A new modified FMEA

by Stenly Tangkuman2

A new modified FMEA model for ranking the risk of maintenance waste considering hierarchy of root causes and effects

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Abstract: Implementing sustainable manufacturing practice requires efficiency of the resource utilisation and activities which add value to the operations. From this point of view, development of an improved methodology to access the criticality of non-added value (waste) is important and believed to support the realisation of sustainable manufacturing operation. While previous studies on improving methodology to support sustainable operation from product and process design are abundantly available in the references, the contribution from maintenance field is in contrary. The goal of this study is to modify the quality improvement tool, failure mode and effect analysis (FMEA) to access the criticality of waste in maintenance operation. In an attempt to realise the above goal, an empirical study to propose the theoretical and actual maintenance waste from industrial practice is undertaken. In order to assist maintenance decision maker to quantify criticality of maintenance waste occurrence, a new model to rank waste maintenance mode, called the waste priority number (WPN) is given. Illustrative on using model for practical purpose is given.

Keywords: modified FMEA; maintenance waste; waste priority number; WPN; AHP; root causes.

Reference to this paper should be made as follows: Sutrisno, A., Gunawan, I., Khorshidi, H.A. and Tangkuman, S. (2015) 'A new modified FMEA model for ranking the risk of maintenance waste considering hierarchy of root causes and effects', *Int. J. Quality Engineering and Technology*, Vol. 5, Nos. 3/4, pp.217–237.

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1 Introduction

Driven by growing issues pertaining to sustainability, nowadays global manufacturers face the challenge of creating sustainable manufacturing practice (Garetti and Taisch, 2012). In order to cope with above situation, development or modification of engineering tools and methodology for supporting sustainable manufacturing operations is believed to support the success in creation of sustainable manufacturing practices. While the role and contribution of studies advancing sustainability from product design and manufacturing discipline are abundantly available in literature, the situation is contrary from maintenance management and engineering discipline. According to Venkatasubramanian (2005) as cited in Constantino et al. (2013), contribution of maintenance discipline supporting sustainable manufacturing operations is still mostly focus on extending equipment lifetime. Furthermore, investigation on opportunities to advance engineering maintenance methodology as proposed by Garg and Deskmukh (2006) and Ding and Kamaruddin (2015) are overlooking on providing direction on developing method to maintenance waste minimisation. Motivated by scarcity on studies to support creation of sustainable manufacturing operation from maintenance perspective, this study intended to develop the new modification model of the one of the quality improvement tool, the failure mode and effect analysis (FMEA), to minimise the waste of maintenance activities from the lean manufacturing perspective. Instead of considering the impact of equipment's' failure as exemplified by Constantino et al. (2013), this study takes another direction by developing decision support model to rank maintenance waste by considering the weight of maintenance waste causes and consequences of maintenance wastage. The goal of this study is twofold. First, it is intended to portray the modes of maintenance wastage from the lean perspective and second to propose a new model for ranking maintenance waste as basis of waste alleviation by considering the weight of causes of maintenance waste and impact of maintenance waste. The structure of the paper is as in the following. In Section 2, an overview of studies on applying modified FMEA and their limitations are described followed by establishment of a hierarchy model to rank the cause of maintenance waste based on the AHP. In Section 3, a multi criteria model to appraise the consequences of maintenance wastage by considering multi factors on the impact of maintenance waste is given. Section 4 relates to the formulation of a new equation describing the metric of maintenance waste, the maintenance waste priority ranking, to access criticality as similar to the RPN in conventional modified FMEA and a chart depicting the framework of the proposed model. In Section 5, a case example and discussion of the proposed model is provided. At last conclusion and opportunities for further study are proposed.

2 Modification of FMEA – an overview and observable limitations

Introduced in 1950s to increase reliability military related operations, FMEA methodology is continuously developed or modified to fit the specific applications' requirement. In an attempt to advance its methodology to appraise the risk of faulty event occurrences, many advances decision supporting tools to appraise the risk of failure occurrence events such as fuzzy logic, grey relational theory, graph theory and many others have been developed and embedded into the traditional FMEA as discussed by Liu et al. (2013). However, considering the mode of the non-conformity and non-value added events' occurrence in specific situation such as in remanufacturing of used product (Lam et al., 2000) and evaluating criticality of non-value added activity in lean framework, the terminology and the index for ranking risk criticality as used in conventional FMEA is changed. The differentiating variables between conventional FMEA based on MIL STD 1629A and Modified FMEA are given as depicted in Table 1.

Table 1 Differentiating variables between conventional and modified FMEA

Differentiator	*Conventional FMEA*	*Modified FMEA*
Terminology usage	Failure mode	Waste mode
Risk metric	Risk priority number	Waste priority index
Risk quantifying parameter	Failure occurrence scale	Waste occurrence scale
	Failure mode detectability	Waste mode detectability
	Failure effect severity	Waste effect severity

In similar situation, modifications of FMEA with the focus to remedy the limitation of the conventional FMEA based on MIL STD 1629A have been proposed by Sankar and Prabhu (2000), Pillay and Wang (2003), Sawhney et al. (2010), Sellapan and Palanikumar (2013), Chen and Wu (2013), Paciarotti et al. (2014) and De Souza and Carpinetti (2014). Despite increasing number of studies intended to enhance modification of FMEA as described in aforementioned before, in our opinion, some limitations are still existing and demanding further investigation to fix their limitations. Those limitations are in the followings.

- Previous modified FMEA models overlooked on the situations that due to multiple attributes, there is a need to stratify the hierarchy of failure causes and consequences based on specific criteria as basis toward more systematic failure risk evaluation. The ignorance on the importance of failure cause stratification may cause inappropriate failure mitigation.
- Previous modified FMEA studies assumed that every failure causing factor is having the equal contribution to the occurrence of a particular failure mode to be rectified which is contrary in real situation and may imply to inappropriate failure rectification method ending in waste resource utilisation.
- In the case of modification of FMEA for waste appraisal, the failure analysis used in a modified FMEA model in the study of De Souza and Carpinetti (2014) neglect on considering the impact of waste mode effect by considering multi criterion as commonly encountered by practitioners in industry.

Motivated by above-mentioned limitations, it is became imperative to develop an improved modified FMEA model which narrowing down previous modification of FMEA references with emphasised on accessing criticality of maintenance waste. In subsequent sections, the classification and the theoretical mode of maintenance wastage given and followed by the model to consider the hierarchy of maintenance waste, and a multi criteria decision making model on accessing the criticality of maintenance waste impact considering various consequences and also controllability of maintenance waste consequences.

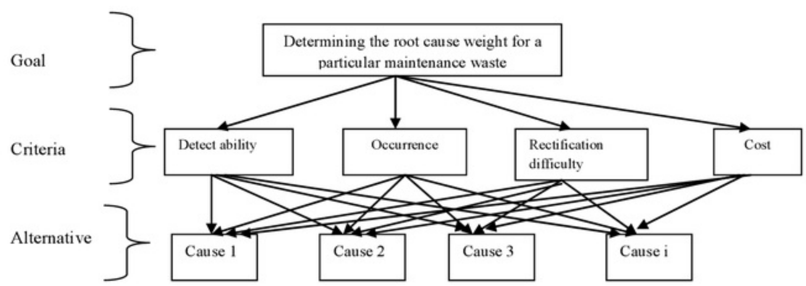
Table 2 Typology of theoretical maintenance waste adapted from references

Maintenance waste category	*Maintenance waste mode*	*Reference*
Overproduction	Delivering maintenance working order which is not intended for immediate use	Al-Baik and Miller (2014
	Designing process information which will not be used by customer	De Souza and Carpinetti (2014)
	Delivering maintenance order request using voluminous paper documents	
Waiting time/interruption/delay	Waiting time spent for executing corrective and or preventative maintenance	Sternberg et al., (2013)
	Waiting time spent for maintenance approval/ spare part purchasing	
	Waiting time spent to re-test the repaired machines	
	Waiting time spent for executing corrective and or preventative maintenance	
Transportation	Motion between maintenance workshop and operation office	
	Motion in sharing maintenance documents/maintenance apparatus	
Incorrect processing	Re-handling maintenance erroneous maintenance job	
	Rectifying mistake in spare part order	
Excess inventory	Excessive spare part maintenance	
Defect	Waste due to re-repair repaired equipment	
	Maintenance information missing	
	Misunderstand maintenance order	
	Erroneous maintenance activities due to bad maintenance data	
Excessive resource utilisation	Waste pertaining to the excessive equipment and bad maintenance planning	Sternberg et al., (2013)
Under utilisation of people	Centralised decision making	Al-Baik and Miller (2014)
	Limiting autonomous maintenance	
	Ineffective knowledge sharing	
Burdening the environment	Excessive use of material auxiliaries, water, electricity, emission and noise	Simboli et al. (2014)

3 Classification of theoretical mode of maintenance waste

Since the introduction of The Toyota Production Systems (TPS), classification of waste is continuously developed ranging from the original model of the 7 Classical Type of waste of Ohno and extended by Liker (2004) and Gibbons et al. (2012) which adds one additional waste, resource polarisation; as the new mode of waste. Pertaining to maintenance engineering context, maintenance waste in this study is defined as any activities which does not added value in preserving the functionality of an engineering physical assets to meet the targeted performance. Currently, due to the global community concern against the destruction of environments caused by the pollutions, and excessive use of auxiliaries and noise, Simboli et al. (2014) introduced the 9th mode of waste, burdening the environment. In line with the versatility of the application of the lean philosophy in service sectors, the taxonomy and mode of waste in service is proposed. In particular to maintenance as supporting operation to manufacturing; the taxonomy, category and the modes of theoretical maintenance waste adopted from many references are given as in Table 2.

Figure 1 A chart depicting the hierarchy of maintenance waste causes



Source: Modified from Braglia (2000)

4 Hierarchical model of maintenance waste cause and their quantification weight

When applying modified FMEA to appraise the risk of maintenance waste, a metric called the waste priority number (WPN) is used as surrogate of maintenance waste risk. The WPN index is having the similar function like the risk priority number (RPN) in conventional FMEA. Pertaining to its function as indicator of criticality of failure or waste mode occurrences, the highest of the WPN score of a failure mode, the more risky the corresponding waste mode would be. In this regard, immediate corrective and or preventative measures should be taken to reduce the adverse consequences of the riskiest waste mode. In an attempt to find the root causes of critical maintenance waste problem, application of a typical root cause from vast array root cause analytical methods such as in Mahto and Kumar (2008) can be used for waste alleviation. Upon the root cause of maintenance waste occurrence identified, appropriate corrective measured is applied. Usually, for specific maintenance waste mode W_k there will be m maintenance waste causes CW_{ik}. Considering that each maintenance waste having its own degree of detect ability, probability occurrence, expected cost consequences, and rectification difficulty, it is become important for decision makers to determine their hierarchy for prioritising preventative or corrective measures. The higher the hierarchy of maintenance waste cause, the more critical its weight would be. In this study, the hierarchy of maintenance root cause waste is represented by its maintenance cause weight $W_{WC_{ik}}$. Assuming independencies among failure causes occurrences, the structural model representing the hierarchy of maintenance waste mode and its probable causes is given as in Figure 1.

If $W_{WC_{ik}}$ represents the weight of the maintenance causes affecting the occurrence of the waste maintenance mode k, then the weight of the waste priority score showing the impact of the corresponding maintenance waste cause is given as

$$W_{WC_{ik}} = D_{C_{ik}} O_{C_{ik}} R_{C_{ik}} C_{C_{ik}} \tag{1}$$

For ease of determining the weight of the maintenance root causes, the scale and criteria used to appraise above mentioned root cause of maintenance waste is given in Table 3.

Table 3 Criteria for evaluation the hierarchy of maintenance waste cause

Scale	*Detect ability of waste cause*	*Probability of occurrence of waste cause*	*Rectification difficulty of waste cause*	*Expected cost due to the occurrence of waste cause*
0.9–1.0	Absolutely difficult to detect the cause of waste	Certainty on the probability of cause occurrence	Impossible to rectify	Extremely high
0.8–0.9	Very difficult to detect the cause of failure	Very high probability of cause occurrence	Very difficult	Very high
0.6–0.7	Difficult to detect the failure cause	High probability	Medium difficult	Moderate
0.4–0.5	Medium difficult to detect the waste cause	Medium probability of detection	Low difficult	Medium
0.2–0.3	Easy to detect the waste cause	Low probability of detection	Very low difficult	Low
0.1	Very easy to detect the waste cause	Very low probability of detection	Extremely low difficult	Very low

4.1 Waste probability avoidance score

The waste probability avoidance score reflects the probability of the maintenance waste avoidance during maintenance operation. Considering that probability is having a score ranging from 0 to 1, the determination of maintenance waste probability avoidance score is based on numerical value between 0 and1. Numerical score 0 represents impossibility of a particular waste mode to be avoided and 1 represent the certainty to avoid the maintenance waste occurrence. Since the number of many maintenance waste types may occur during a specific time period, in compliment with probability of maintenance waste avoidance scale, in this study, the frequency scale of maintenance waste is added and formulated as the ratio between the occurrences of a particular maintenance waste over the total of maintenance waste occurred. Supposing that OW_i represents the score of the occurrence of maintenance waste mode i during period of (0, t), then the score of the occurrence rate of the maintenance waste of waste mode i is given by

$$OW_i = \frac{OW_i}{\sum_{i=1}^{k} OW_i} \tag{2}$$

Table 4 represents the criteria and the linguistic of maintenance waste score.

Table 4 Criteria for determining the score of the maintenance waste avoidance probability

Linguistic interpretation	*Time span criteria*	*Score*
Very high probability of waste variable occurrence	Waste variable is occurred all the time. It is impossible to avoid occurrence of waste variable	0.9–1
High probability of waste variable occurrence	Waste variable occur every 1 month. Low possibility to avoid waste variables	0.7–0.8
Medium probability of waste variable occurrence	Waste variable occur every 1-3 month. Medium possibility to avoid waste variables	0.5–0.6
Low probability of waste variable occurrence	Waste variable occur every 4-6 month. High chance to get rid of waste variables	0.3–0.4
Very low probability waste variable occurrence	Waste variable may occur in more than 1 year. Very high chance to get rid of waste variables	0.1–0.2

4.2 Waste detect ability occurrence

By using control or inspection methods owned by firm, companies can determine the scale of waste ease of detection. In other words, wastes detect ability occurrence representing the probability of company's ability to detect the occurrence of specific waste. Denote the waste detect ability occurrence with DW_k. Linguistic interpretation and criteria to detect the scale of waste detectability are given as in Table 5.

Table 5 Criteria for determining the score of the waste detect ability occurrence

Linguistic interpretation	*Detection criteria*	*Score*
Very high probability waste variable undetected	Waste variable is almost undetected. It is impossible to detect the occurrence of maintenance waste variable using available detection tools	0.9–1.0
High probability of waste variable undetected	Medium probability to detect the occurrence of maintenance waste using available detection tool	0.7–0.8
Medium probability of waste variable undetected	High possibility to detect the occurrence of waste variable using detection tool	0.5–0.6
Low probability of waste variable undetected	Very high to detect the occurrence of maintenance waste variable available detection tool	0.3–0.4
Very low probability of maintenance waste undetected	Waste variable occurrence is certainly detectable with confident	0.1–0.2

4.3 *Waste severity scale*

The occurrence of a particular waste will cause many consequences. Those could be in the form of increased lead time, dissatisfied consumers, safety matters, financial losses and others. Evaluation of the waste occurrence should consider many aspects such as economics, environmental, safety, reputational and so on. Considering that maintenance waste may have many consequences in terms of negative technological, economical, safety, reputational impacts; the use of multi criteria decision tool such as the analytical hierarchy process (AHP) can aid decision makers in appraising severity of maintenance waste consequences using multiple criterion (Singh and Kulkarni, 2013). Now denote SW_k as severity of maintenance waste.

4.4 *Waste effect controllability scale*

Despite the occurrence of a maintenance waste affecting negatively to the firm operations, the severity of maintenance waste occurrence will be low in case that the company's controllability of corresponding maintenance waste consequences is high. Considering this situation, the criticality of maintenance waste consequences is reversal with possibility of the company controllability level to the corresponding maintenance waste. Now, denote the probability of maintenance waste controllability as PCW_k. The controllability index is related to the existence of control factors. In this study, *control factors* are any factors whose value determines the controllability of waste effects. The identification of control factors can be accomplished by using decision makers' judgment, pre-limitary test, or previous experiences in dealing with previous maintenance waste occurrence. As the company spending financial and intellectual capital in mitigating negative impact of waste variables, the financial and organisational competency attributes can be used as basis to estimate the value of control factors. Some other organisational attributes such as adequacy of facilities, quality of administrative control and its supporting data can be used as control variable. If PCW_k represents the probability scale of k^{th} control variable to control the adverse impact of the waste mode k, the value of CCI_k is represented as equation (3):

$$PCW_k = \frac{\sum_k (H_k + F_k + M_k)}{3} \quad (3)$$

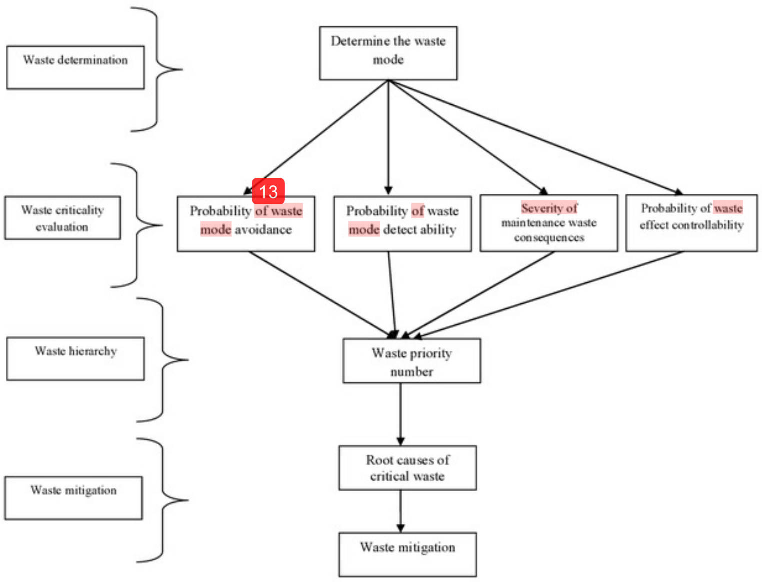
With H_k, F_k, and M_k denote human resource capability, facility and monetary adequacy which owned by the company respectively to tackle the negative impact of maintenance waste k. The larger value of PCW_k indicates the larger probability of the company to control the adverse impact of maintenance waste mode consequences. In this paper, for the sake of simplicity, a 0.1–1 scale is used to weight the scale of control variables. The rating determination of specific control measures is assumed based on average score from summation of human, facility and financial criteria.

Table 6 Criteria for scaling control variables

Linguistic interpretation of control variables			
Human competency and capability	*Facility adequacy*	*Monetary adequacy*	*Rating*
Very high capability of owned human capital to tackle the waste variables	Very high availability of facilities to tackle the waste variables	Very high availability of company monetary adequacy to tackle the waste variables	0.1–0.2
High capability of owned human capital to tackle the waste variables	high availability of facilities to tackle the waste variables	high availability of company monetary adequacy to tackle the waste variables	0.3–0.4
Medium capability of owned human capital to tackle the waste variables	Medium availability of facilities to tackle the waste variables	Medium availability of company monetary adequacy to tackle the waste variables	0.5–0.6
Low capability of owned human capital to tackle the waste variables	Low availability of facilities to tackle the waste variables	Low availability of company monetary adequacy to tackle the waste variables	0.7–0.8
Very low capability of owned human capital to tackle the waste variables	Very low availability of facilities to tackle the waste variables	Very low availability of company monetary adequacy to tackle the waste variables	0.9–1

The criteria to weight above mentioned control variables are presented in Table 6.

Figure 2 A chart depicting the procedure to rank the maintenance waste mode



Based on the logic that the criticality of a maintenance waste equals to the rank of maintenance waste causes, its probability occurrence, detect ability and severity and reversal with companies capability to control its occurrences, the criticality of waste occurrence is given as

$$WPN_k = \frac{W_{WC_{ik}} OW_k DW_k SW_k}{CW_k} \tag{4}$$

The notation method for the variables in equation (4) is as follow:

WPN_k waste priority number for maintenance waste mode k

$W_{WC_{ik}}$ weight of maintenance waste mode k due to cause i

OW_k occurrence rate of maintenance waste mode k

DW_k detect ability level of maintenance waste mode k

SW_k severity level of the consequences due to the occurrence of maintenance waste mode k

PCW_k probability level of company's controllability against to the consequences of maintenance waste mode k

k 1,2,3,……

i 1,2,…,r_k.

The modified FMEA Sheet representing above mentioned factors in assessing criticality of waste is given as in Table 7.

Table 7 A typical modified FMEA sheet for maintenance waste prioritisation

Waste mode	*Effect*	*Waste effect*		*Waste cause*					*Waste priority number*
		Detect ability	*Severity*	*Cause*	*Occurrence*	*Detect ability*	*Rectification difficulty*	*Weight*	
WM_1	E_1	DW_1	SW_1	C_1	OW_1	DC_1	RC_1	WC_1	WPN_1
WM_2	E_2	DW_2	SW_2	C_2	OW_2	DC_2	RC_2	WC_2	WPN_2
…	…	…	..	…	…	…	…	…	…
WM_k	E_k	DW_k	SW_k	C_k	OW_k	DC_k	RC_k	WC_k	WPN_k

In an attempt to implement the proposed methodology into practice, a chart depicting the procedure in applying the modified FMEA model is given in Figure 1. Referring to Figure 1, the phase of implementing the modified FMEA for waste evaluation are consisting of three phases; waste determination, waste criticality assessment, waste hierarchy positioning and waste mitigation.

5 Research methodology

In an attempt to validate the proposed modified FMEA model, a case study type research is used since the goal of this study is on answering the 5Ws questions and the researchers has no control over it (Yin, 1994). The company where the case example applied is an electricity–generating company. Aiming to reach the research goals; company visit, interviews, departments meeting and investigating archival documents from maintenance and operations unit of the company are accomplished. For obtaining relevant research data pertaining to how maintenance and operation are practiced in its everyday activities, structured interview with maintenance, quality assurance and operations manager who has more than 15 years of working experiences is conducted. The goal in conducting the interview was to determine the real mode of maintenance waste based on the theoretical maintenance waste mode as exemplified by maintenance waste theory given in Table 2. In addition, it is also intended to determine the level of maintenance waste avoid ability; detect ability and controllability of maintenance waste effect. Furthermore, structured interview is also intended to determine the criteria used by company to determine the criticality of the maintenance waste consequences and root cause weighting factors as basis for determining the criticality of maintenance waste as in equation (4). Waste classification model as in Al-Baik and Miller (2014), De Souza and Carpinetti (2014), Sternberg et al., (2013) and Simboli et al. (2014) is adapted in maintenance environments and used as basis to develop the classification of real maintenance waste mode and the results are depicted in Table 8.

Table 8 Typology of Maintenance Waste and Its Corresponding Causes

Maintenance waste category	*Maintenance waste mode*	*Maintenance waste cause*
Overproduction	Duplicating maintenance data	Bad maintenance data circulation method
		Delay in maintenance report making
Waiting time/interruption/delay	Additional waiting time spent for executing corrective and or preventative maintenance	Incomplete maintenance apparatus
		Absence of competence technicians when irresolvable maintenance problem occurred
		Spare part unavailability
Transportation	Extra movement between maintenance workshop and administrative office	Substandard maintenance inspection result demanding re-inspection
		Inappropriate building lay out
	Motion in sharing maintenance documents/maintenance apparatus	Bad maintenance data circulation
Incorrect processing	Reiterating maintenance data completing	Bad maintenance data management
	Unavailability of appropriate spare part catalogue when spare part replacement occurred	Inaccurate inventory planning and maintenance archive
Excess inventory	Excessive spare part maintenance	Inappropriate spare part planning
Defect	Erroneous maintenance activities	Knowledge gap between maintenance managers and their sub-ordinate
		Unclear maintenance working order
Excessive resource utilisation	Carelessness on the usage of power for maintenance activity	Lack of self-discipline using energy consumption
Under utilisation of people	Limiting autonomous maintenance	Low working ethos among maintenance crew
	Ineffective knowledge sharing	Information distortion among maintenance crew
Environmental burden	Excessive usage on electricity and fuel during maintenance activities	Pressure on achieving electricity generating target
	Usage of old machine	Bad maintenance budgeting for machine replacement
	Using apparatus not as specified	Unaware of the consequences in doing such practices

Source: Own research

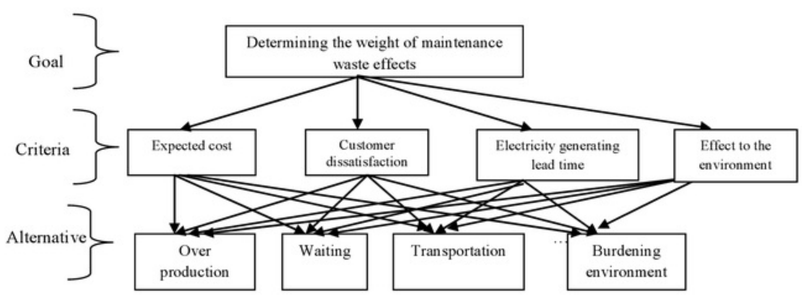
6 Results and discussions

Table 8 showed the typologies of maintenance waste mode and its probable maintenance waste causes from the study undertaken. According to the result, there are 9 (nine) maintenance waste categories ranging from the 7 classical waste and added with 9th maintenance waste in the form of burdening the environment (Simboli et al., 2014). Referring to this study, some maintenance waste modes are causing by single causal factors, while others are due to multiple maintenance waste causes. For example, the maintenance waste mode "additional waiting time for executing maintenance work" is probably due to three possible causes; "incomplete maintenance apparatus", "absence of competence technicians when irresolvable maintenance problem occurred", and "spare part availability problem".

In this study, for illustrative purposes, we only deal with the three modes of maintenance waste namely, 'overproduction', 'waiting/interruption/delay', and 'defect'. The calculation method for other type of waste can be accomplished similarly.

In attempt to demonstrate the proposed model for accessing the risk of maintenance waste causes, the criteria used to access the severity of maintenance waste consequences are expected cost incurred when a particular maintenance waste occurred, customer dissatisfaction, the impact of maintenance waste to the environment and electricity generating lead time. The electricity generating lead time in this study is defined as the time span from the occurrence of the maintenance work order request until the success on generating electricity due to the completion of maintenance work. The hierarchical model used to represent weighting impact of maintenance waste model using AHP Framework is then given in Figure 3.

Figure 3 A hierarchical model for appraising the weight of maintenance waste consequences



The weight of the maintenance waste category was based on the pair wise comparison among aforementioned criteria using the AHP method. Upon performing the calculation, the weight of the case example of three above mentioned weight is given in Table 9. Meanwhile, the weight score of every maintenance waste mode occurrence is obtained from multiplication between the weight of every maintenance waste category and the result of pairwise comparison using the same criteria multiplied by the weight of every maintenance waste category obtained from previous step.

The waste occurrence rate is determined by using the ratio between the frequencies of a particular maintenance waste occurrence and the total maintenance waste occurrence for all maintenance waste categories. Realising that the result of the calculation may yield the small figure which will be meaningless, for the sake of simplicity to avoid the small figure which will be meaningless, the WPN is then multiplied with 10^6.

The result of the calculation is given in Table 10.

Table 9 The weight of maintenance waste category of case example

Maintenance waste category	*Weight*
Overproduction	0.350
Waiting time/interruption/delay	0.158
Defect	0.272
Maintenance waste mode	*Weight*
Duplicating maintenance data	0.329
Additional waiting time spent for executing maintenance process	0.158
Erroneous maintenance activities	0.513

Referring to the case example, based on the four criteria of the impact of maintenance waste occurrences, ‘waiting time/interruption/delay’ is becoming the most critical maintenance waste type followed by ‘overproduction’ and ‘defect’. For the maintenance waste ‘overproduction’, ‘bad maintenance circulation data’ is becoming the most critical root cause. Meanwhile, for the ‘waiting time/interruption/delay’, the critical root cause is ‘spare part unavailability’. At last, for solving maintenance waste ‘defect’, decision makers should concentrate on the 2 root causes, “knowledge gaps among maintenance crew”, and “ unclear maintenance working order”.

Table 10 Modified FMEA sheet for ranking maintenance waste of case example

Maintenance waste category (weight)	*Maintenance waste mode (weight)*	*Waste occurrence rate*	*Waste avoidance probability score*	*Effect*	*Maintenance waste effect*			*Maintenance waste cause*	*Occurrence*	*Detect ability*	*Rectification difficulty*	*Weight*	*Maintenance waste priority number*
					Controllability	*Detect ability*	*Severity*	*Cause*					
Overproduction (0.350)	Duplicating maintenance data (0.329)	0.25	0.10	Productivity loss	0.20	0.1	0.0115	Bad maintenance data circulation method	0.8	0.1	0.2	0.016	230
		0.25	0.10	Energy generating opportunity loss	0.30	0.7	0.080	Delay in maintenance report making	0.1	0.1	0.1	0.001	46.7
Waiting time/interruption/delay (0.378)	Additional waiting time spent for executing maintenance process (0.158)	0.50	0.30	Productivity loss	0.30	0.2	0.0119	Incomplete maintenance apparatus	0.9	0.1	0.7	0.063	119.7
		0.50	0.30	Customer dissatisfaction	0.50	0.2	0.0119	Absence of competence technicians when un-resolvable maintenance problem occurred	0.3	0.1	0.8	0.024	28.7
		0.50	0.30		0.50	0.30	0.0119	Spare part unavailability	0.4	0.1	0.5	0.020	142
Defect (0.272)	Erroneous maintenance activities (0.513)	0.25	0.2	Maintenance quality loss	0.30	0.20	0.027	Knowledge gap between maintenance managers and their sub-ordinate	0.3	0.2	0.6	0.036	2.0
		0.25	0.2	Endangering crew safety	0.20	0.10	0.013	Unclear maintenance working order	0.2	0.3	0.1	0.006	2.0

7 Discussions

Referring to its strategic role in maintaining resource utilisation for manufacturing operation, determining an improved model for maintenance waste reprioritisation is important for supporting the realisation of sustainable manufacturing practice. However, advancement of modified FMEA model as exemplified by previous FMEA references as briefly described in Section 2 are focusing on manufacturing operations and overlooked on its application in maintenance operation. In addition, determination of the risk metric as shown by the RPN estimation is overlooking on situation that due to company controllability against the negative consequences on the risk event occurrence, the corresponding RPN could be smaller. In this study, a new model for accessing the criticality of maintenance waste occurrence is proposed in an attempt to narrow down the limitation of previous modified FMEA references. In the proposed modified FMEA model, the hierarchy of maintenance waste root causes is weighted using various weighting factors. The method to quantify the contribution of root cause of maintenance waste mode occurrence is improved compared to the attribution of root cause impact to the magnitude of the risk metric as exemplified by the work of Sutrisno and Kwon (2010) and Ae et al. (2015) and De Souza and Carpinetti (2014).

Next, realising that reaching zero maintenance waste occurrences is almost impossible to achieve considering the nature of maintenance activities affected by outer factors, the scale of probability of waste avoidance is used as one of the basis for ranking criticality of maintenance waste. In similar situation, organisational controllability level is considered when determining the criticality of maintenance waste consequences. Those two aspects are not considered in previous modified FMEA studies.

In our opinion, above mentioned aspects, though important and inherent in dealing with criticality of maintenance waste risk, is not considered in previous modified FMEA models. Pertaining to its benefits on offer, this study offers many benefits to both of practice and theoretical purposes. First, our study offered on the theoretical and actual mode of maintenance waste which to our knowledge is never been investigated by previous FMEA studies.

Second, the model proposes the new classification of probability components of failure analysis into three components which are different from previous modified FMEA references. Those were probability of waste mode avoidance, detect ability and controllability components which in our opinion, is inherent in failure assessment and overlooked by previous modified FMEA components.

Third, it presents on the utilisation of multi criterion aspect in appraising the severity of maintenance waste effects making it enable to adapt the real situation where decision makers usually using many criterion in declining their decision. As at last, it develops a framework of modified FMEA model for accessing the risk of maintenance waste occurrence in which to our knowledge, is never discussed in previous studies. In summary, the proposed modified FMEA model improved limitations of the previous modified FMEA studies by providing method to consider many aspects in dealing waste prioritisation such as inclusion of waste avoid ability, waste effect controllability and a multi criteria approach in accessing the severity of the waste effect occurrence.

Despite the contributions offered, some limitations are still observable in the proposed modified FMEA model. First, depending on its application context, difference industrial settings may give different maintenance waste modes and in consequences different WPN will be exist. Next, we still observe that the different root cause of maintenance waste may give the same hierarchy even though it is having different components prioritisation criteria. Another limitation of the study is concerning to the exclusion of safety -related waste which is important to consider concerning to the use of human in maintenance operations.

8 Implications

Attempted to becoming primary study in classifying theoretical and actual mode of maintenance waste, this study provides implications to an improved waste categorisation and practical maintenance waste alleviation model.

9 A framework of maintenance waste classifications

In the references, most of the example of the mode of non-value added (waste) typology is coming from product design, manufacturing and service operations. See for example on the study of Rossi et al. (2011) on waste mode of product design, De Souza and Carpinetti (2014) on waste mode in service and manufacturing. In addition, typology of the waste mode is derived from the seven classical waste and the 8th waste as exemplified by Gibbons et al. (2012). In this study, additional waste, the 9th waste mode in the category of 'burdening the environment' is given with example. Considering on the 9th waste mode will give benefit on the comprehensiveness on portraying the mode of maintenance waste in industry wishing to implement green oriented maintenance model in their everyday practices.

10 Practical maintenance waste prioritisation

Finding an improved methodology for curbing the root cause of non-value added operation in maintenance is a step closer to realise sustainable manufacturing considering critical role of maintenance as supporting function to reliable operation. By providing an improved methodology to access the criticality of maintenance waste, decision makers enable to find the rank of critical maintenance waste mode and the hierarchy of the probable causes. In this study, a simple decision support model to rank the risk of maintenance waste is provided in the hope to ease of maintenance practitioners using less complicated modified FMEA model to appraise maintenance waste modes in practical situation.

11 Conclusions and opportunities for future investigation

Identifying and ranking negative consequences of the non-value added (waste) event occurrence is important to realise sustainable operation. Unfortunately, endeavours to modify the tool to rank the risk of waste occurrence are mostly dedicated into manufacturing sectors and not in the maintenance engineering discipline. Therefore, modification of the FMEA in accessing the risk of maintenance waste is necessary supporting the realisation of sustainable operation, since maintenance is having the vital role to reliability of manufacturing operations.

In this paper, the framework, typology, exemplary and a new model for evaluating the criticality of maintenance waste mode is proposed in attempt to narrowing down the scarcity on study modifying FMEA in maintenance sector. Such study was not found in previous references. The framework presents new components for criticality assessment of maintenance waste modes using modification of FMEA. Different from previous studies on modifying FMEA methodology which neglect organisational controllability in dealing with effect of maintenance waste occurrences, probability of waste effect controllability aspect is considered thus enable to consider the organisation's controllability capability in dealing with specific maintenance waste occurrence. In addition, the use of AHP in accessing the hierarchy of maintenance waste consequences enables manager to consider many qualitative and quantitative criteria on the impact of maintenance waste occurrence. Illustrative example on using the modified FMEA model is given to provide exemplary on using the model in practice.

This study opens many further opportunities for investigations. For instance, in some situations, solving the root cause of maintenance waste usually consider contradiction among competing solutions. In resolving above situation, extending this study by utilising the TRIZ method for selection conflicting corrective actions in modified FMEA is a new opportunity for study. Next, in this study, inter relationship among waste modes are not considered in accessing the criticality of maintenance waste effect which contrary to real situation. Ignorance on such situation, may give inappropriate maintenance waste alleviation. Future study could consider such situation. Integrating modified FMEA with QFD to select change management model toward lean maintenance practices is another opportunity which to our knowledge is still unexplored and warrant for deeper investigations. At last, linking the waste priority metric with performance measurement tools to realise maintenance performance improvement is another option for future study.

Acknowledgements

The authors would like to thank the Indonesian Ministry of Research Development and Higher Education for funding this study under contract number 023.04.1.673453/2015 for research project entitled 'Enhancement of Modified FMEA Model to Support the Implementation of Green Oriented Maintenance Practice'.

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