PRIORITIZING SUSTAINABILITY IMPACT OF FAILURE MODE AND EFFECT ANALYSIS IN THE PALM OIL MILL USING ANALYTICAL HIERARCHY PROCESS

W.H.W., Mahmood¹, I., Abdullah², M.H.F., Md Fauadi², M.N.A. Rahman³, M.F. M. Halim¹, M.A. Said¹, M.S.M. Sabri⁴

¹Faculty of Technology Engineering, Universiti Teknikal Malaysia Melaka, 76100, Melaka, Malaysia.
²Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, 76100 Melaka, Malaysia.
³Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Selangor, Malaysia.
⁴Felda Palm Industries Snd. Bhd., Kilang Sawit Kemahang, Peti Surat 35, 17507 Kelantan, Malaysia

Abstract. This paper presents an Analytical Hierarchy Process (AHP) model for prioritizing multi-criteria sustainability impact of Failure Mode and Effect Analysis (FMEA). It focuses on the Malaysian palm oil mills that have been widely criticized on various sustainability issues. The data collection for pair-wise comparison of decision judgement are taken from three experts of palm oil milling process and an additional expert from the academic background. The multi-criteria of each sustainability impacts (technical, economic, environmental, and social) are assessed for the weights of the occurrence, severity, and detection of the FMEA. The result of the study suggested that the degree of failure severity for social impact is considered as the highest priority for palm oil mills. This paper provides insights for management to improve organizations’ sustainability performance at the operational level by considering sustainability impact in analyzing failure mode and effect of equipment.

Keywords: Manufacturing Sustainability, Palm Oil Mill, FMEA, AHP.

1.0 INTRODUCTION

Manufacturing industry is set to adapt to the foundation of a sustainable operation in achieving growth economically without disregard the environment and social well-being. Sustainability in the manufacturing emphases on managing the production processes with sustainable input such as energy, people, equipment and machines, coupled with the objective of reducing waste, rework, inventory and delays as well as reducing the environmental footprint [1]. The key components are comprising of using processes that minimize negative environmental impacts and conserve energy and natural resources. It
also ensure the safe process and product for employees, consumers, and communities and balancing environmental, economic and social objectives of the organization.

The milling process of palm oil has had a long history of environmental challenges, leave a significant eco-footprint, including large quantities of polluted waste materials, GHG emissions, and biodiversity loss, that requires serious attention [2]. With the impact of climate change threatens to escalate in the absence of adequate safeguards, there is a need to promote sustainability in the Malaysian palm oil mills for a more environment- and resource-friendly manner, for the success of the firms economically and environmental and social well-being of the future generations. The determination to make palm oil production more sustainable becoming the greatest challenge for Malaysia, current leading producer and exporter of palm oil in the world.

As many sustainability impacts of the palm oil industry are strongly influenced by its manufacturing process, it is critical that the operation management function embraces sustainability management engaging overall stage of operation. Consideration of the equipment performance in the palm oil mill is essential for sustainable operation. Equipment failure could bring huge impact not only to performance in term of the technical aspect but also to economic, environment and society [3]. To resolve this issue, Failure Modes and Effects Analysis (FMEA) advanced in finding, measuring, and evaluating potential failure modes of equipment in manufacturing. There are several literatures addressed individual sustainability elements of FMEA in isolation, however, only a few studies have reflected the whole sustainability elements. The evaluation of overall sustainability elements is a multi-criteria decision problem because a number of criteria must be taken into consideration when assessing the degree to which these initiatives conform to the dimensions of sustainability. The analytic hierarchy process (AHP) provides a framework to cope with multiple criteria situations involving intuitive, rational, quantitative and qualitative aspects. Therefore, the paper use AHP approach and presents the model of the multi-criteria sustainability impacts prioritizing for palm oil mills' FMEA. The paper is structured as follow. Subsequent the introduction, Section 2.0 presents literature review highlighting the impact of equipment failure on the palm oil mill sustainability and the integration of FMEA and AHP approach. Materials and methods of the study are justified in Section 3.0. Section 4.0 discussed the results of the study. Section 5.0 concludes the study.

2.0 LITERATURE REVIEW

2.1 Equipment Failure and Palm Oil Mill Sustainability

Equipment performance as one of the major contributors to the performance and profitability of manufacturing systems is gaining increasing importance in the manufacturing operation. In the palm oil mills equipment are subject to deterioration and failures as the consequence of usage, aging, fatigue, environmental conditions or other extreme events. Such system deterioration may lead to higher production cost, lower product quality and increase the probability of breakdown. Unexpected breakdowns not only increase the operating cost of the productive machines but in fact, the cost of lost production is inevitable for operation interruptions [4]. Unplanned maintenance arises when equipment is repaired as it fails, usually on an emergency basis and the downtime incurred by the operation usually occurs at an inopportune moment and can also cost money because of lost business. Failure of even a single component will not only idle the machine and facility but also the failure can quickly idle the entire production system. The failure may come from lack of maintenance, improper or intensive operation, and unstable operating environment.

The economic impacts also including the movement of finance in relation to measuring cost, returns and payments economic measures that relate to stakeholders such as suppliers, government and shareholders [5]. Organizations are increasingly aware of the costs resulting from the imposition of fines
and penalties for environmental damage. Additional investment funds, sometimes offering profits, are being made available for environmental protection and clean-up programs, such as sewage treatment, waste disposal, etc. resulting from the failure of equipment. Finding the proper balance is important in securing an organization’s competitiveness on the global market [6].

Equipment failure causes leaking, production stoppage, and malfunctioning equipment may often be the reason for extra crude palm oil losses. Oil losses due to process instabilities and leakage result in increased oil concentration in the mill effluents and thus, rise the environmental pollution. Moreover, equipment that does not perform as it’s designed could also be resulting in the product quality. This could increase the number of rejects therefore indirectly escalates the production waste, including hazardous effluents, fibers, and other residues from palm oil mills. Efficient process control and effective measures in the palm oil milling process could minimize waste generation and wastage of resources indirectly, as well as reduce the pollutant load to be removed in the effluent treatment processes [7].

Failure event of the manufacturing operation could affect the social sustainability of the organization. The social components of the manufacturing organization include employees, customers, and communities. Employee safety, health, and satisfaction could be affected by the failure events in the manufacturing operation. The serious failure could lead to process safety disaster and causes accidents possibly with several fatalities [8]. Besides, employee satisfaction comprising morale, teamwork, and industrial harmony can be affected as employee extended hours or overtimes and number of work stoppages due to increase of failure events.

2.2 Integration of FMEA and AHP Approach

Several management tools have been applied for analysis of system failures and performance. Among others, FMEA is a powerful tool used to identify critical components, parts, or functions and to evaluate the effect of different failure modes that will lead to undesirable outcomes such as production loss, injury or even an accident. For criticality analysis application, FMEA is referred as Failure Mode, Effects and Criticality Analysis (FMECA). The tool has been extensively adopted across many manufacturing and service industries providing risk assessment so that appropriate measures can be applied to eliminate or reduce the risk of the product, equipment, and process. The application of FMEA in identifying and prioritizing failure causes of the system considering the ranking based on the Risk Priority Number (RPN). The RPN is obtained is by multiplying the three main criteria in FMEA; Severity, the rating of seriousness failure effect, Occurrence, the rating of probability failure frequency, and Detection, the rating of probability failure detection before the impact of the failure is recognized. The failures with higher RPNs are assumed to be more important and should be given higher priorities.

The adoption of AHP helps in structuring the complexity, measurement, and synthesis of rankings. These features make it suitable for a wide variety of applications, proven as a theoretically sound and market tested and accepted methodology [9]. In the AHP approach, the decision problem is structured hierarchically at different levels with each level consisting of a finite number of decision elements. The upper level of the hierarchy represents the overall goal, while the lower level consists of all possible alternatives. One or more intermediate level embody the decision criteria and sub-criteria AHP approach for FMEA.

The integration of AHP and FMEA tools has been reported by other researchers. Savino et al. [10] conducted through fuzzy AHP implemented within an FMEA. The social issues that may drive the selection of maintenance policies and the relative maintenance plans were studied. A new component for criticality assessment of maintenance waste modes using a modification of FMEA was proposed by considering the integration of the AHP approach [11]. Meanwhile, the use of AHP in accessing the hierarchy of maintenance waste consequences enables the manager to consider many qualitative and quantitative criteria on the impact of maintenance waste occurrence. It is suggested that integration of the
AHP approach enhances the precision of prioritizing failure modes by eliminating the limitations of traditional FMEA. In searching for the most important and risky potential failure modes and overcoming the shortcomings of RPN calculation, a fuzzy AHP and Similarity to Ideal Solution (TOPSIS) were considered for FMEA of an automotive company. The proposed approach also considered assessment of the experts’ judgement in linguistic variables, the advantage of using this model considers the importance of the risk factors.

3.0 MATERIALS AND METHODS

Using AHP approach, the identification the interrelationships among the dimensions and criteria is done to provide the foundation for finding the weight of each sustainability elements of the FMEA criteria. The methodology follows the research flows in Fig. 1. Firstly, the problem is defined and kind of knowledge sought is determine. The decision is structured in a hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).

Then, a semi-structured interview is conducted in gathering information. The questions consisted of the FMEA criteria and sustainability sub-elements was designed to collect the experts’ judgement for the pair-wise comparison of the Saaty scale [9] as shown in Table 1. Three experts with working experience of more than five years in the palm oil mill from three different palm oil mills were selected for the interview. Additionally, an expert judgement from the academic was included in the study. This academic respondent has knowledge and experience in the field of manufacturing sustainability. The data of the experts’ judgement was analyzed using geometric mean for construction of the pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it. The priorities obtained from the comparisons to weigh the priorities are used in the level below. Then each element in the level below is added its weighed values and its overall or global priority is obtained. This process of weighing and adding is continued until the final priorities of the alternatives in the bottom-most level are obtained.
Define goal: FMEA from Sustainability Perspective

Decomposition of goal into lower level considering FMEA criteria and Sustainability elements

Develop of hierarchy model

Data collection from palm oil mill using semi-structured interview

Perform pair-wise comparison

Is pair wise comparison consistent?

Yes

Determine priority weights of individual factors and sub-factors

No

Synthesis findings

Figure 1. Research Flows

4.0 RESULTS AND DISCUSSIONS

4.1 Hierarchy Model
The hierarchy model can be divided into three levels as illustrated in Fig 2. From Fig. 2, the first level is the decision objective. The dimensions for FMEA indicators are listed in the second level. The third level is the sub elements of sustainability criteria. The weight of the elements is determined from the judgements of the experts in the production line. By assigning corresponding weights on the FMEA criteria, it is overcoming oversimplification of RPN calculation. This approach considering that each sustainability elements have individual degree of detectability, probability occurrence, expected cost consequences, and difficulty to rectify, it is become necessary to determine their hierarchy.
4.2 Pair-Wise Comparison of Decision Judgement

Assessment on the pair-wise comparisons among FMEA criteria, occurrence, severity, and detection of failure modes and sub-categories for technical impact, environmental impact, economic impact and social impact using a nine-point scale of intensity. In order to be assured of the consistencies, Consistency Index (CI) and Consistency Ratio (CR) were calculated in the hierarchy model as suggested by [9]. Inconsistency might happen that evaluators may be varying in their judgments. The CR is used to measure the consistency of the pair-wise comparisons and decision making. Thus, CI and CR are obtained from the following relations:

\[ CI = \lambda_{\text{max}} \frac{-n}{n - 1} \]  
\[ CR = \frac{\text{CI}}{\text{RI}} \times 100 \]  
\[ \lambda_{\text{max}} = \sum_{l}^{n} (AW)_{ij} /nw_{l} \]

where \( n \) is the rank of the matrix or the number of elements or sub-elements of each level, RI is the average index for randomly generated weights, and \( \lambda_{\text{max}} \) is the largest eigenvector of the positive reciprocal square matrix (A) and RI values for matrices of the order 1–10 are given in the Table 2. An acceptable values of CR is less than 10%. If the CR values are more than 10%, it will highlight that the pair-wise comparisons are inconsistent and hence, discarded. In such a case, the assessment can be revised.

Using AHP approach, the identification the interrelationships among the dimensions and criteria is done to provide the foundation for finding the weight of each criterion. The weight of the elements is from the judgements of the experts in the production line. By assigning corresponding weights on the FMEA criteria, it is overcoming oversimplification of RPN calculation. This approach considering that each sustainability elements have individual degree of detectability, probability occurrence, expected cost.
consequences, and difficulty to rectify, it is become necessary to determine their hierarchy.

From the data of the palm oil mill under study, priority weights of the FMEA criteria are presented in Table 3. From Table 3, the degree of severity (Ss) showed the highest weight value, 0.353. The weight value for the probability of detection (Ds) is 0.333 and the lowest weight value is 0.314 for the probability of occurrence (Os). The CI is 0.005, and the CR is 0.965% indicating that the degree of consistency is an acceptable value. Pair-wise comparison and was prepared between the sections based on the elements of the probability of occurrence (Os) and the sub-element of sustainability factors is presented in Table 4. The results of the synthesis show that RI value is 0.890, for n is equal to four. The CR is 4.682%, indicated that the pair-wise comparison is consistent and accepted. The local weights priority for sub-elements are 0.235 for probability of failure occurrence for technical impact (w1), 0.204 for probability of failure occurrence for environmental impact (w2), 0.269 for probability of failure occurrence for economic impact (w3), and 0.292 for probability of failure occurrence for social impact (w4).

### Table 1. Nine-Point Pairwise Comparison Scale [9]

| Rate | Definition | Explanation |
|------|------------|-------------|
| 1    | Equal importance | Two elements contribute equally to the objective |
| 2    | Weak       | Between equal and moderate |
| 3    | Moderate importance | Experience and judgment slightly favor one element over another |
| 4    | Moderate plus | Between moderate and strong |
| 5    | Strong importance | Experience and judgment strongly favor one element over another |
| 6    | Strong plus | Between strong and very strong |
| 7    | Very strong or demonstrated importance | An element is favored very strongly over another; its dominance demonstrated in practice |
| 8    | Very, very strong | Between very strong and extreme |
| 9    | Extreme importance | The evidence favoring one element over another is one of the highest possible order or affirmation |

For the degree of severity, (Ss), the results of the pair-wise comparison matrix of the sub-element for sustainability impacts are presented in Table 4. From the synthesis of the standardized matrix, the result of the priority weight for each sub-elements are 0.212, 0.233, 0.273, 0.282 for degree of failure severity for technical impact (w5), degree of failure severity for environmental impact (w6), degree of failure severity for economic impact (w7), and degree of failure severity for social impact (w8) respectively. The value of $\lambda_{\text{max}}$ is 4.163, and the RI and CI values are 0.890 and 0.054. The CR is 6.099%, less than 10%, indicated that the pair-wise comparison is consistent and accepted.

### Table 2. Average Random Consistency Index (RI) Based on Matrix Size [9]

| n   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-----|---|---|---|---|---|---|---|---|---|----|
| RI  | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 |

### Table 3. Priority Weights of the Occurrence, Severity, and Detection

| Sustainability Perspective | FMEA Os Ss Ds $T_i$ $W_i$ $AW_i$ $AW_i/T_i$ |
|----------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|

7
Meanwhile, the results of the pair-wise comparison matrix of the sub-element for the probability of detection, (Ds), is exhibited in Table 6. The highest priority weight is the probability of failure detection for social impact (w12), 0.296 and the lowest is the probability of failure detection for environmental impact (w10), 0.225. The priority weight for the probability of failure detection for economic impact (w11) and the probability of failure detection for technical impact (w9) are 0.229 and 0.229 respectively. The results show that the \( \lambda_{\text{max}} \) value is 4.158 and the RI value is 0.890. The value for CI is 0.053 and the value of CR is 5.934\% indicated that the pair-wise comparison is consistent and accepted.

From the pair-wise comparison, the local weights and global weights of the FMEA criteria and the sustainability elements sub-criteria, the ranking of priority of the sustainability impact of failure equipment in the palm oil mill is established. The result is shown in Table 7. From the Table 7, the results indicated that the highest priority of the palm oil mill is the degree of failure severity for social impact (w8) with the weight of 0.100. Whereas the lowest priority is the probability of failure occurrence for environmental impact (w2) with the weight of 0.064.
Table 7. Priority of the Sustainability Impact for Palm Oil Mill

| Decision components and elements                                      | Local weight | Global weight | Priority rank |
|-----------------------------------------------------------------------|--------------|---------------|---------------|
| Probability of failure occurrence (Os)                                | 0.314        |               |               |
| Probability of failure occurrence for technical impact (w1)           | 0.235        | 0.074         | 11            |
| Probability of failure occurrence for environmental impact (w2)       | 0.204        | 0.064         | 12            |
| Probability of failure occurrence for economic impact (w3)            | 0.269        | 0.084         | 5             |
| Probability of failure occurrence for social impact (w4)              | 0.292        | 0.092         | 4             |
| Degree of failure severity (Ss)                                       | 0.353        |               |               |
| Degree of failure severity for technical impact (w5)                  | 0.212        | 0.075         | 9             |
| Degree of failure severity for environmental impact (w6)              | 0.233        | 0.082         | 7             |
| Degree of failure severity for economic impact (w7)                   | 0.273        | 0.096         | 3             |
| Degree of failure severity for social impact (w8)                     | 0.282        | 0.100         | 1             |
| Probability of failure detection (Ds)                                 | 0.333        |               |               |
| Probability of failure detection for technical impact (w9)            | 0.229        | 0.076         | 8             |
| Probability of failure detection for environmental impact (w10)       | 0.225        | 0.075         | 10            |
| Probability of failure detection for economic impact (w11)            | 0.250        | 0.083         | 6             |
| Probability of failure detection for social impact (w12)              | 0.296        | 0.099         | 2             |

5.0 CONCLUSION

With the rising concern on the sustainability impact from the palm oil milling process, the organizations are under pressure to improve the production performance towards manufacturing sustainability at the mills. This paper addressed the sustainability impact of the failure of equipment perspective. Because the sustainability impacts is a multi-criteria decision-making problem, the study applied AHP approach to prioritize the sustainability impact in terms of technical, economic, environmental and social in relation to the occurrence, severity, and detection criteria of FMEA. The judgement of the pair-wise comparisons was assessed by experts from the palm oil mills that have been working for more than five years and an academic expert in the manufacturing sustainability field. From the analysis, analyses, weights of technical, economic, environmental and social impacts are determined. The results emphasized the degree of failure severity for social impact as the highest priority weight rank for the sustainability impact in the palm oil mill. The results of the study serve as an input for calculation of the risk priority number in the FMEA. Thus, for further research can be extended by focusing on the analysis of the failure mode of the critical equipment of the real manufacturing system. A case study in the palm oil mills could be favorable to demonstrate the feasibility of the model.

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