
FUZZY COPRAS METHOD FOR PERFORMANCE MEASUREMENT IN TOTAL PRODUCTIVE MAINTENANCE: A COMPARATIVE ANALYSIS

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Abstract. Modern manufacturing firms should be supported by effective maintenance to become successful in their operations. One of the approaches for improving the performance of maintenance activities is to implement a total productive maintenance (TPM) strategy. Overall equipment effectiveness (OEE) is the key measure of TPM. According to the results of the literature review, the performance elements measured by the OEE tool are not sufficient to describe the effectiveness of TPM implementation. Hence, we aim at developing and evaluating new performance measures oriented towards the quantification of TPM implementation effectiveness under fuzzy environment. For the evaluation of each performance measure, at first, the nominal group technique has been used. Then to determine whether these performance measures are statistically significant, conjoint analysis based experimental design has been applied. In the second step, COmplex PRoportional ASsessment of alternatives with Grey relations (COPRAS-G) and the fuzzy COPRAS method has been developed to evaluate these performance measures in TPM. Proposed fuzzy COPRAS method gives the reassuring results of ranking newly developed performance measures in TPM.

Keywords: COPRAS-G, performance measurement, new performance measures, total productive maintenance, conjoint analysis, fuzzy COPRAS.

JEL Classification: C6.

Introduction

TPM is a new concept for maintenance that better optimizes the equipment effectiveness, minimizes breakdowns and encourages operators to autonomous maintenance for day-to-day activities involving total workforce (Andersson 2015). TPM aims to improve equipment effectiveness during the lifetime of the equipment.

Nakajima (1988) initiated TPM concept in the 1980s, which brought measurable metric named OEE for measuring productivity of individual equipment in a factory. It explains and measures losses of significant sides of manufacturing specifically availability, performance, and quality rate.

OEE approach has been starting to be widely used as an important quantitative metric for measurement of productivity in manufacturing operations (Huang *et al.* 2003). The use of OEE varies from one industry to another, and it is tailored to fit to comply with industries' specific requirements.

According to the literature review on performance evaluation in TPM, OEE metric has widely been used as an important performance measure, but it is not adequate to define the effectiveness of TPM. Jeon *et al.* (2011) also suggested measuring the performance of TPM in terms of efficiency. This has caused to a requirement for a thoroughly described performance measurement system for TPM which is capable of considering different significant elements of productivity in a manufacturing process. Therefore, in this study new performance measures having an impact on TPM are proposed and proposed performance measures are evaluated under fuzzy environment.

The innovative side of this study is to develop new performance measures in TPM and also to evaluate these performance measures developed fuzzy COPRAS method in which no defuzzification step used for avoiding information loss. In the proposed fuzzy COPRAS method, all calculations are performed in accordance with fuzzy arithmetic.

In this study, it is aimed to develop new performance measures impact on TPM and using a multi criteria decision making method based on the concepts of COPRAS under fuzzy environment. The rest of the paper is organized as follows. Section 1 explains the problem and literature review. Section 2 introduces the literature review and the fundamentals of COPRAS-G method. In Sections 3 and 4, an application of COPRAS-G and proposed fuzzy COPRAS method for evaluation of developed new performance measures in TPM are presented. In the last section, results and conclusion are given.

1. Problem of the definition and literature review on TPM

Many investigations have been underlined from a review of literature and case studies for implementing TPM successfully in manufacturing organizations. For example, Davis (1996) brings a crucial adding to the perceiving of implementation issues connected to the TPM program. Attri *et al.* (2014) presents a graph theoretic approach to evaluate the innumerable barriers in real life cases during TPM implementation. Chlebus *et al.* (2015) also focus the important issues when implementing TPM approach. Rodrigues and Hatakeyama (2006) claimed that the achievement of TPM implementation is closely related to the management of employees. The important thing is to find out key metrics for the assessment of performance indicators of the program. Piehnicki *et al.* (2015) investigate priority of critical success factors for implementing TPM properly.

Generally, TPM can be defined with regards to quantitative metric that is OEE which at the end can be taken into account a combination of the operation maintenance, equipment management and available resources (Hansen 2002). It determines and measures

losses of important aspects of manufacturing specifically availability, performance, and quality rate. Calculated OEE for one manufacturing line can be used for comparison of the line performance across the factory, therefore highlights any weak line performance and indicates where to focus TPM resources. This is a widely accepted metric as a quantitative tool for measurement of productivity in manufacturing operations (Dal *et al.* 2000). Even the OEE is a popular quantitative tool and has been widely used in the literature; its usage is limited for the productivity measurement of single equipment (Huang *et al.* 2003).

Scott and Pisa (1998) remarked that although the benefits in OEE are valuable, they are not sufficient since no machine is separated from others. Their remark is that manufacturing processes involves complex interacts among process tools, materials, machines, people, departments, companies, and processes. Therefore it is important to focus on performance of the whole plant instead of performance of single equipment. Oechsner *et al.* 2003 also stated that the main goal is to obtain efficient integrated system not perfect single equipment.

A survey for literature of TPM using the electronic databases such as Emerald, Science Direct, Springer, ASME, and etc. gives 191 published papers (only titles). The results of this research are given in Table 1. According to Table 1, out of the total of 149 papers, 87 papers (near about 58.39 per cent of total articles) are of TPM implementation and case study types, 33 papers (near about 22.15 per cent of total articles) are of empirical research on TPM, 20 papers (near about 13.42 per cent of total articles) are of model and simulation type studies and 9 papers (near about 6.04 per cent of total articles) are of literature type study.

Table 1. Classification of research papers on TPM

Years	Empirical research	Literature review	Implementation and case study	Modelling and simulation
1994 and below	9		15	2
1995–2000	9	1	14	4
2001–2002	2		6	1
2003–2004	3		5	1
2005			3	1
2006	1	1	6	2
2007			1	
2008	1	2	6	1
2009	2		2	
2010	1		6	1
2011	2	1	7	3
2012	1	1	11	1
2013	1	1	1	1
2014	1	2	2	1
2015			2	1

Based on the results of literature review, very little progress has been made related to the analysis of TPM effectiveness. It is concluded that analysing the TPM performance needs more future systematized applications focused at reinforcing theoretical frames and raising importance of the implementation of more practical approaches. Therefore, in this study new performance measures having an impact on TPM are developed. The proposed performance measures are evaluated under fuzzy environment. According to literature review and the best knowledge of the authors, this is the first study that employs proposed fuzzy COPRAS method to evaluate newly developed performance measures in TPM.

2. Methodology

TPM implementation and practicing is a cultural change and an organization wide activity. For this reason, measuring the effectiveness of TPM is ordered an organization wide program based on some factors having impact on TPM. The overall aim is to develop a standard methodology for measuring various improvements, resulting from TPM implementation. Proposed TPM effectiveness system can be divided into three phases: (i) the design of the new performance measures, (ii) the evaluation of the new performance measures, and (iii) the implementation and the use of the new performance measures to carry out analysis/reviewing.

The present findings show that there should be greater use of TPM than literature suggests as a performance improvement process and those improvements must be measured both subjectively and quantitatively. So there are a large number of conflicting tangible and intangible factors that should be considered in development of new performance measures. In this study, after developing new performance measures, it is aimed to handle the multi criteria decision making (MCDM) problems under uncertain information to evaluate the new performance measures.

Literature review indicates that recently developed MCDM methods such as COPRAS, ARAS, SWARA, MOORA, WASPAS and etc., and their modifications have been applied to solve different kinds of problems using fuzzy and grey number theory (Zavadskas *et al.* 2014). Liu and Zhang (2013) also proposed a novel method integrating entropy weight and an improved ELECTRE III method to select supplier in supply chains. Liu and Wu (2012) suggested a new model based on multi-granularity linguistic variables and VIKOR method for assessment of competency of human resources managers. Zhang *et al.* (2013) developed a new decision making analysis method based on grey relational projection. Liu and Teng (2014, 2015) presented extended TODIM method with the form of 2-dimension uncertain linguistic variables and the intuitionistic uncertain linguistic variables. In these methods, we apply COPRAS-G and improved fuzzy COPRAS methods for assessment of new performance measures in TPM. It possesses some advantages. For instance, it uses not certain, unclear information about the alternatives' criterion values stated in terms of intervals; it is more appropriate in real life applications; its calculations are not complex; it needs smaller samples not involved a typical distribution; and it is an effective method in taking care of discrete data. The overall structure of the study is shown in Figure 1.

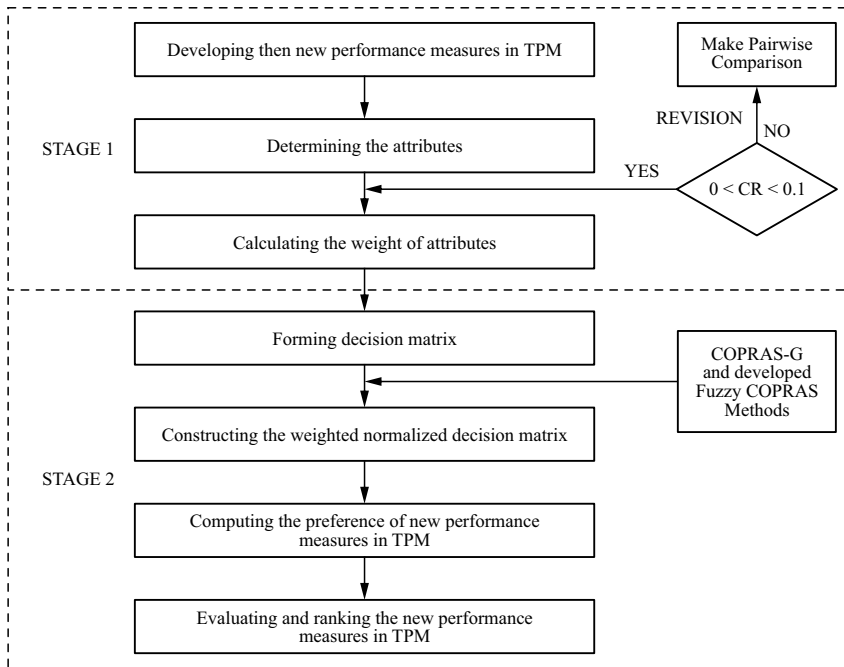


Fig. 1. The overall structure of the study

2.1. Literature review on COPRAS-G method

Multiple attributes decision aid provides several powerful and effective tools for confronting sorting problems (Kahraman *et al.* 2015; Mardani *et al.* 2015). The idea of COPRAS-G method is based on the real conditions of decision making and applications of the Grey systems theory (Zavadskas *et al.* 2014).

A literature review for COPRAS-G method using “Scopus” gives 149 published papers (all fields) among these, 35 papers mention COPRAS-G method in “article title, abstract, keywords”. The papers mentioned COPRAS-G method in “article title, abstract, keywords” are surveyed by analysing the publishing frequencies with respect to years; the document type; the research areas; the most cited papers on COPRAS-G method, respectively shown as in Figures 2–4 and Table 2.

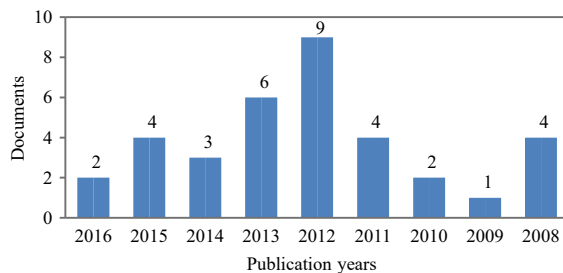


Fig. 2. Published papers using COPRAS-G method over years

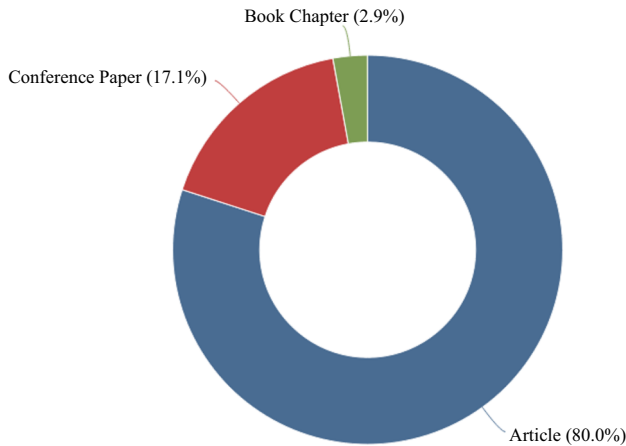


Fig. 3. The classification of published papers using COPRAS-G according to document types

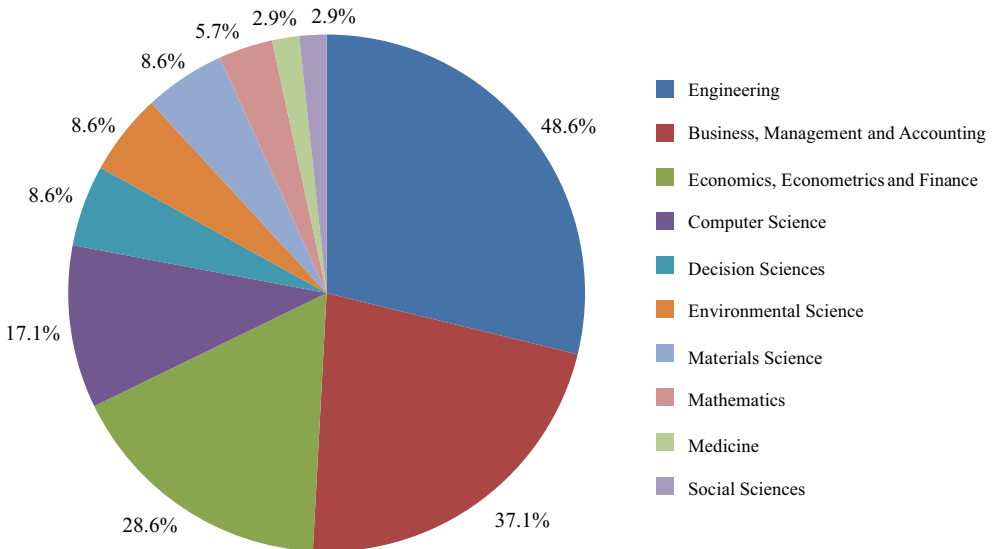


Fig. 4. Research areas of the examined papers using COPRAS-G

According to Figure 3, 28 papers using COPRAS-G are published as an article, 6 papers as a conference paper and 1 paper as a book chapter. The areas of *Engineering*, *Business Management and Accounting*, *Economics, Econometrics and Finance* are the most studied research fields on COPRAS-G shown in Figure 4.

In recent years, the COPRAS-G method and its hybrid modifications have been applied to the solution of complicated MCDM problems using fuzzy sets theory. Ecer (2015) proposed a hybrid model based on fuzzy AHP and COPRAS-G methods to evaluate the performance of internet banking branches. Ghorabae *et al.* (2014) proposed multiple

Table 2. Most cited articles on COPRAS-G according to application problem

References	Publication journal	Cited times	Application problem	Other MCDM technics and tools integrated with COPRAS-G
Zavadskas <i>et al.</i> (2008a)	Journal of Civil Engineering and Management	154	Selection of the effective dwelling house walls	–
Zavadskas <i>et al.</i> (2010)	Journal of Civil Engineering and Management	137	Risk assessment of construction projects	TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)
Zavadskas <i>et al.</i> (2009)	Informatica	106	General contractor choice	Fuzzy set theory
Zavadskas <i>et al.</i> (2008b)	Technological and Economic Development of Economy	85	Selection of project managers	–
Chatterjee and Chakraborty (2012)	Materials and Design	56	Material selection	–
Maity <i>et al.</i> (2012)	Materials and Design	31	Cutting tool material selection	PROMETHEE II (EXPPROM2), ORESTE (Organization, Rangement Et Synthèse De Donnes Relationnelles), OCRA (operational competitiveness rating analysis) AHP (Analytic Hierarchical Process)
Hashemkhani Zolfani <i>et al.</i> (2012)	Technological and Economic Development of Economy	26	Company supplier selection	AHP (Analytic Hierarchical Process)
Bitarafan <i>et al.</i> (2012)	Archives of Civil and Mechanical Engineering	25	Evaluating the construction methods of cold-formed steel structures in reconstructing the areas damaged in natural crises	AHP
Nguyen <i>et al.</i> (2014)	Expert Systems with Applications	21	Machine tool selection	Fuzzy ANP (Analytic Network Process), TOPSIS-G, SAW-G (Simple Additive Weighting), GRA (Grey relational analysis)
Aghdaie <i>et al.</i> (2013)	Engineering Economics	24	Machine tool selection	SWARA (Step-wise weight assessment ratio analysis)
Rezaeiya <i>et al.</i> (2012)	International Journal of Strategic Property Management	18	Greenhouse locating problem	ANP
Tamošaitiene and Gaudutis (2013)	Journal of Civil Engineering and Management	15	Assessment of high-rise building	–
Tavana <i>et al.</i> (2013)	Expert Systems with Applications	14	Social media platform selection	Fuzzy ANP
Mazumdar <i>et al.</i> (2010)	International Journal of Productivity and Quality Management	12	Evaluation and appraisal of teachers' performance	–

criteria group decision-making for supplier selection based on COPRAS method with interval type-2 fuzzy sets. Liou *et al.* (2016) presented a new hybrid COPRAS-G Multi attribute decision making (MADM) model for selecting suppliers in green supply chain management. Zavadskas and Antucheviciene (2007) were firstly suggested multiple-criteria complex proportional evaluation under fuzzy environment to assessment the rural building's regeneration alternatives. Yazdani *et al.* (2011) developed a risk based methodology for critical infrastructures using fuzzy COPRAS (COPRAS-F) extended of COPRAS method. Antucheviciene *et al.* (2012) applied TOPSIS-F, COPRAS-F and VIKOR-F to rank the redevelopment decisions of derelict buildings under fuzzy environment. Chatterjee and Bose (2012), Nguyen *et al.* (2015) and also Akhavan *et al.* (2015) studied different MCDM problems using COPRAS-F method. COPRAS method has also been handled by new extensions of fuzzy sets such as intuitionistic or hesitant fuzzy sets (Razavi Hajiagha *et al.* 2013; Bausys *et al.* 2015; Gitinavard *et al.* 2016).

2.2. COPRAS-G methodology

The COPRAS-G method employs a stepwise ordering and assessing procedure of the alternatives with respect to importance and utility degree based on the Grey systems theory. Zavadskas *et al.* (2008a, 2009) represented the basic notions of the COPRAS-G method include the following steps:

1. Selecting the set of the most important attributes, describing the alternatives.
2. Constructing the decision-making matrix $\otimes X$:

$$\otimes X = \begin{bmatrix} x_{11} & \dots & \otimes x_{1m} \\ \dots & \ddots & \dots \\ \otimes x_{n1} & \dots & \otimes x_{nm} \end{bmatrix}; \tag{1}$$

$$= \begin{bmatrix} [w_{11}; b_{11}] & \dots & [w_{1m}; b_{1m}] \\ \dots & \ddots & \dots \\ [w_{n1}; b_{n1}] & \dots & [w_{nm}; b_{nm}] \end{bmatrix}, j = \overline{1, n}; i = \overline{1, m}, \tag{2}$$

where: $\otimes x_{ji}$ is determined by w_{ji} (the smallest value, the lower limit) and b_{ji} (the biggest value, the upper limit).

3. Determining weights of the attributes q_i .
4. Normalizing the decision-making matrix $\otimes X$:

$$\begin{aligned} \overline{w}_{j1} &= \frac{w_{ji}}{\frac{1}{2} \left(\sum_{j=1}^n w_{ji} + \sum_{j=1}^n b_{ji} \right)} = \frac{2w_{ji}}{\left(\sum_{j=1}^n w_{ji} + \sum_{j=1}^n b_{ji} \right)}; \\ \overline{b}_{j1} &= \frac{b_{ji}}{\frac{1}{2} \left(\sum_{j=1}^n w_{ji} + \sum_{j=1}^n b_{ji} \right)} = \frac{2b_{ji}}{\left(\sum_{j=1}^n w_{ji} + \sum_{j=1}^n b_{ji} \right)}, \quad i = \overline{1, n} \text{ and } j = \overline{1, m}. \end{aligned} \tag{3}$$

In Eq. (3), w_{ji} is the lower value of the i th attribute in the alternative j of the solution; b_{ji} is the upper value of the attribute i in the alternative j of the solution; m is the number

of attributes; n is the number of the alternatives compared. Then, the decision-making matrix is normalized by Eq. (4):

$$\otimes \hat{X} = \begin{bmatrix} \overline{\otimes x_{11}} & \dots & \overline{\otimes x_{1m}} \\ \dots & \ddots & \dots \\ \overline{\otimes x_{n1}} & \dots & \overline{\otimes x_{nm}} \end{bmatrix} = \begin{bmatrix} \overline{[w_{11}; b_{11}]} & \dots & \overline{[w_{1m}; b_{1m}]} \\ \dots & \ddots & \dots \\ \overline{[w_{n1}; b_{n1}]} & \dots & \overline{[w_{nm}; b_{nm}]} \end{bmatrix}, j = \overline{1, n}; i = \overline{1, m}. \quad (4)$$

5. Calculating the weighted normalized decision-making matrix $\otimes \hat{X}$. The weighted normalized values $\otimes \hat{x}_{ji}$ are calculated as follows:

$$\otimes \hat{x}_{j1} = \otimes \hat{x}_{j1} \cdot q_i; \hat{w}_{j1} = \bar{w}_{j1} \cdot q_i; \hat{b}_{j1} = \bar{b}_{j1} \cdot q_i. \quad (5)$$

In Eq. (5), q_i is the weight of the i th attribute. Then, the weighted normalized decision-making matrix is shown as follows:

$$\otimes \hat{X} = \begin{bmatrix} \otimes \hat{x}_{11} & \dots & \otimes \hat{x}_{1m} \\ \dots & \ddots & \dots \\ \otimes \hat{x}_{n1} & \dots & \otimes \hat{x}_{nm} \end{bmatrix} = \begin{bmatrix} \overline{[\hat{w}_{11}; \hat{b}_{11}]} & \dots & \overline{[\hat{w}_{1m}; \hat{b}_{1m}]} \\ \dots & \ddots & \dots \\ \overline{[\hat{w}_{1n}; \hat{b}_{1n}]} & \dots & \overline{[\hat{w}_{nm}; \hat{b}_{nm}]} \end{bmatrix}. \quad (6)$$

6. Calculating the sums P_j of the attribute values, whose larger values are more preferable:

$$P_j = \frac{1}{2} \sum_{i=1}^k (\hat{w}_{j1} + \hat{b}_{j1}). \quad (7)$$

7. Calculating the sums R_j of attribute values, whose smaller values are more preferable:

$$R_j = \frac{1}{2} \sum_{i=k+1}^m (\hat{w}_{j1} + \hat{b}_{j1}), i = \overline{k, m}. \quad (8)$$

8. Determining the minimal value of R_j :

$$R_{\min} = \min_i R_j, j = \overline{j, n}. \quad (9)$$

9. Calculating the relative weight of each alternative Q_j :

$$Q_j = P_j + \frac{\sum_{j=1}^n R_j}{R_j \sum_{j=1}^n \frac{1}{R_j}}. \quad (10)$$

10. Determining the optimality criterion K :

$$K = \max_j Q_j, j = \overline{1, n}. \quad (11)$$

11. Determining the priority of the project.

12. Calculating the utility degree of each alternative using Q_j and Q_{\max} which are the weight of projects obtained from Eq. (10):

$$N_j = \frac{Q_j}{Q_{\max}} 100\%. \quad (12)$$

3. COPRAS-G method for the evaluation of new performance measures in TPM

In this study, an outline for defining different types of performance measures impact on for TPM is proposed, as shown in Table 3. This classification helps the decision-maker to measure different factors impact on TPM so that attention should be provided to the appropriate factors. It also contributes a systematize method of quantifying asset effectiveness.

In this study, firstly it is illustrated that a framework for identifying different types of performance measures' impact on TPM and then these possible performance measures were analysed by decision makers. These decision makers work at operational, tactical and strategical levels in a company operating in the automotive industry. They determined the ranking of performance measures impact on TPM using the *nominal group technique* and then the twelve performance measures having scored higher than 15 were

Table 3. Factors affecting TPM (Braglia et al. 2009, Muchiri Pintelon 2008)

Category	Factors
Operational related	Planned downtime
	– Number of preventive maintenance
	– Preventive maintenance time
	Unplanned down time
	– Number of unplanned maintenance (equipment failures)
	– Mean time between failure (MTBF)
	– Mean time to repair (MTTR) (failure frequency)
	– Set up (changeovers), adjustments
	– Routine wear parts
	– Minor stoppages & idling
	– Reduced speed
	– Quality losses
– Reduced yield	
Business related	– Stock control
	– Spare parts inventories
	– Internal logistic problems (storage, shipping)
	– Organization problems & labour unrest
	– Environmental, Health & safety problems
– Capital project	
External related	Logistic problems
	– Supplier failure
	– Delivery time
	– Utility shortage (gas, electricity or waters)
	Environmental regulation
	– Production quotas
Natural causes	
– Weather conditions	
Others	– Human factor
	– Availability of maintenance personnel

selected. To determine whether these twelve performance measures are statistically significant, *conjoint analysis* has been performed that is a MCDM technique based on the experimental design. Then if we had used the full factorial design for conjoint analysis there would be 212 combinations because each performance measure has two levels. We should reduce the number of designs. For this reason, in this study *Taguchi design methodology* was used to reduce the number of designs. Then the conjoint analysis was performed by using Taguchi OA 16 table.

Part-worth was estimated based on the value placed on each level of the individual factor. The ANOVA results of conjoint analysis are displayed in Table 4:

Table 4. ANOVA results of conjoint analysis

Model	Sum of squares	df	Mean square	F	Sig.
Regression	333.250	12	27.771	12.343	.031
Residual	6.750	3	2.250		
Total	340.000	15			

According to Table 4, the value of test statistic F is found 12.343. Also significance level α (Sig.) is found to be 0.031, it is concluded that the proposed multiple regression model for the twelve performance measures impact on TPM are statistically significant. Finally the relative weights of these performance measures were calculated. Regarding to calculation, the performance measures that are *number of unplanned maintenance* and *environmental and health & safety problems* have the highest relative weights with the values 16.19% and 15.24%, respectively. Also the performance measures that are *number of preventive maintenance* and *preventive maintenance time* have the relative weights with the value 0. *That means these performance measures don't have the statistically significant impacts on TPM. Therefore these two performance measures are ignored after the COPRAS-G method is performed. In this study, the remaining ten performance measures are evaluated by COPRAS-G method under some attributes.*

The set of attributes and initial values of attributes are determined on the basis of expert, normative and calculation methods. According to the literature investigation and expert's opinions, the committee finally adopted 6 criteria. The selected attributes for TPM performance measures assessment are as follows: x_1 -specific (score) is clear and concentrated to keep away misunderstanding and it should contain measure suppositions and descriptions and be simply explained; x_2 -measurable (score) can be quantified and resembled to other data; x_3 -attainable (score) is achievable, rational, and reliable under the conditions expected; x_4 -realistic (score) conforms to the organization's restrictions and is profitable; x_5 -timely (score) is available within the time frame given; x_6 -cost of measure (score) (Parida *et al.* 2005). The first five attributes are benefit attributes, while the last attribute is cost one. In order to establish the attribute weights pair wise comparison method has been carried out. The consistency index of pairwise comparisons of attributes is calculated and then it is found 0.0106. It is less than 0.1, so the preferences are deemed to be consistent.

Table 5. Initial decision-making matrix with values of the attributes describing the compared alternatives in intervals

Attributes	Specific	Measurable	Attainable
Optimization direction	MAX	MAX	MAX
Attribute weight- q_i	0.0352	0.2329	0.3079
Performance measures	$\otimes x_1$	$\otimes x_2$	$\otimes x_3$
	$w_1 b_1$	$w_2 b_2$	$w_3 b_3$
Environmental, health & safety problems	50 75	75 85	70 80
Organization problems & labour unrest	55 80	52 56	62 76
Human factor	60 78	75 85	70 80
Availability of maintenance personnel	70 93	54 62	55 72
Quality losses	84 89	80 90	75 80
Reduced speed	84 89	75 85	70 80
MTBF	85 95	78 88	60 70
MTTR	85 95	78 88	70 80
Number of unplanned maintenance	80 95	80 90	80 85
Reduced yield	84 89	80 90	85 90
Attributes	Realistic	Timely	Cost of measure
Optimization direction	MAX	MAX	MIN
Attribute weight- q_i	0.2540	0.0506	0.1193
Performance measures	$\otimes x_4$	$\otimes x_5$	$\otimes x_6$
	$w_4 b_4$	$w_5 b_5$	$w_6 b_6$
Environmental, health & safety problems	75 80	65 85	90 80
Organization problems & labour unrest	70 75	57 81	56 52
Human factor	70 80	70 78	58 55
Availability of maintenance personnel	80 90	59 93	62 54
Quality losses	75 85	63 89	90 80
Reduced speed	85 95	80 85	85 80
MTBF	70 75	80 85	70 60
MTTR	80 90	80 88	55 50
Number of unplanned maintenance	80 90	85 90	70 60
Reduced yield	75 85	85 90	90 80

As long as the decision procedure, the decision maker team was demanded to fulfil the decision matrix by making the comparison of alternatives regarding with each of the attributes one by one. The decision matrix created on expert knowledge is formed in order to assess the new performance measures in TPM. Initial decision matrix with values of the attributes defining the compared alternatives in intervals and also the weights of attributes are given in Table 5. According to the data in Table 5, the normalized matrix is obtained by using Eq. (4). In order to obtain the weighted normalized matrix, Eq. (6) is used. For each alternative, P_j , R_j , Q_j and degree of efficiency (N_j) values are calculated according to Eqs. (8), (9), (11) and (12). Rank of alternatives is obtained according to the N_j values of alternatives and presented with S_j .

According to the ranking of the performance measures with COPRAS-G shown in Table 6, the best performance measure is selected as *Number of Unplanned Maintenance (Equipment Failures)*. If the indexes are calculated for the pessimistic (w_i) and optimistic values (b_i) in Table 6, the results are obtained as in Table 7. As it can be seen in Table 7, ranking of performance measures is changed according to the pessimistic approach, but the ranking of performance measures according to optimistic approach and interval values is the same.

Table 6. Solution results

Performance measures	Alternative's weight			Alternative's degree of efficiency	Rank
	P_j	R_j	Q_j	N_j	S_j
Environmental, health & safety problems	0.0853	0.0147	0.0946	87.2397	8
Organization problems & labour unrest	0.0753	0.0094	0.0899	82.9506	10
Human factor	0.0868	0.0098	0.1008	92.9651	6
Availability of maintenance personnel	0.0792	0.0100	0.0928	85.6426	9
Quality losses	0.0918	0.0147	0.1011	93.2615	5
Reduced speed	0.0928	0.0143	0.1024	94.4744	4
MTBF	0.0842	0.0113	0.0964	88.8848	7
MTTR	0.0924	0.0091	0.1075	99.1354	2
Number of unplanned maintenance	0.0962	0.0113	0.1084	100.0000	1
Reduced yield	0.0967	0.0147	0.1060	97.7755	3

Table 7. Solution results for pessimistic, optimistic and interval values of initial decision matrix

Performance measures	Alternatives degree of efficiency N_j			Rank S_j		
	Pess.	Opt.	Int.	Pess.	Opt.	Int.
Environmental, health & safety problems	76.0482	81.0706	87.2397	10	8	8
Organization problems & labour unrest	88.3336	91.9360	82.9506	4	10	10
Human factor	92.3609	91.2876	92.9651	3	6	6
Availability of maintenance personnel	85.4656	95.9997	85.6426	6	9	9
Quality losses	77.6093	83.4960	93.2615	9	5	5
Reduced speed	84.3866	84.1348	94.4744	8	4	4
MTBF	86.2096	87.7309	88.8848	5	7	7
MTTR	100.0000	100.0000	99.1354	1	2	2
Number of unplanned maintenance	93.0913	94.4623	100.0000	2	1	1
Reduced yield	85.0679	85.5509	97.7755	7	3	3

4. Proposed fuzzy COPRAS method for the evaluation of new performance measures in TPM

In this study, fuzzy COPRAS method is developed in eight steps for evaluation of new performance measures in TPM. The aim of this study is to assess performance measures in TPM considering multiple and conflicting criteria under incomplete and vague information using the fuzzy set theory.

In the Step 1, we construct the fuzzy decision matrix as shown in Table 8:

Table 8. Fuzzy decision matrix

Performance measures	$\otimes x_1$			$\otimes x_2$			$\otimes x_3$		
	a_1	b_1	c_1	a_2	b_2	c_2	a_3	b_3	c_3
Environmental, health & safety problems	50	62.5	75	75	80	85	70	75	80
Organization problems & labour unrest	55	67.5	80	52	54	56	62	69	76
Human factor	60	69	78	75	80	85	70	75	80
Availability of maintenance personnel	70	81.5	93	54	58	62	55	63.5	72
Quality losses	84	86.5	89	80	85	90	75	77.5	80
Reduced speed	84	86.5	89	75	80	85	70	75	80
MTBF	85	90	95	78	83	88	60	65	70
MTTR	85	90	95	78	83	88	70	75	80
Number of unplanned maintenance	80	87.5	95	80	85	90	80	82.5	85
Reduced yield	84	86.5	89	80	85	90	85	87.5	90
Performance measures	$\otimes x_4$			$\otimes x_5$			$\otimes x_6$		
	a_4	b_4	c_4	a_5	b_5	c_5	a_6	b_6	c_6
Environmental, health & safety problems	75	77.5	80	65	70	85	80	85	90
Organization problems & labour unrest	70	72.5	75	57	69	81	52	54	56
Human factor	70	75	80	70	74	78	55	56.5	58
Availability of maintenance personnel	80	85	90	59	76	93	54	58	62
Quality losses	75	80	85	63	76	89	80	85	90
Reduced speed	85	90	95	80	82.5	85	80	82.5	85
MTBF	70	72.5	75	80	82.5	85	60	65	70
MTTR	80	85	90	80	84	88	50	52.5	55
Number of unplanned maintenance	80	85	90	85	87.5	90	60	65	70
Reduced yield	75	80	85	85	87.5	90	80	85	90

In step 2, the fuzzy decision matrix is normalized. The linear scale transformation is carried out to change the various criteria scales into a comparable scale. The normalization method is to preserve the property that the ranges of normalized triangular fuzzy numbers belong to [0; 1].

In step 3, we calculate the fuzzy weighted normalized decision matrix.

In step 4, we calculate the sums of the fuzzy \tilde{P}_j criterion values whose larger values are more preferable.

In step 5, we calculate the sums of the fuzzy \tilde{R}_j criterion values whose smaller values are more preferable.

In step 6, we calculate the relative significance of each alternative, \tilde{Q}_j . The fuzzy \tilde{P}_j , \tilde{R}_j , \tilde{Q}_j and \tilde{N}_j values are calculated by the formulas given above as Eqs. (7), (8), (10) and (12), respectively. When these values are calculated, all fuzzy judgments are not converted to real numbers and all calculations are performed in accordance with the fuzzy arithmetic. The values of fuzzy \tilde{P}_j criterion, fuzzy \tilde{R}_j criterion, fuzzy \tilde{Q}_j criterion and fuzzy \tilde{N}_j criterion are given in Table 9. The membership functions of fuzzy \tilde{Q}_j criterion are shown in Figure 5.

Table 9. Fuzzy \tilde{P}_j , \tilde{R}_j , \tilde{Q}_j and \tilde{N}_j values

Performance Measures	\tilde{P}_j			\tilde{R}_j			\tilde{Q}_j			\tilde{N}_j		
Environmental, health & safety problems	0.427	0.470	0.516	0.033	0.035	0.037	0.474	0.526	0.582	74.230	86.730	101.140
Organization problems & labour unrest	0.384	0.429	0.473	0.053	0.055	0.057	0.415	0.464	0.514	64.920	76.530	89.370
Human factor	0.441	0.480	0.520	0.051	0.053	0.054	0.473	0.517	0.562	74.000	85.280	97.720
Availability of maintenance personnel	0.417	0.469	0.521	0.048	0.051	0.055	0.448	0.507	0.567	70.160	83.610	98.540
Quality losses	0.505	0.530	0.556	0.033	0.035	0.037	0.552	0.586	0.622	86.350	96.660	108.130
Reduced speed	0.508	0.535	0.562	0.035	0.036	0.037	0.555	0.589	0.624	86.820	97.120	108.510
MTBF	0.476	0.505	0.533	0.043	0.046	0.050	0.512	0.547	0.584	80.060	90.260	101.590
MTTR	0.507	0.539	0.571	0.054	0.057	0.060	0.536	0.573	0.611	83.910	94.560	106.290
Number of unplanned maintenance	0.519	0.551	0.583	0.043	0.046	0.050	0.554	0.593	0.634	86.670	97.840	110.220
Reduced yield	0.528	0.551	0.573	0.033	0.035	0.037	0.575	0.606	0.639	89.970	100.000	111.150

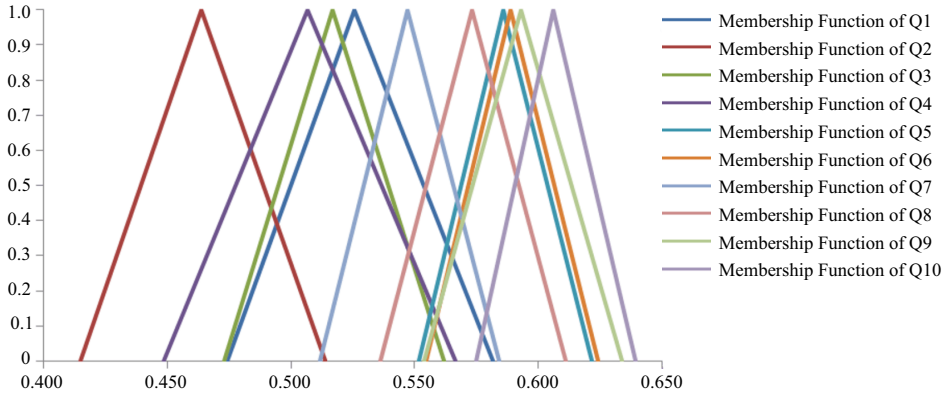


Fig. 5. The membership functions of fuzzy \tilde{Q}_j criterion

In Step 7, we determine the optimally criterion, K. To determine the optimally criterion K, it is used one of the fuzzy ranking method based on α -cuts (Basirzadeh, Abbasi 2008). According to this method, if $A = (x_0, \delta, \beta)$ is a triangular fuzzy number, the parametric values assigned to the fuzzy numbers, represented by $Q^{Tri}(A)$ calculated as follows:

$$Q^{Tri}(\tilde{A}) = 2x_0(1 - \alpha) + \frac{(\beta - \delta)}{2}(1 - \alpha)^2. \tag{13}$$

The fuzzy \tilde{Q}_j criterion values of performance measures are ranked using the above equation and the rankings of the alternatives according to different α -cut levels are given in Table 10. According to Table 10, the best three performance measures for the all level of α -cut are performance measure “reduced yield”, performance measure “number of unplanned maintenance (equipment failures)” and performance measure “reduced speed”. The other performance measures have different rankings for the different levels of α -cuts. According to this Table, the optimally criterion K is TFN (0.5749, 0.6061, 0.6391).

In Step 8, we calculate the utility degree of each alternative and the fuzzy \tilde{N}_j values.

Table 10. The ranking of fuzzy \tilde{Q}_j criterion values of performance measures

α	Ranking of fuzzy numbers according to values of $Q^{Tri}(\tilde{Q}_j)$
0.1	$\tilde{Q}_{10} > \tilde{Q}_9 > \tilde{Q}_6 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.2	$\tilde{Q}_{10} > \tilde{Q}_9 > \tilde{Q}_6 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.3	$\tilde{Q}_{10} > \tilde{Q}_9 > \tilde{Q}_6 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.4	$\tilde{Q}_{10} > \tilde{Q}_6 > \tilde{Q}_9 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.5	$\tilde{Q}_{10} > \tilde{Q}_6 > \tilde{Q}_9 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.6	$\tilde{Q}_{10} > \tilde{Q}_6 > \tilde{Q}_9 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.7	$\tilde{Q}_{10} > \tilde{Q}_6 > \tilde{Q}_9 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.8	$\tilde{Q}_{10} > \tilde{Q}_6 > \tilde{Q}_9 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$
0.9	$\tilde{Q}_{10} > \tilde{Q}_6 > \tilde{Q}_9 > \tilde{Q}_5 > \tilde{Q}_8 > \tilde{Q}_7 > \tilde{Q}_1 > \tilde{Q}_3 > \tilde{Q}_4 > \tilde{Q}_2$

5. Research results and discussion

We used *Taguchi design methodology* in order to reduce the number of designs. The conjoint analysis was performed by using Taguchi OA 16 table. The ANOVA results of conjoint analysis showed that the proposed multiple regression model for the twelve performance measures impact on TPM is statistically significant. In the following, we present a comparative analysis for pessimistic and optimistic COPRAS methods and COPRAS-G and fuzzy COPRAS methods.

Figure 6 shows the comparisons among the methods pessimistic COPRAS, optimistic COPRAS, COPRAS-G and proposed fuzzy COPRAS according to the rankings of the performance measures. In Figure 6, according to the optimistic values, the best performance measure is number of unplanned maintenance (equipment failures); according to the pessimistic values, the best performance measure is MTTR; according to the grey values (COPRAS-G) of performance measures, the best performance measure is also number of unplanned maintenance (equipment failures); according to the fuzzy values (proposed fuzzy COPRAS), also the best performance measure is reduced yield. The last ranked performance measure in the rankings is organization problems & labour unrest with respect to optimistic, grey and fuzzy COPRAS methods. Organization problems & labour unrest is the 4th ranked performance measure with respect to pessimistic COPRAS method.

Proposed fuzzy COPRAS method is preferred over the COPRAS-G method since it is not using the conversion method which does not guarantee one-to-one correspondence between fuzzy numbers and real numbers. In the proposed fuzzy COPRAS method, all fuzzy judgments are not converted to real numbers and all calculations are performed in accordance with the fuzzy arithmetic. Thus, it can be said that *in this method the information loss is not included*. It is seen that proposed fuzzy COPRAS method gives similar but not the same results of other COPRAS methods.

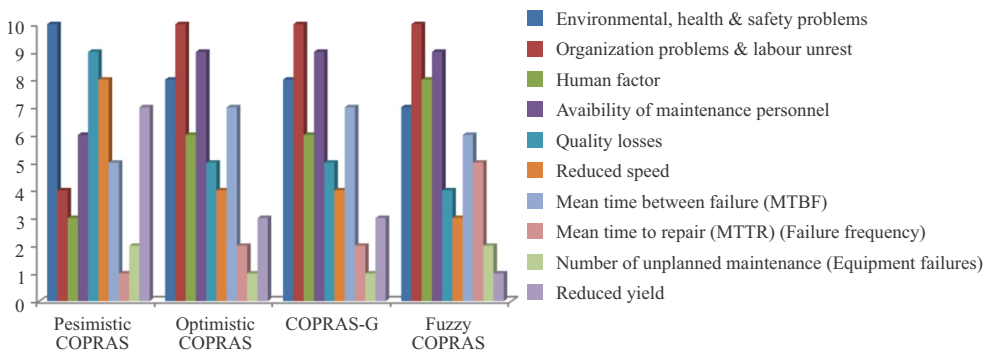


Fig. 6. The comparison of proposed Fuzzy COPRAS and other COPRAS methods

Conclusions

In today's competitive environment, TPM has been widely implemented as a lean production tool for improving manufacturing performance in many organizations. The effectiveness of TPM should be measured by some factors since it can make a great contribution to companies in advancing their manufacturing operations. In most organization, the effectiveness of TPM is measured by only OEE metric. Thereby, in this study, primarily new performance measures having impact on successfully TPM implementation are developed according to literature review and practical aspect including interviews of employees worked at TPM department in different manufacturing companies. Then a fuzzy MCDM model is employed based upon COPRAS method for the evaluation of these performance measures in TPM. Finally a comparison between the proposed fuzzy COPRAS and conventional COPRAS methods is presented. The results of comparison illustrate that the proposed Fuzzy COPRAS method finds almost the same ranks others COPRAS methods.

In this study, it is developed new performance measures oriented towards the quantification of TPM implementation effectiveness and evaluated the new performance measure in TPM under fuzzy environment. In the evaluation process, COPRAS-G is applied for evaluation of new performance measures in TPM. Then the fuzzy COPRAS method is developed for the evaluation of new performance measures in TPM. When developing the fuzzy COPRAS all calculations are made based on the fuzzy arithmetic and fuzzy ranking operations. Therefore, no fuzzy value is converted to a crisp value.

This study helps to operators and executives to visualize the results of the investments made in TPM efforts with newly developed performance measures of TPM. The limitation of the proposed ordinary fuzzy COPRAS is its need for a modification in case of new extensions of fuzzy sets. In the future research, the proposed performance measures are going to be tested in a real-world manufacturing company where the original OEE has been evaluated previously. Proposed fuzzy COPRAS method can also be extended using intuitionistic, hesitant fuzzy sets or neutrosophic sets to evaluate newly developed performance measures in TPM.

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