the criteria under system safety showed that organisational environment was the most important criterion. This was followed by physical environment criterion (Table 7). There was a slight difference between the physical environment and human attributes importance (Table 7). Machine performance was the least important criterion under a system safety goal (Table 7). In term of production cost goal, maintenance cost was the most importance criterion (Table 8). The importance of human attributes criterion under production cost was ranked second. Human attributes criterion importance was slightly more than that of machine performance (Table 8). There was a slight difference between the importance values of organisation and physical environments under production cost goal (Table 8).

Table 7. Pair-wise comparisons of maintenance criteria with respect to system safety

Criteria	C_1	C_2	C_3	C_4	C_5	Priorities
C_1	1.0000	3.7028	3.2056	2.1107	4.5000	0.2710
C_2	1.5482	1.0000	4.1250	0.9718	4.7500	0.3016
C_3	1.8536	1.0946	1.0000	1.9925	2.9000	0.0377
C_4	3.6869	4.5833	2.9222	1.0000	1.3927	0.2632
C_5	1.0135	0.9690	1.9091	4.2361	1.0000	0.1265

Table 8. Pair-wise comparisons of maintenance criteria with respect to production cost

Criteria	C_1	C_2	C_3	C_4	C_5	Priorities
C_1	1.0000	1.5480	4.1250	1.1530	0.9216	0.1425
C_2	3.0625	1.0000	1.0821	3.7500	1.5127	0.1399
C_3	1.3766	3.8333	1.0000	1.6744	3.8514	0.2139
C_4	4.1875	1.2196	3.5389	1.0000	1.0863	0.2237
C_5	3.4583	3.7111	1.6821	3.9583	1.0000	0.2801

From the pair-wise comparison of the manufacturing goals, the most important goal was g_2 (profitability), while g_3 (production lead-time) was the least important goal. The difference between the importance of system safety and production cost was close. This study ranked system safety as second, while production cost was ranked third.

Table 9. Pair-wise comparisons of manufacturing goals

Goals	g_1	g_2	g_3	g_4	g_5	Priorities
g_1	1.0000	4.1250	1.5036	1.1504	1.7988	0.1570
g_2	1.3044	1.0000	3.6250	4.3542	1.3516	0.2750
g_3	3.3333	1.3688	1.0000	3.2292	1.8639	0.1269
g_4	4.3125	0.8897	1.2833	1.0000	3.0778	0.2243
g_5	3.4139	3.8333	2.8250	1.7183	1.0000	0.2168

Based on the information in Tables 4 to 9, the weight for the criteria were determined (Table 10). The most important criterion for the manufacturing system goals was maintenance cost (C_5). This was followed by human attributes criterion (C_4), which had a weight value that was closed to maintenance cost. Physical environment criterion (C_1) was the least important criterion (Table 10). There exists a slight difference between the organisation environment and machine performance criteria (Table 10). The grey relational coefficients for the different principal components were generated by converting linguistic values that were obtained from the different maintenance systems into crisp values (Table 11).

Table 10. Criteria weights based on FAHP

	C_ig_1	C_ig_2	C_ig_3	C_ig_4	C_ig_5	Total	Weights
C_1	0.0182	0.0178	0.0332	0.0608	0.0309	1.1738	0.1677
C_2	0.0007	0.0291	0.0316	0.0676	0.0303	1.2348	0.1764
C_3	0.0400	0.0870	0.0246	0.0085	0.0464	1.3501	0.1929
C_4	0.0691	0.0367	0.0130	0.0590	0.0485	1.6135	0.2305
C_5	0.0289	0.1045	0.0245	0.0284	0.0607	1.6278	0.2325

Table 11. Crisp values for the principal components

	S_1	S_2	S_3	S_4
x_{11}	0.4352	0.8333	0.6574	0.6574
x_{11}	0.6574	0.8333	0.6574	0.8333
x_{11}	0.2130	0.8796	0.6574	0.4815
x_{11}	0.7037	0.8796	0.8333	0.8796
x_{11}	0.7917	0.9222	0.4333	0.7917
x_{21}	0.6574	0.8796	0.6574	0.8796
x_{22}	0.6574	0.8796	0.6574	0.8796
x_{23}	0.2130	0.8796	0.6111	0.7037
x_{24}	0.4667	0.4667	0.7000	0.7833
x_{25}	0.9048	0.7857	0.5595	0.5595
x_{31}	0.8452	1.0714	0.8452	1.0714

x_{32}	0.6574	0.8333	0.4352	0.6574
x_{33}	0.6574	0.8796	0.6574	0.8796
x_{34}	0.3056	0.6746	0.6574	0.8333
x_{35}	0.6574	0.8796	0.8333	0.8796
x_{41}	0.2738	0.7857	0.8452	0.5595
x_{42}	0.3333	0.7857	0.8452	0.7857
x_{43}	0.7857	1.0714	0.9048	1.1310
x_{44}	1.1833	1.2667	0.8667	1.8444
x_{45}	1.0714	1.0714	0.8452	1.3175
x_{46}	0.8452	1.3175	0.8452	1.3175
x_{47}	0.5595	0.9048	0.8452	1.1310
x_{51}	0.3000	0.4667	0.7000	0.3833
x_{52}	0.4667	0.7833	0.7833	0.3833
x_{53}	0.4667	0.7833	0.4667	0.3833
x_{54}	0.7857	0.5000	0.2143	0.5000
x_{55}	0.5595	0.9048	0.5000	0.8452

Based on the results in Table 12, S_1 was the worst ranked maintenance system for all the maintenance system appraisal criteria. In terms of physical and organisation environments criteria, S_2 was the best ranked maintenance system, while S_4 was the best ranked maintenance system in terms of machine, human attributes and maintenance cost criteria (Table 12). From the perspective of maintenance system-wise, the highest grey relational grades for all the maintenance system was human attribute criterion. Furthermore, maintenance cost grey relational grade was the lowest for S_1, S_2 and S_3. The lowest grey relational grade for S_4 was physical environment criterion.

Table 12. Grey relational grade

Goals	S_1	S_2	S_3	S_4
C_1	0.5602	0.8696	0.6478	0.7287
C_2	0.5798	0.7783	0.6371	0.7612
C_3	0.6246	0.8677	0.6857	0.8643
C_4	0.7218	1.0290	0.8568	1.1552
C_5	0.5157	0.6876	0.5329	0.8452

In order to apply VIKOR technique, the grey relational grades for each of the maintenance systems were computed (Table 12). The results obtained showed that maintenance system S_2 had the maximum values for criteria C_1 to C_3, while maintenance system S_4 had the maximum values for criteria C_4 and C_5. The minimum values for criteria C_1 to C_5 were obtained from maintenance system S_1 (Table 13).

Table 13. Calculated best and worst values

	C_1	C_2	C_3	C_4	C_5
f_i^*	0.8696	0.7783	0.8677	1.1552	0.8452
f_i^-	0.5602	0.5798	0.6246	0.7218	0.5157

The values for S, R and Q were generated using the information in Tables 12 and 13 using Equations (17) to (19). From the information in Table 14, the acceptable advantage and stability were checked and it was observed that they were satisfied (Table 15). It could be deduced that the best maintenance system was S_4. Based on the results in Tables 12 and 13, it is obvious that the use of single performance index to appraise maintenance system is not as reliable as a multi-criteria approach.

Table 14. Utility, regret measure and VIKOR index

	S_1	S_2	S_3	S_4
S	0.9999	0.1840	0.7731	0.0899
R	0.2470	0.1181	0.2341	0.0733
Q (v = 0.2)	1.0000	0.1344	0.7858	0.0000
Q (v = 0.5)	1.0000	0.1809	0.8383	0.0000
Q (v = 0.8)	1.0000	0.2273	0.8908	0.0000

The VIKOR results showed there is consistency in the utility, regret measure and VIKOR index results (Table 15). From Table 15, the best maintenance system was S_4, while S_1 was the least ranked maintenance system. The results obtained from this study can be used to benchmark maintenance system. This will reveal best practices that can be used to improve manufacturing goals. Furthermore, the proposed model can be used to carry out internal benchmarking process. This could be factory-wise or maintenance section-wise. It will require minor adjustments of the proposed framework, by changing maintenance system with factory or maintenance section.

Table 15. Ranking of maintenance systems

	1	2	3	4
S	S_4	S_2	S_3	S_1
R	S_4	S_2	S_3	S_1
Q	S_4	S_2	S_3	S_1

From the foregoing, the concept framework has the capacity to generate ranks for maintenance systems. The principal components that were considered for each of the maintenance criterion could be either increase or decrease to suite a maintenance system of interest. For instance, the proposed framework can be applied to service systems. To achieve this, redefinition of the terms used in the proposed framework are required. One of the limitations of the proposed framework is that it relies mainly on subjective responses from decision makers. This implies that biasness of decision makers may affect the outcome of the proposed model. This may be experienced when the model is used to evaluate maintenance sections in a maintenance department.

The contributions of this study are as follows: It introduces the concept of environment, human and machine criteria under a single framework for maintenance system appraisal. The use of VIKOR approach for maintenance system appraisal has been introduced.

6.0 CONCLUSIONS

This study presents a conceptual framework, based on fuzzy analytical hierarchy process (FAHP), fuzzy grey relational analysis (FGRA) and VIKOR, for maintenance systems appraisal. The proposed framework has addressed three problems: (i) determination of weights for maintenance criteria under fuzzy environments using FAHP; (ii) aggregation of maintenance criterion principal components when dealing with fuzzy environment using FGRA; and (iii) appraisal of maintenance systems using VIKOR technique.

This study has shown that the appraisal of maintenance systems using multi-criteria is a more robust means for maintenance activities analysis when compared with single factor performance indicators. The proposed framework applicability was verified using information obtained from four manufacturing systems. The results obtained showed that the proposed framework is a veritable tool for maintenance system appraisal. In addition, the results from the proposed framework have shown that it has the capacity to drive the quest for improved performance of manufacturing systems maintenance departments. Furthermore, there is the need to perform system stability analysis prior to data collection during the proposed framework application. A study which considers the classification of maintenance environment using expert systems could be pursued as a further study. Prioritisation of manufacturing system goals from maintenance perspective could be considered as a future study. A future study which considered the application of proposed framework for ranking maintenance policy in manufacturing system could be pursued.

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