FUZZY PERFORMANCE MEASUREMENT SYSTEM FOR THE MAINTENANCE FUNCTION

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Abstract. Maintenance aims to sustain the manufacturing process by ensuring that the production tools are well managed. However, modern production means are more automated and therefore more complex, so they require a performing maintenance for which planning and implementation are increasingly difficult. This paper, therefore, emphasizes the elaboration of a maintenance performance measurement system. Therefore, for an appropriate and reliable performance evaluation, we adopt a multi-level multi-criteria approach where every criterion influencing the maintenance performance either indirectly or directly are specified. Thereafter, indicators for the specified criteria would be measured using fuzzy logic to overcome limitations due to lack of available resources and data. For a global maintenance measurement, the elementary measurements will be aggregated into a total measurement through a multiple-criteria decision-making method such as MACBETH.

1 Introduction

To remain in a competitive position, the manufacturing systems must be more productive, effective and economical [1]. However, the complexity of these manufacturing systems, the large diversity of manufactured products and the uncertainty of the production environment are behind critical dysfunctions. These malfunctions and failures negatively affect production capacity, production quality and cost, as well as potential health and safety risks and accidents to personnel, plants and the environment [2]. This is the reason behind maintenance, which is no more restricted to repair facilities, but rather involves preventing their dysfunction [3-4]. Consequently, maintenance is now a vital element in the global business success for any manufacturing company [5]. Therefore, a performing maintenance became a necessity and not a possibility.

Achieving the required performance begins with its measurement as without it there are practically any indications of improvement [6]. A performance measurement system is a management tool that allows a company to evaluate how its activities are effective and efficient [7]. This tool is structured in a multi-criteria approach, including a combination of performance indicators selected according to the company's objectives [8]. The main challenge when measuring maintenance performance is defining and choosing indicators that reflect the corporate strategy and provide quantitative feedback on the maintenance strategies performance [9]. Indeed, a suitable indicator would track and control performance, assist identifying performance gaps, and continuous improvement [5]. Therefore, to make this

system more useful, there is an obligation in defining the indicators to be measured, the way in which they should be evaluated and who is responsible for their implementation [10].

However, in an environment characterized by cost, time, resources and skill limitations, measuring the elementary performance is a big issue. For this reason, we propose that the fuzzy logic is used to quantify this elementary performance. Subsequently, by using the multi-criteria decision-making method MACBETH, the elementary performance measurements are aggregated into an overall measure that provides the total maintenance performance. Consequently, the suggested approach allows measuring the global performance and the local performances of the maintenance, as well as defining the necessary actions for a continuous maintenance performance enhancement.

2 Methodology

2.1. The identification of the elementary maintenance performance measurement indicators

In order, to measure maintenance performance correctly, the strategic aspects are specified and aligned with the company's strategy. These strategic aspects are the financial aspect, the technical aspect, the internal process aspect, the support aspect, the human resources aspect and the health, safety and environment (HSE) aspect. Afterwards, they will be disaggregated until reaching elementary indivisible sub-criteria. This paper will focus

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on financial performance measurement, which is presented in Figure 1. A similar methodology is used when assessing the other dimensions of the maintenance performance.

Figure 1 Financial maintenance performance indicators.

With **F1** direct cost, **F2** indirect Cost, **F3** maintenance intensity and **F4** capital replacement value. **CD1** Internal labor cost, **CD2** Subcontract cost, **CD3** Maintenance material purchasing cost (spare part + consumable). **CI1** training and learning costs, **CI2** HSE related cost and **CI3** unavailability cost. **CIS1** palliative cost, **CIS2** contractual penalty, **CIS3** production losses, **CIS4**: Intermediate inventory cost.

2.2. The elementary Performance Measurement using the Fuzzy Logic:

The fuzzy logic has been inserted by Zadeh (1965) [11], in order to overcome the complexity and fuzziness of the real systems, by representing them through linguistic values that will follow a mathematical treatment transformed into numerical ones [12].

2.2.1. Linguistic terms and triangular fuzzy number identification

First, to measure elementary performance, it is necessary to construct the appropriate rating scale. This performance is from 0 to 1. The 0 is a complete dissatisfaction of the target, and the 1 is a complete satisfaction of the target. Then the interval [0, 1] will be subdivided into six sub-intervals. The interval [0, 0.45] denotes a very poor satisfaction (VP), [0.35, 0.5] denotes a poor satisfaction (P), [0.45, 0.65] a medium satisfaction M, [0.6, 0.8] a good satisfaction (G), [0.75, 0.92] a very good satisfaction (VG) and [0.9, 1] indicates an excellent satisfaction (E).

Then for each criterion C_i represented in Figure 1, decision-makers will linguistically express their satisfaction degrees regarding to the objective O_i using a specific term. The result is reported in Table 1.

Table 3 the associated triangular fuzzy numbers

	CD1	CD2	CD3	CI1	CI2
K1	(0.75, 0.85, 0.92)	(0.6, 0.75, 0.8)	(0.6, 0.75, 0.8)	(0.35, 0.45, 0.5)	(0.35, 0.45, 0.5)
K2	(0.6, 0.75, 0.8)	(0.45, 0.6, 0.65)	(0.6, 0.75, 0.8)	(0.45, 0.6, 0.65)	(0.45, 0.6, 0.65)
K3	(0.6, 0.75, 0.8)	(0.6, 0.75, 0.8)	(0.6, 0.75, 0.8)	(0.45, 0.6, 0.65)	(0.35, 0.45, 0.5)
K4	(0.75, 0.85, 0.92)	(0.6, 0.75, 0.8)	(0.6, 0.75, 0.8)	(0.45, 0.6, 0.65)	(0.45, 0.6, 0.65)

Table 4 the associated triangular fuzzy numbers

	CIS1	CIS2	CIS3	CIS4	F3	F4
K1	(0.35, 0.45, 0.5)	(0, 0.35, 0.4)	(0.35, 0.45, 0.5)	(0.35, 0.45, 0.5)	(0.6, 0.75, 0.8)	(0.6, 0.75, 0.8)
K2	(0.35, 0.45, 0.5)	(0, 0.35, 0.4)	(0, 0.35, 0.4)	(0.35, 0.45, 0.5)	(0.45, 0.6, 0.65)	(0.6, 0.75, 0.8)
K3	(0.45, 0.6, 0.65)	(0.35, 0.45, 0.5)	(0.35, 0.45, 0.5)	(0.45, 0.6, 0.65)	(0.45, 0.6, 0.65)	(0.45, 0.6, 0.65)
K4	(0.35, 0.45, 0.5)	(0.35, 0.45, 0.5)	(0.35, 0.45, 0.5)	(0.45, 0.6, 0.65)	(0.6, 0.75, 0.8)	(0.6, 0.75, 0.8)

Table 1 Satisfaction degrees

	CD1	CD2	CD3	CI1	CI2	CIS1	CIS2	CIS3	CIS4	F3	F4
K1	VG	G	G	P	P	P	VP	P	P	G	G
K2	G	M	G	M	M	P	VP	VP	P	M	G
K3	G	G	G	M	P	M	P	P	M	M	M
K4	VG	G	G	M	M	P	P	P	M	G	G

After that, every linguistic term is assigned to the appropriate fuzzy number. In this study, the triangular fuzzy numbers are chosen for their simplicity [13-14-15].

$\tilde{p}_K$ is the triangular fuzzy number of a specific criterion C_i . $\tilde{p}_K = (L_K, M_K, R_K)$ with $K = VP, P, M, G, VG$ and E where L and R are two points on the left and right of the triangular fuzzy number representing the interval $[L_K, R_K]$. M_K is the most possible value. The result is in the table 2.

Table 2 Triangular fuzzy number TFN

Performance Satisfaction Degree	Triangular Fuzzy number
Very poor VP	(0, 0.35, 0.45)
Poor P	(0.35, 0.45, 0.5)
Medium M	(0.45, 0.6, 0.65)
Good G	(0.6, 0.75, 0.8)
Very Good VG	(0.75, 0.85, 0.92)
Excellent E	(0.9, 1, 1)

Then, each linguistic parameter is assigned with the corresponding triangular fuzzy number. The result is shown in Tables 3 and 4.

2.2.2. Aggregation of the fuzzy numbers

In order to get a consensus among the various evaluators, the satisfaction degrees $\tilde{p}_i^K = (L_i^K, M_i^K, R_i^K)$ $K = 1, \dots, n$ expressed by each evaluator on the evaluation criterion C_i should be aggregated into a unique TFN $\tilde{P}_i = (L_i, M_i, R_i)$ using equation (1) [16]:

$$\begin{cases} L_i = \min_k (L_i^K) \\ M_i = \frac{1}{k} \sum_{k=1}^n M_i^K \\ R_i = \max_k (R_i^K) \end{cases} \quad (1)$$

By using equation (1), the various fuzzy numbers expressed by the decision-makers will be aggregated into a single fuzzy number reflecting the satisfaction degree associated to each elementary sub criterion C_{ij} . The result is shown in Tables 5 and 6.

Table 5 Aggregation of TFNs

CIS1	CIS2	CIS3	CIS4	F3	F4
(0.35, 0.48, 0.65)	(0,0.37, 0.5)	(0,0.41, 0.5)	(0.35, 0.52, 0.65)	(0.45, 0.68, 0.8)	(0.45, 0.71, 0.8)

Table 6 Aggregation of TFNs

CD1	CD2	CD3	CI1	CI2
(0.6, 0.8, 0.92)	(0.45, 0.71, 0.8)	(0.6, 0.75, 0.8)	(0.35, 0.56, 0.65)	(0.35, 0.52, 0.65)

2.2.3. Defuzzification

In order to convert the TFN $\tilde{P}_i$ related to each evaluation criterion C_i into crisp value. The $\tilde{P}_i$ will be defuzzify by the CFCS method (Converting the Fuzzy data into Crisp Scores) proposed by Opricovic [17].

In the presented study, the fuzzy logic is utilized for quantifying the elementary maintenance performance related to the criterion C_i . So $\tilde{P}_i = (L_i, M_i, R_i)$ is the membership function of the elementary performance for the criterion C_i .

Then:

The normalization of the TFN:

$$r_i^{max} = R_i, \quad l_i^{min} = L_i$$

$$\Delta_{min}^{max} = R_i - L_i$$

$$x_l = \frac{L_i - l_i^{min}}{\Delta_{min}^{max}} = 0$$

$$x_m = \frac{M_i - l_i^{min}}{\Delta_{min}^{max}} = \frac{M_i - L_i}{R_i - L_i}$$

$$x_r = \frac{R_i - l_i^{min}}{\Delta_{min}^{max}} = 1$$

The Left and Right normalized value x^{ls} and x^{rs} :

$$x^{ls} = \frac{x_m}{1 + x_m - x_l} = \frac{M_i - L_i}{R_i - 2L_i + M_i}$$

$$x^{rs} = \frac{x_r}{1 + x_r - x_m} = \frac{R_i - L_i}{2R_i - L_i - M_i}$$

The total normalized crisp value:

$$x^{crisp} = [x^{ls}(1 - x^{ls}) + x^{rs}x^{rs}]/[1 - x^{ls} + x^{rs}]$$

Finally, the crisp values P_i , which refer to the elementary performance of the criterion C_i :

$$P_i = L_i + x^{crisp}(L_i - R_i) \quad (2)$$

By using this defuzzification method, the aggregated fuzzy numbers will be converted into a performance expression. Therefore, we will get the elementary performance P_i for each C_i criterion. The result is displayed in figure 2.

According to Figure 2, the best performances are $P_{CD1} = 0.78$ and $P_{DC3} = 0.73$. On the other hand, the poor performances are $P_{CIS3} = 0.35$ and $P_{CIS2} = 0.32$.

However, the elementary performance measurements are not suitable to provide a holistic maintenance performance assessment. Because of this, they must be aggregated to form a unified measure.

Figure 2 Financial elementary performances

2.3. The overall maintenance performance measurement

The evaluation criteria and aspects have a different effect on the performance. As a result, to identify the relative importance of each evaluation criterion and aspect, a multi-criteria decision-making MCDA method such as MACBETH is needed. Indeed, this method allows quantifying the relative weight of each criterion by using the comparative attractiveness of each criterion as expressed linguistically by the decision-makers [18].

To do this, the decision-makers will express the attractiveness relating to the evaluation criteria of the same hierarchical level. By using the MACBETH method and the M-MACBETH software, each criterion and sub-criterion will be weighted. The weights W_i of F1, F2, F3, and F4 are shown in Figure 3.

Figure 3 Financial criteria weighing using M-MACBETH.

After that, the overall maintenance performance is calculated through the aggregation of the elementary performance using the weighted arithmetic mean as in equation (3).

$$P_{ag} = Ag(P_1, \dots, P_n) = \sum_{i=1}^n W_i P_i \quad (3)$$

The result is displayed in figure 4.

Figure 4 Aggregation of the elementary performances

As a result, the overall maintenance financial performance is 0.62. In other words, the company has achieved 62% of its maintenance financial target. In addition, the weighting of the criteria by MACBETH allows to precisely identify the most critical improvement areas, in this study the performance of the direct cost and that of the indirect cost are the most critical. Therefore, these two criteria must be prioritized for further improvement.

4 Conclusion

The performance measurement system of the maintenance function introduced in this paper is elaborated through three sections. Since the first part defines and prioritizes the performance measurement indicators that are the most appropriate. The second section, by using the fuzzy logic the elementary performances are quantified through a qualitative evaluation. Subsequently, in the third section, these elementary measures are aggregated to an overall maintenance performance measure. All of this will give the company a synthesized and further detailed visibility on both local and global performance for an optimal maintenance improvement.

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