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Fuzzy-Grey Relational Analysis Applied to Optimal Maintenance Strategy Selection: The Case of Egbin Thermal Power Station, Nigeria

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ABSTRACT

One way to reduce maintenance cost and maximize system safety and reliability is to implement the most appropriate maintenance strategy for the system. There are different maintenance strategies and the task of choosing the optimal strategy is cumbersome due to numerous decision criteria associated with decision making. The purpose of this paper is to develop a model for the selection of a mix of maintenance strategies for a complex industrial system. The fuzzy-GRA method is proposed which combine the fuzzy set theory (FST) with the Grey relational analysis (GRA). The application of the proposed model was demonstrated with a case of a critical equipment of Egbin thermal power station in Nigeria. Four maintenance strategies: corrective maintenance (CM), preventive maintenance (PM), total productive maintenance (TPM), and condition-based maintenance (CBM) were evaluated based on four decision criteria. From the fuzzy-GRA analysis, TPM was ascertained to be the best approach for maintaining the equipment. The fuzzy-GRA method generated entirely same result when compared with the fuzzy-VIKOR techniques.

1. INTRODUCTION

Maintenance can be defined as all activities intended towards preserving the condition or restoring the condition of a system in which it can effectively perform it task (BS 2010). The aim of maintenance activities is to ensure consistent system or equipment operability, faults detection and elimination or prevention of functional failure (Borjalilu and Ghambari, 2018).

The importance majority of industries attached to maintenance has increased tremendously since the inception of the industrial age which in recent times translated to improved productivity and minimum system or equipment breakdown at minimal cost (Carpitella et al., 2021). The cost of maintenance is generally high in most organizations ranging from 15 to 70% of the total cost of production (Ilangkumaran and Kumanan 2012). This can be attributed to (1) the high cost of bringing the equipment to its standard operable condition, (2) penalty cost incurred due to production loss and (3) damage and safety hazards to personnel and environments caused by failure (Ilangkumaran and Kumanan 2012). One way to reduce maintenance cost and maximize system reliability is to implement the most appropriate maintenance strategy for the system (Borjalilu and Ghambari, 2018). The task of maintenance strategy selection is very important as improper maintenance strategies can result to severe production loss for the industry. It has been reported in the literature that the cost estimate of these losses amounts to $50,000 per annum (Carpitella et al., 2021). On the other hand, choosing the best maintenance approach can produce a cost savings of around 28% of the total cost (Karabağ et al., 2020; Carpitella et al., 2021).

However, the task of maintenance strategy selection is complex due to numerous decision criteria such as reliability and cost involves in the decision-making process (Shafiee et al., 2019). Multicriteria decision making (MCDM) approaches have been used in the selection of appropriate maintenance strategy for diverse industries systems. Carpitella et al. (2021) used the Analytic Network Process (ANP) technique to evaluate the best maintenance strategy for a subsystem of a marine salt manufacture firm. The authors evaluated the performance of four maintenance strategies (reactive maintenance (RM), preventive maintenance (PM), condition based maintenance (CBM), and opportunistic maintenance (OM)) with respect to five criteria: safety and security, cost, reliability, availability, feasibility and added value. In the study carried out by Bakhat and Rajaa (2020) the optimal maintenance strategy was selected for a macro system using a combination of fuzzy AHP and fuzzy WASPAS. Kurian et al. (2020) investigated the application of ANP for the selection of the best maintenance strategy for a cement industry in India. Seiti et al. (2017) demonstrated the use of risk based AHP for maintenance strategy selection for a rolling mill. The use of Fuzzy-ANP was studied by Borjalilu and Ghambari, (2018) for determining optimal maintenance method from among CM, PM, CBM, Predictive Maintenance (PDM), and RCM for 5 MW power house.

On the basis of the literature presented, there is no doubt, different authors in the past have applied various MCDM approaches such as AHP and ANP to solve maintenance strategy selection problems in diverse fields. To the best of our knowledge, fuzzy-GRA method is yet to be explored in analysing maintenance strategy selection. There is therefore, the need to study the application of the technique for maintenance strategy selection. In addition, the fuzzy GRA has the capability of comparing reference series with each alternative and thus the approach provides an exceptional ranking to alternatives (Kuo et al., 2008; Olabanji and Mpofu 2020). The excellent ranking ability of the approach have attracted authors in the application of the method to successfully solve multicriteria decision problem in areas such as material selection (Sanghvi et al., 2020), system performance evaluation (Li and Zhao 2016).

The industry of focus is the thermal power generation industry in Nigeria and specifically Egbin thermal power station. The power generation station has been generating power far below installed capacity and the major reason attributed to this is the problem of improper maintenance of the power plants (Emovon et al., 2018). However, to achieve a sustainable power supply which is the goal of every energy supplier, the power plant for generating electricity must remain safe and reliable and this can only be attained through effective maintenance of the plant. It was reported in the work carried out by Ozcan et al. (2017) that performing proper maintenance on power plant is of paramount importance as it assists in elongating the operable life and invariably improving sustainable electricity generation of the plant. In this paper, four maintenance strategies (CM, PM, TPM and CBM) are considered and evaluated for performance against four decision criteria and the best approach selected using fuzzy GRA for effective maintenance of Egbin thermal power station plant.

2. METHODOLOGY

2.1. Fuzzy GRA Method

The GRA approach was developed by Deng (1982) for solving multicriteria decision problem. The principle of ranking is based on the level of similarity between the reference alternative and each comparison alternative (Kuo and Liang 2011; Banaeian et al., 2018). The limitation of the GRA method is the application of only precise data in the decision analysis but in real life data may be imprecise. To overcome this limitation, the GRA method is integrated with the fuzzy set theory (FST) to produce a hybrid refer to as fuzzy-GRA. In this hybrid approach, linguistic variables are applied by decision makers to assigned ratings to alternatives against decision criteria (Kaya and Kahraman, 2010). The linguistic variables are translated to duzzy triangular number (TFN). TFN are three numbers: *l*, *m,* and *p*. Tables 1 and 2 indicate linguistic scale for assigning fuzzy rating to alternatives against decision criteria and for assigning fuzzy rating to decision criteria.

Table 1: Fuzzy linguistic variables and TFN for each criterion (Banaeian et al., 2018)

Linguistic	Abbreviation	TFN
Very low	VL	0, 0.1, 0.2
Low	L	0.1, 0.2, 0.3
Medium	M	0.4, 0.5, 0.6
High	H	0.7,0.8 ,0.9
Very Hhigh	VH	0.8, 0.9, 1

Table 2: Fuzzy linguistic variables and TFN for each alternatives (Kore et al., 2017; Azizi et al., 2015)

Linguistic variables	Abbreviation	TFN
Very low	VL	1,1,3
Low	L	1,3,5
Medium	M	3,5,7
High	H	5,7,9
Very high	VH	7,9,10

The Fuzzy GRA algorithm steps are as follows (Banaeian et al., 2018):

Step 1: Determination of combined decision matrix

In the fuzzy-GRA approach, the first step involves the decision makers assigning fuzzy rating to the maintenance strategy alternatives against decision criteria using fuzzy scale in Table 2. In a scenario involving *k* number of decision makers assigning rating to alternative *i* with respect to decision criterion *j,* the combine rating of the decision makers was determined as follows (Kaya and Kahraman, 2010):

$$\tilde{u}_{ij} = \frac{1}{k}\left[\tilde{u}_{ij}^{1} + \tilde{u}_{ij}^{2} +, \dots \tilde{u}_{ij}^{k}\right] \tag{1}$$

Where $\tilde{u}_{ij}^{k}$ is the *k*th decision maker fuzzy rating of *i*th alternative against *j*th criterion.

In the group decision making process, *k* number of decision makers assigned fuzzy weights to decision criteria. The combined fuzzy decision criteria weights were obtained as follows (Wang et al., 2007):

$$\tilde{w}_{j} = \frac{1}{k}\left[\tilde{w}_{j}^{1} + \tilde{w}_{j}^{2} +, \dots \tilde{w}_{j}^{k}\right] \tag{2}$$

Where $\tilde{w}_{j}^{k}$ is the fuzzy weight of criterion *j* assigned by *k*th decision maker.

The combined fuzzy rating of alternatives, were used to form a decision problem matrix as follows (Kaya and Kahraman, 2010):

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$$\widetilde{U}_{ij} = \begin{bmatrix} \tilde{u}_{11} & \tilde{u}_{12} & \dots & \tilde{u}_{1n} \\ \tilde{u}_{21} & \tilde{u}_{22} & \dots & \tilde{u}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{u}_{m1} & \tilde{u}_{m2} & \dots & \tilde{u}_{mn} \end{bmatrix} \quad (3)$$

On the other hand, the combined decision criteria weights was expressed as:

$$\widetilde{w}_j = [\widetilde{w}_1 + \widetilde{w}_2 +, \dots, \widetilde{w}_n], \qquad j = 1, 2, 3, \dots, n \quad (4)$$

Where $\tilde{u}_{ij}$ is the alternative, *i*, rating against criterion *j* and $\widetilde{w}_j$ indicate fuzzy weight of criterion *j* and $\tilde{u}_{ij} = (l_{ij}, m_{ij}, p_{ij})$

Step 2: Normalisation of combined decision matrix

The decision matrix was normalized to ensure all decision criteria are compatible and the normalized matrix is expressed as:

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{p_j^+}, \frac{m_{ij}}{p_j^+}, \frac{p_{ij}}{p_j^+}\right) i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (5)$$

Where:

$p_j^+ = \max_i p_{ij}$

Step 3: Determination of reference series

Each criterion reference number was evaluated using the following equation:

$$\tilde{R}_o = \left\{\tilde{r}_{o1}, \tilde{r}_{o2}, \dots, \tilde{r}_{on} = \max_i \tilde{r}_{ij}\right\} \quad j = 1, 2, \dots, n \quad (6)$$

Step 4: Evaluation of the distance ∂_{ij} between the value of reference and each comparison value

The distance ∂_{ij} between the value of reference and each comparison value was evaluated by applying the vertex approach as follows:

$$\partial_{ij}(\tilde{R}_{oj}, \tilde{r}_{ij}) = \sqrt{\frac{1}{3}\left[(r_o^l - r_{ij}^l)^2 + (r_o^m - r_{ij}^m)^2 + (r_o^p - r_{ij}^p)^2\right]} \quad (7)$$

Step 5: Determination of the grey relational coefficient

The grey relational coefficient $\Im_{ij}$ is given as:

$$\Im_{ij} = \frac{\min \partial_{ij} + \rho \max \partial_{ij}}{\partial_{ij} + \rho \max \partial_{ij}} \quad (8)$$

Where ρ is a revolving coefficient ranging from the value of 0 to 1

Step 6: Defuzzification

The fuzzy weights assigned by the decision makers indicated in Equation 4 were converted into crisp real number through defuzzification expressed as follows:

$$Crisp(\widetilde{w}_j) = w_j = \frac{l + 2m + p}{4} \quad (9)$$

Step 7: Determination of the grey relational grade

The grey relational grade φ_i of the alternatives were evaluated by summing the product of criteria weights and the grey relational coefficient as follows:

$$\varphi_i = \sum_{j}^{n} w_j \Im_{ij} \quad , i = 1, 2, \ldots, m \quad (10)$$

Where w_j is the weight of the *j*th criterion

Applying grey relational grade φ_i the alternatives were ranked with the alternative with the highest value being the best option.

2.2. Case Study

To illustrate the applicability of the fuzzy GRA method, a case of Egbin thermal power station is utilized. The power station was established in 1985 with an installed capacity of 1320 MW which is produced from six installed plants (steam turbine generators) each with a capacity of 220MW (Anyaka, 2020). The productivity of the station has been low due to improper maintenance strategy adopted for maintenance of its plants (Emovon and Samuel, 2017). The present approach which is mainly CM and PM (based on equipment operation manual) is not effective as frequent equipment failure and breakdown occurs. To optimize productivity, there is need to adopt a mix of maintenance strategy for each of the numerous equipment of the plant. Effort to use specialist opinions in the past to select best mix of strategies failed. In this study, a fuzzy GRA method is proposed to produce a mix of maintenance strategy for the plant system. The boiler, one of the critical equipment of the power plant was used to demonstrate the suitability of the proposed technique. A single decision maker (expert) opinion was used in assigning rating to the four maintenance strategies against four decision criteria using fuzzy scale in Table 2. The assigned rating is shown in Table 3. To determine decision criteria weights, the single decision maker was asked to assigned rating to the decision criteria. The assigned ratings are indicated in Table 4.

Table 3: Decision makers assigned fuzzy rating for a power plant

Alternatives	Maintenance cost (MC)			Reliability (R)			Safety (S)			Ease of implementation (EI)		
CM	(7	9	10)	(1	1	3)	(1	1	3)	(7	9	10)
PM	(5	7	9)	(1	3	5)	(1	3	5)	(5	7	9)
TPM	(5	7	9)	(7	9	10)	(7	9	10)	(1	3	5)
CBM	(1	1	3)	(7	9	10)	(7	9	10)	(1	1	3)

Table 4: Decision makers assigned fuzzy weights for decision criteria

Criteria	MC			R			S			EI		
Fuzzy weights	(0.4	0.5	0.6)	(0.4	1	0.6)	(0.7	0.8	0.9)	(0.1	0.2	0.3)

In the ranking of alternatives maintenance strategies involving only a single decision maker, the first step is the normalization of the decision matrix in Table 3 using Equation 5. The normalized decision matrix is shown in Table 5. It is worth noting that if a group of decision makers are used in the decision-making process, the fuzzy GRA analysis will start with Equation 1 i.e., aggregation of the individual rating of alternatives. The reference series for each alternative maintenance strategy are then evaluated using Equation 6. Next, the evaluation of the distance ∂_{ij} between the value of reference and each comparison value was carried out using Equation 7. The result obtained for CM(MC), PM(MC), TPM(MC) and CBM(MC) were utilized to demonstrate the calculation process. Having evaluated ∂_{ij}, the next step was the determination of grey relational coefficient ($\Im_{ij}$) using Equation 8. The fuzzy weights of the decision criteria were defuzzified applying Equation 9. The grey relational grades of the alternatives are evaluated by summing the product of criteria weights and the grey relational coefficient using Equation 10.

3. RESULTS AND DISCUSSION

The normalized decision matrix obtained by the normalization of the decision matrix in Table 3 using Equation 5 are presented in Table 5. The decision matrix is normalized to ensure all decision criteria: MC, R, S, and EI values are compatible.

Table 5: Normalised decision matrix

Alternatives	MC			R			S			EI		
CM	(0.7	0.90	1)	(0.1	0.10	0.3)	(0.1	0.10	0.3)	(0.7	0.90	1)
PM	(0.5	0.70	0.9)	(0.1	0.30	0.5)	(0.1	0.30	0.5)	(0.5	0.70	0.9)
TPM	(0.5	0.70	0.9)	(0.7	0.90	1)	(0.7	0.90	1)	(0.1	0.30	0.5)
CBM	(0.1	0.10	0.3)	(0.7	0.90	1)	(0.7	0.90	1)	(0.1	0.10	0.3)

The normalization process is demonstrated with results obtained for CM (MC), PM(MC), TPM(MC) and CBM (MC) in Table 5 as follows:

$$CM(MC) = \left(\frac{7}{10}, \frac{9}{10}, \frac{10}{10}\right) = (0.7, 0.9, 1)$$

$$PM(MC) = \left(\frac{5}{10}, \frac{7}{10}, \frac{9}{10}\right) = (0.5, 0.7, 0.9)$$

$$TPM(MC) = \left(\frac{5}{10}, \frac{7}{10}, \frac{9}{10}\right) = (0.5, 0.7, 0.9)$$

$$CBM(MC) = \left(\frac{1}{10}, \frac{1}{10}, \frac{3}{10}\right) = (0.1, 0.1, 0.3)$$

The reference series for each alternative maintenance strategy are presented in Table 6. The values are used for the evaluation of the distance ∂_{ij} between reference value and comparison value.

Table 6: Reference series $\tilde{R}_o$ for alternative maintenance strategy

$\tilde{R}_o$	MC			R			S			EI		
	(0.7	0.9	1)	(0.7	0.9	1)	(0.7	0.9	1)	(0.7	0.9	1)

The result of distance ∂_{ij} between reference value and comparison value are presented in Table 7. The values are used for evaluating the grey relational coefficients.

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Table 7: Distance ∂_{ij} between reference value and comparison value

Alternatives	MC	R	S	EI
CM	0.0000	0.7047	0.7047	0.0000
PM	0.1732	0.5686	0.5686	0.1732
TPM	0.1732	0.0000	0.0000	0.5686
CBM	0.7047	0.0000	0.0000	0.7047

The result obtained for CM(MC), PM(MC), TPM(MC) and CBM(MC) were utilized to demonstrate the calculation process.

$$CM(MC) = \sqrt{\frac{1}{3}[(0.7 - 0.7)^2 + (0.9 - 0.9)^2 + (1 - 1)^2]} = 0.0000$$

$$PM(MC) = \sqrt{\frac{1}{3}[(0.7 - 0.5)^2 + (0.9 - 0.7)^2 + (1 - 0.9]} = 0.1732$$

$$TPM(MC) = \sqrt{\frac{1}{3}[(0.7 - 0.5)^2 + (0.9 - 0.7)^2 + (1 - 0.9)^2]} = 0.1732$$

$$CBM(MC) = \sqrt{\frac{1}{3}[(0.7 - 0.1)^2 + (0.9 - 0.1)^2 + (1 - 0.3)^2]} = 0.7047$$

The evaluated grey relational coefficient for each alternative is presented in Table 8. The values are used together with decision criteria weights for calculating the grey relational grade.

Table 8: Grey relational coefficient $\Im_{ij}$

Alternatives	MC	R	S	EI
CM	1.000	0.333	0.333	1.000
PM	0.670	0.383	0.383	0.670
TPM	0.670	1.000	1.000	0.383
CBM	0.333	1.000	1.000	0.333

The grey relational coefficient obtained for CM(MC), PM(MC), TPM(MC) and CBM(MC) were utilized to demonstrate the calculation process as follows:

Where $\max \partial_{ij} = 07047, \min \partial_{ij} = 0.0, \rho = 0.5$

$$\text{CM(MC)} = \frac{0.0 + (0.5 * 0.7047)}{0.0 + (0.5 * 0.7047)} = 1.00$$

$$\text{PM(MC)} = \frac{0.0 + (0.5 * 0.7047)}{0.1732 + (0.5 * 0.7047)} = 0.670$$

$$\text{TPM(MC)} = \frac{0.0 + (0.5 * 0.7047)}{0.1732 + (0.5 * 0.7047)} = 0.670$$

$$\text{CBM(MC)} = \frac{0.0 + (0.5 * 0.7047)}{0.7047 + (0.5 * 0.7047)} = 0.333$$

The defuzzified weights obtained for MC, R, S and EI using Equation 9 are 0.25, 0.25, 0.4 and 0.1 respectively. The grey relational grades of the alternatives are calculated by summing the product of criteria weights and the grey relational coefficient. The results are presented in Table 9 together with the alternatives rank.

Table 9: Grey relational grade and rank

Alternatives	φ_i	Rank
CM	0.5667	3
PM	0.4833	4
TPM	0.8559	1
CBM	0.7667	2

From Table 9, the best maintenance strategy for the boiler is the TPM having the maximum score of 0.8559. For this analysis the worst approach for maintenance of the boiler is the PM having the minimum score of 0.4833. By implementing TPM the company maintenance challenges will be overcome as the benefits of the proposed approach include among others (Poduval et al., 2015): (1) cost effective maintenance approach, (2) equipment failure minimization, (3) work place safety maximization, and (4) equipment effectiveness maximisation due to involvement of both operation and maintenance personnel. The proposed fuzzy GRA method is simple and can be implemented with ease in any industrial system.

To further validate the fuzzy GRA method, the boiler maintenance strategy selection decision problem was solved with the fuzzy VIKOR and the comparative analysis results generated are indicated in Table 10. From the analysis results in Table 10, both approaches generated same rankings for the four maintenance strategies in the following order TPM> CBM> CM>PM with TPM being rank best strategy for the boiler. According to Banaeian et al., (2018) fuzzy GRA requires lesser time to generate result than the fuzzy VIKOR. This is due to fuzzy GRA technique having lesser analysis steps than the fuzzy VIKOR method. The fuzzy GRA approach is therefore recommended to decision makers for analysing maintenance strategy selection problems.

Table 10: Comparative analysis results of fuzzy GRA and fuzzy VIKOR techniques

Alternatives	φ_i (GRA rank)	Q_i (VIKOR rank)
CM	0.5667(3)	0.4511(3)
PM	0.4833(4)	0.3582(4)
TPM	0.8559 (1)	0.0000(1)
CBM	0.7667(2)	0.2207(2)

Q_i indicating VIKOR performance index

4. CONCLUSION

In this paper the fuzzy GRA model was presented for analysing the best maintenance strategy for managing an industrial system. The proposed technique combines the FST and the classical GRA methods. The fuzzy GRA suitability was demonstrated with a case of a boiler a subsystem of Egbin thermal power plant. By implementing the fuzzy GRA model on the case study, the performance values obtained for the four maintenance strategies: CM, PM, TPM and CBM were 0.5667, 0.4833, 0.8559, and 0.7667 respectively. The TPM having the highest fuzzy GRA performance value was chosen as the best strategy for the subsystem (boiler) of the Egbin thermal power station.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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