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A SPARE PARTS CRITICALITY EVALUATION METHOD BASED ON FUZZY AHP AND TAGUCHI LOSS FUNCTIONS

METODA OCENY KRYTYCZNOŚCI CZĘŚCI ZAPASOWYCH OPARTA O ROZMYTY PROCES HIERARCHII ANALITYCZNEJ AHP I FUNKCJĘ STRAT TAGUCHI

Effective and efficient operation of a manufacturing system highly depends on the timely and correct implementation of maintenance operations. One of the most important factors affecting the successful implementation of maintenance operations is the determination of suitable inventory control policies for maintenance spare parts. Effective spare parts inventory management requires the criticality evaluation of spare parts. In this study, a novel spare parts criticality evaluation approach is proposed. First, the evaluation criteria are determined based on literature review and expert opinion and Fuzzy Analytical Hierarchy Process (AHP) is used to determine the criteria weights. Next, Taguchi loss functions and simulation modeling are employed for the calculation of loss values for the spare parts. Finally, a criticality ranking of the spare parts is obtained based on the weighted loss values which are calculated using criteria weights and loss values. The applicability of the proposed approach was tested by applying it to a spare part criticality evaluation problem faced by a manufacturing company.

Keywords: *criticality evaluation; fuzzy AHP; simulation; spare parts; Taguchi loss functions.*

Skuteczne i wydajne funkcjonowanie systemu produkcyjnego w dużym stopniu zależy od terminowej i prawidłowej realizacji działań konserwacyjnych. Jednym z najważniejszych czynników wpływających na pomyślną realizację działań konserwacyjnych jest określenie odpowiednich zasad kontroli zapasów części zamiennych do konserwacji. Efektywne zarządzanie zapasami części zamiennych wymaga oceny krytyczności części zamiennych. W niniejszym badaniu, zaproponowano nowe podejście do oceny krytyczności części zamiennych. W pierwszej kolejności, ustalane są kryteria oceny na podstawie przeglądu literatury, a do określenia wagi kryteriów stosuje się analizę ekspercką oraz rozmyty proces hierarchii analitycznej (AHP). Następnie, do obliczania wartości strat dla części zapasowych wykorzystywane są funkcje straty Taguchi i modelowanie symulacyjne. W efekcie, uzyskuje się ranking krytyczności części zapasowych na podstawie wartości ważonych strat, które są obliczane przy użyciu wag kryteriów i wartości strat. Możliwość praktycznego zastosowania proponowanego podejścia zweryfikowano na przykładzie problemu oceny krytyczności części zapasowych w przedsiębiorstwie produkcyjnym.

Słowa kluczowe: *Ocena krytyczności; rozmyty proces hierarchii analitycznej AHP; symulacja; części zamienne; funkcje straty Taguchi.*

1. Introduction

Availability of machines has a direct impact on the productivity and profitability of manufacturing systems. High machine availability can only be achieved by ensuring the effective implementation of maintenance operations. One of the most important factors affecting the effectiveness of maintenance operations is the availability of spare parts [5]. That is why manufacturing companies put great emphasis on the determination of suitable inventory control policies for spare parts.

The aim of a spare part inventory control policy is to prevent spare part shortages while minimizing inventory holding and ordering costs. There are various spare part inventory control methodologies proposed in the literature. Extensions of classical inventory models [21], mathematical programming [8], reliability-based optimization models [20], Monte Carlo simulation [12] and meta-heuristics [22] are some of the approaches employed in the development of those methodologies. The interested reader is referred to reviews by Kennedy et al. [10] and Iragi et al. [9] for further information on spare part inventory control policies.

Spare part inventory control policies are generally determined based on the criticality of spare parts. Hence spare parts criticality evaluation is a vital issue in spare parts inventory management. There are several issues which complicate the criticality evaluation of spare parts. First of all, multiple and often conflicting criteria (e.g., price, demand, lead time) must be considered. Second, there is a high level uncertainty associated with various parameters such as time between failures, repair times and the quantity of spare parts needed in a failure instance. Third, criteria weights must be determined based on the opinions of the decision maker. Hence the employed weight determination method should allow the decision maker to convey his/her preferences in a natural way.

The above-cited difficulties forced researchers to develop various spare part criticality evaluation methodologies. Majority of those methodologies employ multi criteria decision making (MCDM) methodologies due to the multi-criteria nature of the problem. Analytical Hierarchy Process (AHP) is the most commonly used MCDM methodology. Braglia et al. used AHP in order to obtain the criticality classification of spare parts in a factory operating in paper industry [2]. Molenaers developed a criticality classification method by integrating AHP and decision diagrams [13]. Stoll et al. developed a three dimensional (viz., spare part value, criticality and demand predictability) methodology by employing AHP and decision trees [17].

Fuzzy versions of MCDM methodologies were also employed in order to consider the vagueness associated with the spare part criticality evaluation process. Zeng et al. developed a spare part criticality evaluation approach by integrating AHP, fuzzy comprehensive evaluation and grey relational analysis [25]. Duran developed a fuzzy AHP model for the ranking of several spare parts [6].

Development of spare part criticality evaluation approaches based on the minimization of risk and/or cost is another popular research area. Yang and Du developed a spare part criticality evaluation method which is based on the minimization of mean turn-around time and spare parts inventory cost [24]. They calculated a risk priority number for each spare part by incorporating grey relation number and turn-around-time. The spare parts criticality evaluation approach proposed by Wongmongkolrit et al. uses the ratio between opportunity cost and spare parts inventory cost [23] .

In this paper a novel spare parts criticality evaluation approach is proposed by integrating fuzzy AHP, simulation and Taguchi loss functions. Fuzzy AHP is employed in order to determine the weights for spare part evaluation criteria. Next, the loss values for the spare parts are calculated using simulation and Taguchi loss functions. Finally, the weighted loss values for the spare parts are calculated by using loss values and the criteria weights. A criticality ranking of spare parts is proposed based on the weighted loss values.

The proposed approach has several advantages over the previously proposed spare parts criticality evaluation approaches. First, the inherent uncertainty and imprecision in criteria weight assignment process is handled by using fuzzy AHP. Second, the specification limits for the spare part evaluation criteria are set by the decision maker. Third, the spare part evaluation criteria with different units and scales are converted into a common measurement unit called weighted loss. Fourth, the use of simulation modeling allows for the consideration of uncertainty associated with various maintenance related parameters including time between failures and repair times.

The rest of the paper is organized as follows. Brief information on fuzzy AHP and Taguchi loss functions are provided in sections 2 and 3, respectively. Section 4 presents the details on the application of the proposed approach to a spare part criticality problem faced by a manufacturing company. Finally, conclusions and future research directions are presented in section 5.

2. Fuzzy Analytical Hierarchy Process

Analytical Hierarchy process (AHP) [16] is a commonly used MCDM methodology due to its simple and well-defined steps. It defines a decision problem using a hierarchical structure. Pair-wise comparisons are carried out among criteria and alternatives based on the opinions of experts. Tangible and intangible criteria can be analyzed using AHP. Besides those advantages, it has also some disadvantages. The vagueness in pair-wise comparisons cannot be adequately modeled using AHP. In addition, an unbalanced scale of judgments is employed in pair-wise comparisons. Fuzzy AHP can deal with those problems since it combines fuzzy logic and AHP.

There are several fuzzy AHP solution methodologies proposed in the literature [3, 4, 19]. Among those methodologies, Chang's extent analysis [4] is the most popular methodology due to its ease of use.

Prior to the application of Chang's extent analysis, two sets are defined: an object set ($X = \{x_1, x_2, ..., x_n\}$) and a goal set ($U = \{u_1, u_2, ..., u_n\}$). The extent analysis is carried out for each object by considering each goal gi.. That is why there will be m number of extent analysis values for each object and extent analysis values will be represented with the following triangular fuzzy numbers:

$$M_{g_i}^1, M_{g_i}^2, ..., M_{g_i}^m, \quad i=1,2,...,n \tag{1}$$

Chang's extent analysis is performed in four steps:

Step 1: The value of fuzzy synthetic extent of object *i* can be determined using the following expression:

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \tag{2}$$

where fuzzy inverse is represented with -1 and fuzzy multiplication is represented with $\otimes$.

$\sum_{j=1}^{m} M_{g_i}^j$ is calculated by applying fuzzy addition operation to extent analysis values:

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{3}$$

and the value of $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^i \right]^{-1}$ is obtained using equation 4:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \tag{4}$$

and then equation 5 is employed in order to compute the inverse of the vector presented in equation 4:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^i \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right) \tag{5}$$

Step 2: The degree of possibility that $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is calculated using equation 6:

$$V(M_2 \geq M_1) = \sup \left[\min_{y \geq x} (\mu_{M_1}(x), \mu_{M_2}(y)) \right] \tag{6}$$

and it can be represented as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) \tag{7}$$

$$\begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \tag{8}$$

where the ordinate for the highest intersection point between μ_{M_1} and μ_{M_2} is represented with d (see Figure 1). $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ must be calculated in order to compare M1 and M2.

Step 3: For a convex fuzzy number, we can represent the degree of possibility to be greater than *k* convex fuzzy numbers $M_i (i = 1, 2, ..., k)$ as follows:

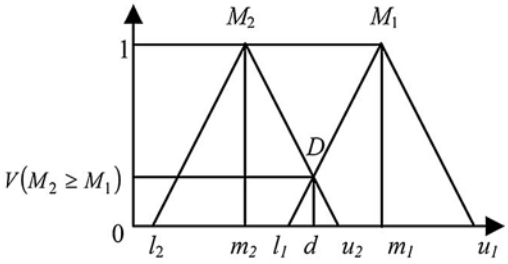

Fig. 1. Highest Intersection point of M1 and M2

$$\begin{aligned} &V(M \geq M_1, M_2, ..., M_k) = \\ &V\left[(M \geq M_1),(M \geq M_2),...,(M \geq M_k)\right] = \\ &\min V(M \geq M_i), \quad i=1,2,...,k, \text{For } k=1,2,...,n;\ k \neq i \end{aligned} \tag{9}$$

Assuming that $d'(A_i) = \min V(S_i \geq S_k)$, the weight vector can be defined as follows:

$$W' = (d'(A_1), d'(A_2), ..., d'(A_n))^T \tag{10}$$

Step 4: The normalized weight vectors are obtained via normalization:

$$W = (d(A_1), d(A_2), ..., d(A_n))^T \tag{11}$$

3. Taguchi Loss Functions

There are rigid specification limits in traditional quality control. In other words, a product can only be accepted if its characteristics are within pre-defined specification limits. The loss function concept proposed by Taguchi [18] is a popular alternative to traditional quality control. In this concept, there is no loss if the value of a performance measure is equal to the target value. If there is a deviation from the target value, a loss will occur. A quadratic function is employed in order to measure the loss [1].

Taguchi developed many loss functions. The most commonly used three loss functions are "target is the best", "lower is better" and "higher is better". Figures 2 through 4 present the graphs of these loss functions. The loss equations of these three functions are given in equations 12 through 14.

"Target is the best" loss function:

$$L_x = k(x-t)^2 \tag{12}$$

"Lower is better" loss function:

$$L_x = k(x)^2 \tag{13}$$

"Higher is better" loss function:

$$L_x = k/(x)^2 \tag{14}$$

where L_x is the loss value for a specific value of characteristic x, t is the target value and k is the loss coefficient.

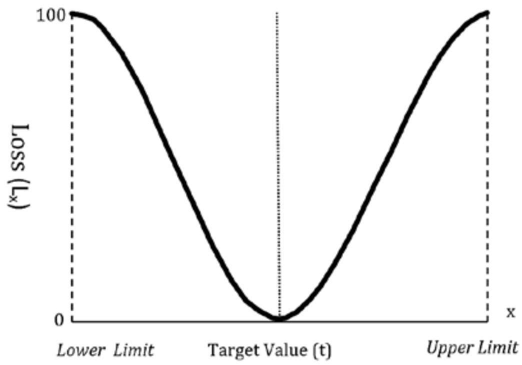

Fig. 2."Target is the best" loss function

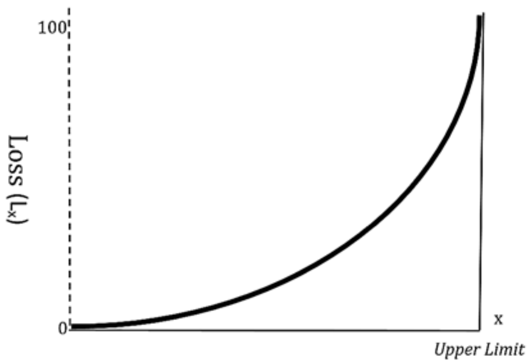

Fig. 3. "Lower is better" loss function

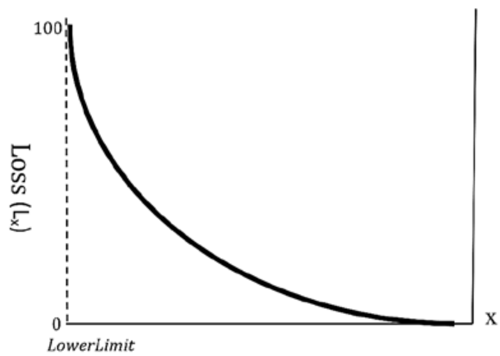

Fig. 4. "Higher is better" loss function

Taguchi loss functions have been used to solve various problems in different domains including supplier evaluation [14], marketing of real estate [7, 11] and evaluation of advanced manufacturing technologies [15].

4. Spare Part Criticality Evaluation Using Fuzzy AHP and Taguchi Loss Functions

In this study, we propose a spare parts criticality evaluation approach by integrating Fuzzy AHP and Taguchi loss functions. First, spare parts evaluation criteria are determined based on expert opinion and a literature review. Fuzzy AHP is employed for the calculation of criteria weights. Then, an appropriate loss function is determined for each criterion. Criteria values for each spare part are determined based on company records and the results obtained from a simulation model. Taguchi loss values are also calculated for each spare part. Finally, weighted Taguchi loss values are calculated by using the criteria

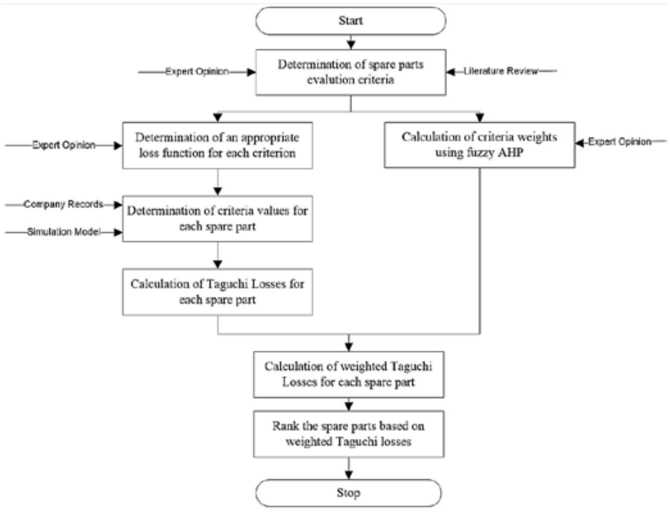

Fig. 5. Steps of the proposed approach

weights and Taguchi loss values of spare parts. Steps of the proposed approach are presented in Figure 5.

The proposed approach was applied to a spare parts criticality evaluation problem faced by a manufacturing company. The problem involves ten spare parts and the following subsections present the steps followed while solving this problem.

4.1. Determination of Evaluation Criteria

Spare part evaluation criteria were determined by reviewing the literature and interviewing the experts working for the company. The evaluation criteria with associated references from the literature can be seen in Table 1.

Following the determination of the evaluation criteria, the criteria values for the spare parts were determined by investigating the company records. Those values are presented in Table 2. In this table, WEIB, EXPO and LOGN represents Weibull, Exponential and Lognormal distributions, respectively. The numbers in parentheses are the parameters of those distributions. If the replacement of a spare part is required, the replacement quantity can be more than one. Table 3 presents the probabilities of replacement quantities for each spare parts based on the company records.

Table 1. Evaluation criteria with associated references

Criteria	References
Price (P)	Yang and Du [24]; Duran [6]; Stoll et al. [17]
Demand (D)	Yang and Du [24]; Duran [6]; Stoll et al. [17]
Repair Time (RT)	Yang and Du [24]; Zeng et al. [25]
Lead Time (LT)	Zeng et al. [25]; Stoll et al. [17]
Number of Potential Suppliers (NS)	Zeng et al. [25]

4.2. Determination of Criteria Weights

Fuzzy AHP was used for the determination of the weights for the spare part evaluation criteria. Table 4 presents the scale for linguistic weight conversion. Pair-wise comparison matrix is given in Table 5. The values in this matrix were determined by interviewing the experts working for the company. The linguistic preferences of Table 5 were converted into triangular fuzzy numbers and presented in Table 6.

Chang's extent analysis was implemented in four steps:

Step 1: Equations 2-5 were used to calculate the fuzzy synthetic extent (S_i) values for spare part evaluation criteria:

$$S_P = (6.3333, 8.0000, 10.0000) \otimes (1/36.4, 1/27.8, 1/21.5) = (0.1740, 0.2874, 0.4654)$$

$$S_D = (4.5000, 6.0000, 8.0000) \otimes (1/36.4, 1/27.8, 1/21.5) = (0.1236, 0.2156, 0.3723)$$

$$S_{RT} = (2.7524, 3.3333, 4.2333) \otimes (1/36.4, 1/27.8, 1/21.5) = (0.0756, 0.1198, 0.1970)$$

$$S_{LT} = (4.5000, 6.0000, 8.0000) \otimes (1/36.4, 1/27.8, 1/21.5) = (0.1236, 0.2156, 0.3723)$$

$$S_{NS} = (3.4000, 4.5000, 6.1667) \otimes (1/36.4, 1/27.8, 1/21.5) = (0.0934, 0.1617, 0.$$

Step 2: Equations 6-8 were used to calculate $V(M_2 \geq M_1)$ values for the criteria:

$$V(S_P \geq S_D) = 1.0000, V(S_P \geq S_{RT}) = 1.0000, V(S_P \geq S_{LT}) = 1.0000, V(S_P \geq S_{NS}) = 1.0000$$

$$V(S_D \geq S_P) = 0.7341, V(S_D \geq S_{RT}) = 1.0000, V(S_D \geq S_{LT}) = 1.0000, V(S_D \geq S_{NS}) = 1.0000$$

$$V(S_{RT} \geq S_P) = 0.1208, V(S_{RT} \geq S_D) = 0.4338, V(S_{RT} \geq S_{LT}) = 0.4338, V(S_{RT} \geq S_{NS}) = 0.7120$$

$$V(S_{LT} \geq S_P) = 0.7341, V(S_{LT} \geq S_D) = 1.0000, V(S_{LT} \geq S_{RT}) = 1, V(S_{LT} \geq S_{NS}) = 1.0000$$

$$V(S_{NS} \geq S_P) = 0.4733, V(S_{NS} \geq S_D) = 0.7520, V(S_{NS} \geq S_{LT}) = 0.7520, V(S_{NS} \geq S_{RT}) = 1.0000$$

Step 3: The weight vector was determined by using equations 9 and 10:

$$W' = (1.0000, 0.7341, 0.1208, 0.7341, 0.4733)$$

Table 2. Characteristics of the spare parts

Spare Part	Price ($)	Time Between Failures Distribution (days)	Repair Time Distribution (hours)	Probability of Replacement	Number of Potential Suppliers	Lead Time (days)
S01	74	2.5 + WEIB(2.97, 2.79)	0.14+LOGN(0.798, 0.559)	0.44	2	2
S02	145	8.5+WEIB(8.38, 1.87)	1.5 + WEIB(2.69, 1.99)	0.65	3	5
S03	322	10.5 + WEIB(7.86, 1.59)	0.5 + EXPO(5.5)	0.72	6	5
S04	147	0.5 + EXPO(21.9)	0.5 + LOGN(4.25, 3.44)	0.54	2	4
S05	54	18.5+WEIB(12.4,1.94)	4.5 + LOGN(2.44, 1.48)	0.75	3	6
S06	98	0.999 + WEIB(56.1, 0.987)	0.5 + WEIB(13.4, 1.13)	0.90	2	6
S07	53	11.5 + WEIB(8.38, 2.94)	2.5 + WEIB(2.63, 2.08)	0.80	1	4
S08	237	4 + WEIB(23.4, 0.676)	3.5 + EXPO(2.15)	0.75	8	8
S09	93	2.5 + WEIB(6.25, 1.04)	1.5 + WEIB(1.51, 2.77)	0.44	2	7
S10	174	1.5 + WEIB(6.93, 2.3)	0.5 + WEIB(3.44, 3.4)	0.64	2	8

Table 3. Probabilities for replacement quantities

Spare Part	Replacement Quantity			
	1	2	3	4
S01	0.64	0.36	-	-
S02	0.80	0.20	-	-
S03	1	-	-	-
S04	0.76	0.24	-	-
S05	0.45	0.28	0.15	0.12
S06	0.58	0.32	0.10	-
S07	0.40	0.24	0.21	0.15
S08	1	-	-	-
S09	0.62	0.17	0.15	0.06
S10	0.68	0.32	-	-

Table 4. Conversion scale for linguistic weights

Linguistic scale	Triangular fuzzy numbers	Triangular fuzzy reciprocal numbers
Equal (E)	(1,1,1)	(1,1,1)
Moderate (M)	(2/3,1,3/2)	(2/3,1,3/2)
Strong (S)	(3/2,2,5/2)	(2/5,1/2,2/3)
Very Strong (VS)	(5/2,3,7/2)	(2/7,1/3,2/5)
Absolutely Preferred (A)	(7/2,4,9/2)	(2/9,1/4,2/7)

Table 5. Pair-wise comparisons

	P	D	RT	LT	NS
P	E	M	VS	M	S
D	1/M	E	S	M	M
RT	1/VS	1/S	E	1/S	1/M
LT	1/M	1/M	S	E	M
NS	1/S	1/M	M	1/M	E

Table 6. Pair-wise comparisons converted into triangular fuzzy numbers

	P	D	RT	LT	NS
P	(1,1,1)	(2/3,1,3/2)	(5/2,3,7/2)	(2/3,1,3/2)	(3/2,2,5/2)
D	(2/3,1,3/2)	(1,1,1)	(3/2,2,5/2)	(2/3,1,3/2)	(2/3,1,3/2)
RT	(2/7,1/3,2/5)	(2/5,1/2,2/3)	(1,1,1)	(2/5,1/2,2/3)	(2/3,1,3/2)
LT	(2/3,1,3/2)	(2/3,1,3/2)	(3/2,2,5/2)	(1,1,1)	(2/3,1,3/2)
NS	(2/5,1/2,2/3)	(2/3,1,3/2)	(2/3,1,3/2)	(2/3,1,3/2)	(1,1,1)

Step 4: The values in weight vector were normalized and the following normalized weight vector was obtained:

$$W = (0.3266, 0.2397, 0.0394, 0.2397, 0.1546)^T$$

4.3. Calculation of Loss Values for Spare Parts

Target values, ranges and specification limits for each spare part evaluation criterion were determined by interviewing the experts working for the company. Table 7 presents those values. According to Table 7, the first four criteria were modeled using "Smaller is better" Taguchi loss function and the last criterion was modeled using "Higher is better" Taguchi loss function.

The criteria values for each spare part are presented in Table 8. The values for „Price", „Lead Time" and „Number of suppliers" are directly taken from Table 2. The values for „demand" and „repair time" were obtained by running a simulation model built in Arena 14.0 simulation software. Figure 6 presents the flow chart for the simulation model. The model was replicated 30 times with a replication length of one year. The demand and repair time values presented in Table 8 are the mean values from 30 replications.

Relative values for "lower is better" criteria (viz., Price, Demand, Repair Time and Lead Time) are calculated by considering the lowest value. For instance, the relative value of spare part S01 for "price" criterion is calculated as 39.6226 (100*(74-53)/53). Relative values for "higher is better" criterion (Number of Potential suppliers) are calculated by considering the highest value. For instance, the relative value of spare part S01 for "number of potential suppliers" criterion is calculated as 25 (100*2/8).

Taguchi losses of the spare parts are presented in Table 9. The calculation of Taguchi losses can be illustrated by considering "price" criterion. According to Table 7, the specification limit for this criterion is 20%. This means that the loss is zero for the spare part with the lowest price and the specification limit is up to 20% of the lowest price. The loss value will be 100% if the price of a spare part is equal to the specification limit. Since "price" is modeled using "smaller is better" Taguchi loss function, equation 13 can be used in order to determine the loss coefficient k as follows:

$$100 = k \cdot (0.2)^2 \Rightarrow k = 2500$$

The same equation was used in order to determine the loss coefficients for "demand", "repair time" and "lead time" as 1600, 2500 and 4444.4, respectively. Since "number of potential suppliers" criterion is modeled using "higher is better" Taguchi loss function, equation 14 was used while determining the loss coefficient of this criterion as follows:

$$100 = k / (0.8)^2 \Rightarrow k = 64$$

The relative values presented in Table 8 and the loss coefficients determined above are entered into appropriate Taguchi loss function equations to compute the Taguchi loss values presented in Table 9. For instance, the loss value of spare part S01 for "price" criterion can be determined using equation 13 as follows:

$$L = 2500 \cdot (39.6226 / 100)^2 \Rightarrow L = 392.4884$$

Table 7. Target values, ranges and limits for the spare part evaluation criteria

Criteria	Target Value	Range	Specification Limit
Price	Lowest	0%-20%	20% or higher
Demand	Lowest	0%-25%	25% or higher
Repair Time	Lowest	0%-20%	20% or higher
Lead Time	Lowest	0%-15%	15% or higher
Number of Potential Suppliers	Highest	80%-100%	80% or lower

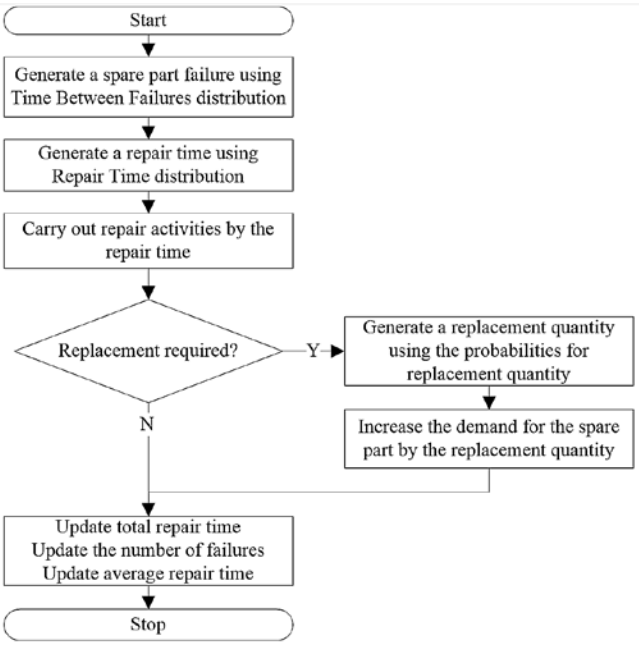

Fig. 6. Flow-chart of the simulation model

4.4. Criticality Evaluation Using Weighted Loss Values

The weighted Taguchi loss values of the spare parts were calculated using the weights proposed by fuzzy AHP and the loss values presented in Table 9. The following equation was employed while calculating the weighted loss values:

$$WL_j = \sum_{i=1}^{n} w_i \cdot x_{ij} \tag{15}$$

where WL_j is the total weighted Taguchi loss of spare part j, w_i is the weight of criterion i and x_{ij} is the Taguchi loss of spare part j for criterion i.

Table 10 presents the weighted and the normalized weighted loss values for the spare parts. Criticality ranking of spare parts is also provided in the last column of this table. Figure 7 presents the graphical depiction of normalized weighted loss values. According to Table 10 and Figure 7, spare part S03 with the highest weighted loss value is the most critical spare part. Spare parts S08, S10 and S06 have also high weighted loss values. These three spare parts can also be considered as critical spare parts. On the other hand, spare parts S01, S04, S07 and S02 have very low weighted loss values. These spare parts can be regarded as non-critical spare parts.

Table 8. Characteristic and relative values for the spare parts

Spare Part	Price		Demand		Repair Time		Lead Time		Number of Potential Suppliers	
	Value	Relative Value (%)	Value	Relative Value (%)	Value	Relative Value (%)	Value	Relative Value (%)	Value	Relative Value (%)
S01	74	39.6226	29.7	364.0625	0.95	0	2	0	2	25
S02	145	173.5849	12.9	101.5625	4.05	326.3158	5	150	3	37.5
S03	322	507.5472	10.9	70.3125	5.93	524.2105	5	150	6	75
S04	147	177.3585	7.8	21.875	4.99	425.2632	4	100	2	25
S05	54	1.8868	11.8	84.375	6.85	621.0526	6	200	3	37.5
S06	98	84.9057	7.5	17.1875	12.68	1234.737	6	200	2	25
S07	53	0	22.7	254.6875	4.85	410.5263	4	100	1	12.5
S08	237	347.1698	6.4	0	5.66	495.7895	8	300	8	100
S09	93	75.4717	22.9	257.8125	2.82	196.8421	7	250	2	25
S10	174	228.3019	30.7	379.6875	3.59	277.8947	8	300	2	25

Table 9. Taguchi losses of the spare parts

Spare Part	Price	Demand	Repair Time	Lead Time	Number of Potential Suppliers
S01	392.4884	21206.64	0	0	1024
S02	7532.93	1650.391	26620.5	10000	455.1111
S03	64401.03	791.0156	68699.17	10000	113.7778
S04	7864.009	76.5625	45212.19	4444.444	1024
S05	0.889996	1139.063	96426.59	17777.78	455.1111
S06	1802.243	47.26563	381143.8	17777.78	1024
S07	0	10378.52	42132.96	4444.444	4096
S08	30131.72	0	61451.8	40000	64
S09	1423.994	10634.77	9686.704	27777.78	1024
S10	13030.44	23066.02	19306.37	40000	1024

Table 10. Weighted loss values and criticality ranking of the spare parts

Spare Part	Weighted Loss	Normalized Weighted Loss	Criticality Rank
S01	5369.729	0.0412	10
S02	6372.061	0.0489	7
S03	26344.32	0.2021	1
S04	5591.741	0.0429	9
S05	8404.225	0.0645	6
S06	20036.65	0.1537	4
S07	5846.344	0.0449	8
S08	21860.11	0.1677	2
S09	10212.53	0.0784	5
S10	20291.65	0.1557	3

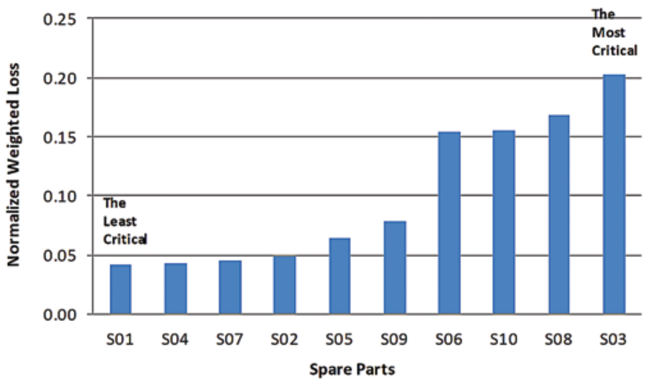

Fig. 7. Graphical depiction of normalized weighted loss values

5. Conclusions

Maintenance is a critical function for the availability of manufacturing systems. An important issue in maintenance management is the criticality evaluation of maintenance spare parts. In this paper, a novel spare part criticality evaluation approach integrating fuzzy AHP, Taguchi loss functions and simulation modeling was proposed. The applicability of the proposed approach was tested by applying it to a spare part criticality evaluation problem faced by a manufacturing company.

In this study, a criticality ranking of several spare parts was obtained. In future studies, a criticality classification approach can be developed in order to classify a high number of spare parts into several criticality classes. Multi criteria sorting methodologies such as FlowSort and Promsort can be used for the development of this multi-criteria spare part criticality classification approach.

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