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Quantitative risk modelling of occupational safety in green-port

Debrina Puspita Andriani[1]*, Vina Dwi Novianti[1], Rheza Adnandy[1], Qurrota A'yunin[1]

[1]Department of Industrial Engineering, Universitas Brawijaya, Malang, Indonesia

*Corresponding author : debrina@ub.ac.id

Abstract. Three industrial revolutions are known to have been able to improve the welfare of the community. The fourth industrial revolution or industry 4.0 made many studies carried out on plans, implementations, and other actions that will affect the community. Some industries also began competing to apply industry 4.0 in their systems, including case in this study. This study was conducted in one of the port terminals that are known to be the one and only port that has implemented semi-automatic technology and environmentally friendly in the developing countries. The port operates semi-automatically, so the operating system uses computerization and minimal manpower. As a modern port, this port is equipped with advanced technology, such as automated stacking cranes, ship to shore, and grab ship un-loader, CNG trucks, combined terminal tractors, and others. Port working system is also different from the other ports where only equipment and vehicles that fuelled electricity and gas are allowed to operate in this port, so they also are known as green-ports. Based on preliminary research that had been done, even though the technology and work systems that are applied are sophisticated, but it was known that there were still some occupational accidents that should not have happened, especially in the ship to shore area. The aim of this research was conducted to identify the probability of hazards that occur based on historical data and minimize the risk of further occupational accidents using risk analysis and modelling. Statistical, mathematical, and computational approaches were carried out to obtain risk quantification and develop risk mitigation and response strategies. Thus, the results of the study are expected to help this port as a pilot green-port for other ports, so that it will have a massive positive impact on the change in a more environmentally friendly transportation system.

Keywords: green port, industry 4.0, occupational safety, risk modeling, transportation system

1. Introduction

Indonesia as an archipelago country has a good potential in marine resources and transportation as a driving force the economic development nationwide [1,2]. In fact, the marine transportation carries out around 88% of the transport in Indonesia [3]. This condition indicates that an effort to improve the policy and management of marine transportation is important, especially safety and security of the marine mode of transportation [4].

There are quite lot accidents in marine transportation that most happen because of low concern aspects of the safety and security [5]. Majority (80 to 85%) of all recorded maritime accidents are the

result of senseless and avoidable human errors, so maritime accidents have increased [6,7]. The ship operation system contains a complex interrelation among technical, human, and environment factors that control the ship handling process. The successful of ship handling will reduce accident [8].

In the container port, new container ships today are gearless. They are no longer equipped with their own cranes, but depend on the port to provide specialized handling appliances [9]. Coupled with industry 4.0 development and environmental and social issues, the flexibility and speed of intervention brought about by new developments of ICT solutions, including automation and the Internet of things, pave the way to renewing sustainable and environmentally friendly transportation systems or known as green port [10-12]. Governments in ASEAN countries also have been implementing various green activities seeking to reduce the environmental impact of shipping and related activities [13,14].

As environmental concerns over managing ports are being emphasized, evaluating the greenness of the port accordingly draws a serious academic and research attention [15-17]. One of the concerns and strategic issues was about safety and security management at green port [18-20]. From the studies, the effective transportation safety risk management in transport hubs can increase interoperability in transporting goods and people [21]. Safety risk management of green port construction is a systematic and complex job and is concerning the overall situation and long-term strategic perspective. Thus, it is well known that in properly analysing the greenness of a port needed are various quantitative and qualitative factors as well as an adequate evaluation structure. Appropriate strategies should be performed for responding to risks, when the risks are identified and analysed. Furthermore, the expert knowledge should be adopted in calculating the qualitative factors because there are no secondary data available for them [22].

Experts often rely too much on their own views, expertise, and insights. This became the limitations of the risk model, because human intervention is stronger and strategic into the process of carrying out risk management analysis [23]. In order to overcome these difficulties, uncertainty development model, i.e. Fuzzy logic, Markov Model, Bayesian Network, and Artificial Neural Network, for investigating expert evaluations could be applied [24]. Qualitative, quantitative, and uncertainty model analysis can be combined as an appropriate method for assessing the risk in the green port.

A qualitative and a quantitative risk analysis have been successfully employed as useful approach for estimating the consequences and the frequencies of an accident in a lot of industrial areas, and then calculate the possible risks in a probabilistic way [25]. To identify the possibilities of risks for industrial areas, different methods of analysis have been developed over time, such as Failure Mode and Effect Analysis (FMEA), Failure Mode Effect and Criticality Analysis (FMECA), Failure Tree Method (FTA), DRBFM (Design Review by Failure Mode), Degradation Mode and Criticality Analysis (DMCA), Hazard and Operability Studies (HAZOP), Hazard Analysis and Critical Control Points (HACCP), and Structured What-If Technique (SWIFT), etc. [26, 27]. In this study, FMEA used to analyse the risks at green port, because FMEA are widely used across the study under the topic of risk management by providing the effective detectability for potential risks and helps to prevent them to occur [28-30]. Moreover, FMEA is also one of the risk analysis techniques recommended by international standards [31].

FMEA used to assess the failure and to identify the industrial failures based on the determination of Risk Priority Number (RPN) [32]. Although RPN calculation is comprehensive and easy to understand and use, the approach presents some limitations, such as the large number of duplicates and the difficulty of assessing the RPN indices because it was only qualitative approach [33]. In order to eliminate the shortcomings, this study puts an easy and efficient risk analysis approach, called Fuzzy FMEA.

In the absence of a quantitative probability model, fuzzy logic can classify the key risks consistently, considering both available data and expert opinions [34]. It also can be developed a model on the basis of data found as qualitative terms from experts' judgements and quantitative values from available data [35]. Recently, many studies reported and applied Fuzzy FMEA as risk analysis technique to evaluate the risks instead of conventional FMEA in various industries [36-39].

This study was conducted at the one and only port that prioritized service with semi-automatic appliance and green port standards in Indonesia. With adequate infrastructure and facilities to ensure the prosperity of the world economy, ports with safe and reliable operations are very important for the protection of life and human health, the environment, and the economy [40]. Although using advanced technology, there is an increase in occupational accidents every year where the location of the dock becomes the highest location for occupational accidents in the recent years. Therefore, this study aims to analyse the risks and determine the appropriate response, so that the port is able to improve efficiency, service quality, and reduce productivity costs to achieve sustainability [41].

2. Research Method

This study began with field and literature studies to identify the problems. The data collected was the risk of occupational accidents. Generally, risk analysis has two complementary branches, qualitative and quantitative. Quantitative analysis allows you to quantify the effect level for each type of risk, not only qualitative analysis that identifies the risk areas of a process. In addition, the basic methods for risk analysis are analogy, methods of expertise, statistical methods, and modelling. Quantitative risk analysis was used in analyzing data that had been collected. This analysis has been successfully employed as a useful tool estimating the consequences and the frequencies of an accident in many industrial areas to calculate the possible risks in a probabilistic way [42]. The phases included risk identification, risk analysis and priority determination, and also risk response planning. Da Silva and Crispim explained in their study that these steps could be applied in practice [43].

The first step, risk identification, was aimed to determine the potential risk of occupational accidents that had been occurred at ports, especially at dock area of the green port. This phase was carried out through interviews and discussions with the port expert to obtain risk indicators, the risk management manager. The following step, analysis and prioritization of risks, was analyzed by quantitative risk approach that Failure Mode Effect Analysis (FMEA), while modeling in the prioritization of risk was used fuzzy logic approach. FMEA was used to analyze based on the severity of the risk (severity), the level of possible risk (occurrence), and the level of difficulty or ease of risk control (detection) [44]. These scores were obtained through observations, interviews, and discussions with the risk management manager. The FMEA results were used as input to determine the risk priority number with fuzzy logic approach. In this study, MATLAB was used for fuzzy analysis.

This study focused on implementing fuzzy FMEA to identify the potential risks that may occur along occupational activity at port. Fuzzy FMEA is adopted to overcome the limitations of the subjectivity of experts' assessment in the risk factors evaluation stage [45]. Fuzzy logic sets used to establish a model for risk quantification. The measurement of Fuzzy FMEA can be done the following steps [28, 46, 47]:

1. Determining the value of O, S, and D.
2. Calculating the aggregation of fuzzy ranking measurement of the factors O, S, and D based on Eq. (1), (2), and (3).

$$\tilde{R}_i^O = \frac{1}{n}\sum_{j=1}^{m} h_j \tilde{R}_{ij}^O = \left(\sum_{j=1}^{m} h_j \tilde{R}_{ijL}^O, \sum_{j=1}^{m} h_j \tilde{R}_{ijM1}^O, \sum_{j=1}^{m} h_j \tilde{R}_{ijM2}^O, \sum_{j=1}^{m} h_j \tilde{R}_{ijU}^O \right) \tag{1}$$

$$\tilde{R}_i^S = \frac{1}{n}\sum_{j=1}^{m} h_j \tilde{R}_{ij}^S = \left(\sum_{j=1}^{m} h_j \tilde{R}_{ijL}^S, \sum_{j=1}^{m} h_j \tilde{R}_{ijM}^S, \sum_{j=1}^{m} h_j \tilde{R}_{ijU}^S \right) \tag{2}$$

$$\tilde{R}_i^D = \frac{1}{n}\sum_{j=1}^{m} h_j \tilde{R}_{ij}^D = \left(\sum_{j=1}^{m} h_j \tilde{R}_{ijL}^D, \sum_{j=1}^{m} h_j \tilde{R}_{ijM}^D, \sum_{j=1}^{m} h_j \tilde{R}_{ijU}^D \right) \tag{3}$$

where, $\tilde{R}_i^O = (R_{iL}^O, R_{iM_1}^O, R_{iM_2}^O, R_{iU}^O)$, $\tilde{R}_i^S = (R_{iL}^S, R_{iM}^S, R_{iU}^S)$, dan $\tilde{R}_i^D = (R_{iL}^D, R_{iM}^D, R_{iU}^D)$ the aggregate value of the occurrence (O), severity(S), and detection (D) of potentially risk.

3. Performing aggregate weighting calculations for severity, occurrence, and detection factors based on Eq. (4), (5), and (6).

$$\tilde{w}^O = \frac{1}{n}\sum_{j=1}^{m} h_j \tilde{w}_j^O = \left(\sum_{j=1}^{m} h_j \tilde{w}_{jL}^O, \sum_{j=1}^{m} h_j \tilde{w}_{jM}^O, \sum_{j=1}^{m} h_j \tilde{w}_{jU}^O\right) \tag{4}$$

$$\tilde{w}^S = \frac{1}{n}\sum_{j=1}^{m} h_j \tilde{w}_j^S = \left(\sum_{j=1}^{m} h_j \tilde{w}_{jL}^S, \sum_{j=1}^{m} h_j \tilde{w}_{jM}^S, \sum_{j=1}^{m} h_j \tilde{w}_{jU}^S\right) \tag{5}$$

$$\tilde{w}^D = \frac{1}{n}\sum_{j=1}^{m} h_j \tilde{w}_j^D = \left(\sum_{j=1}^{m} h_j \tilde{w}_{jL}^D, \sum_{j=1}^{m} h_j \tilde{w}_{jM}^D, \sum_{j=1}^{m} h_j \tilde{w}_{jU}^D\right) \tag{6}$$

where, $\tilde{w}^O = (w_L^O, w_M^O, w_U^O)$, $\tilde{w}^S = (w_L^S, w_M^S, w_U^S), \tilde{w}^D = (w_L^D, w_M^D, w_U^D)$ the aggregate value of the fuzzy weights for the three risk factors: occurrence (O), severity (S), and detection (D).

4. Determining the Fuzzy Risk Priority Number (FRPN) for each risk events, based on Eq. (7).

$$FRPN_i = \left(\tilde{R}_i^O\right)^{\frac{\tilde{w}^O}{\tilde{w}^O + \tilde{w}^S + \tilde{w}^D}} \times \left(\tilde{R}_i^S\right)^{\frac{\tilde{w}^S}{\tilde{w}^O + \tilde{w}^S + \tilde{w}^D}} \times \left(\tilde{R}_i^D\right)^{\frac{\tilde{w}^D}{\tilde{w}^O + \tilde{w}^S + \tilde{w}^D}} \tag{7}$$

5. Ranking based FRPN value, where the value of the largest FRPN is a top ranking.

3. Results and Discussion
Results and discussion based on data that had been collected. This phase included risks identification, risks analysis, risks priority determination, and risks response plan.

3.1. Risks identification
Risks identification was conducted through interviews and discussions with experts from the port, risk management manager. The identification result showed the dock as the highest location in the port of occupational accidents. There were three categories of major appliances that were operated in the container loading and unloading process, i.e. ships, combine tractor terminals (CTT), and ship to shore (STS). Risks identification was based on the major appliances used at the port dock shown in Figure 1.

Figure 1. Appliances were operated in container dock: a) CTT, b) STS.

There were 19 risks of occupational accidents identified and then analyzed using FMEA. The identified risks also had been considered their hazardous events. R1 was failure mode for the ring of a flare was broken. R1 happened because there was hazardous event that the ring of flare had hated by a ship. Table 1 shows the results of identification of the risk of occupational accidents at container port dock. Risks at ships, CTT, and STS were showed by failure modes of R1-R7, R8-R12, and R13-R19, respectively.

Table 1. Risk Identification Result of Occupational Accidents at Dock

Code	Risk Event
R1	The ring of a flare was broken
R2	The ship's bridge lights were broken
R3	The port fender chain was broken when the ship had docked
R4	Gangway ship broken

Code	Risk Event
R5	Doors ship damaged (broken window)
R6	Lost objects or accessories of ships and docks
R7	The ship's railing collapsed
R8	CTT stopped functioning when were carrying loads (broken down)
R9	*Container Twist lock broken during loading and unloading process*
R10	CTT tires erupted when transporting cargo
R11	CTT tires leak / tear when transporting cargo
R12	Failure to drive the CTT during mobilization
R13	The container failed to be lifted during the loading and unloading process
R14	The STS gear box oil leaked
R15	The STS gearbox oil valve was open
R16	STS lights off
R17	Perforated container
R18	The referrer container cable broke when handling STS
R19	Shorted circuit of STS cable during loading and unloading process

3.2. Risks analysis

Identified risks were analyzed and evaluated for the effects, causes, and controls that have occurred and conducted by the port at this time. Every operation of the appliance used at the port dock had been known to contain the risk of occupational accidents that arose due to a cause and made a consequence, and controls had been performed to overcome the risk. R1 raised the danger when the ship leaned and beacon lights broken. This risk was due to a ring of lights being hit by a ship. The control or action had been done at this time was to prepare a scout ship to guide the ship in the process of anchoring.

Each risk that had been identified was evaluated and given a score for severity (S), occurrence (O), and detection (D). The assessments were in accordance with the evaluation criteria and ranking system in FMEA approach [26]. The result of an assessment of the risks of occupational accidents at container port docks is showed in Table 2.

R1 given a severity score of 6.5, moderate - high category, where the severity made the system to unable operate with minor damage. The occurrence score given on 3.5, low - moderate category, where the probability of failure was relatively slight or occasionally a failure. Whereas for detection factor, given a score on 3.5 that was included in the high - moderately high category where the ability of the controller to detect the cause of failure and the subsequent failure mode was very medium to high.
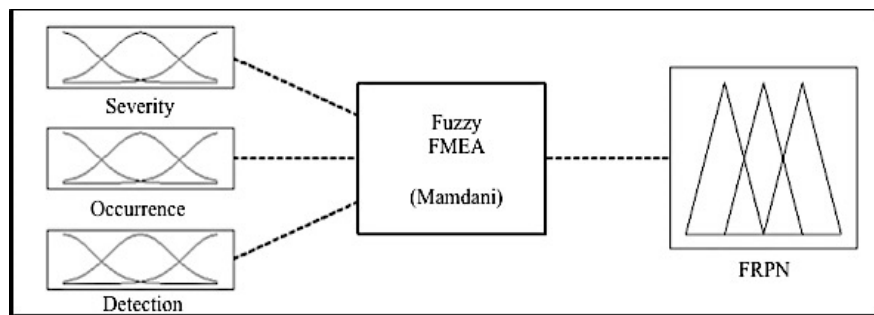
Table 2. Assessment of S, O, and D Variables at Dock

Code	Severity (S)	Occurrence (O)	Detection (D)
R1	6.5	3.5	3.5
R2	3	3.5	2
R3	8.5	5	7
R4	4.5	3.5	3.5
R5	5.5	4	3.5
R6	9	2.5	2
R7	4.5	7	4.5
R8	5	4	3.5
R9	8	4	4
R10	6	7.5	6
R11	6.5	7	6
R12	9	6	4.5
R13	8	7	5
R14	4	3.5	4.5
R15	4	3	3.5

Code	Severity (S)	Occurrence (O)	Detection (D)
R16	5	3.5	5.5
R17	8.5	4	4
R18	7	4	4.5
R19	10	3.5	5

3.3. Risks priority determination

Determination and modeling the risk priority number in this study used Fuzzy Risk Priority Number (FRPN) with MATLAB. The stages of fuzzy logic in this process were starting by determining the membership function for each input variables (S, O, and D), determining the membership function for the output variable (FRPN), and finally inputting rules in the output control. The model for fuzzy FMEA in this study is shown in Figure 2.
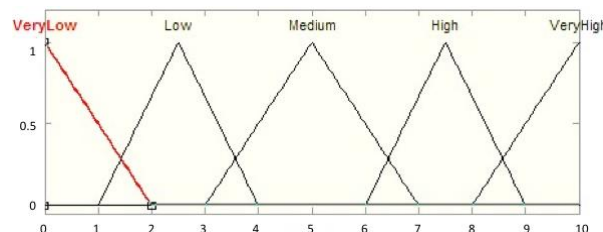

Figure 2. Fuzzy FMEA Model.

The membership function was used as the input variable with the fuzzification process. The membership function of the input variables used to draw graphics that was in accordance with the domain of fuzzy membership functions. Table 3 was the domain of input variables: S, O, and D. After it was known, the membership function described in graphical form. The graph of the membership function of each input variable can be seen in Figure 3.

Table 3. Fuzzy Input Variable Domain (S, O, and D)

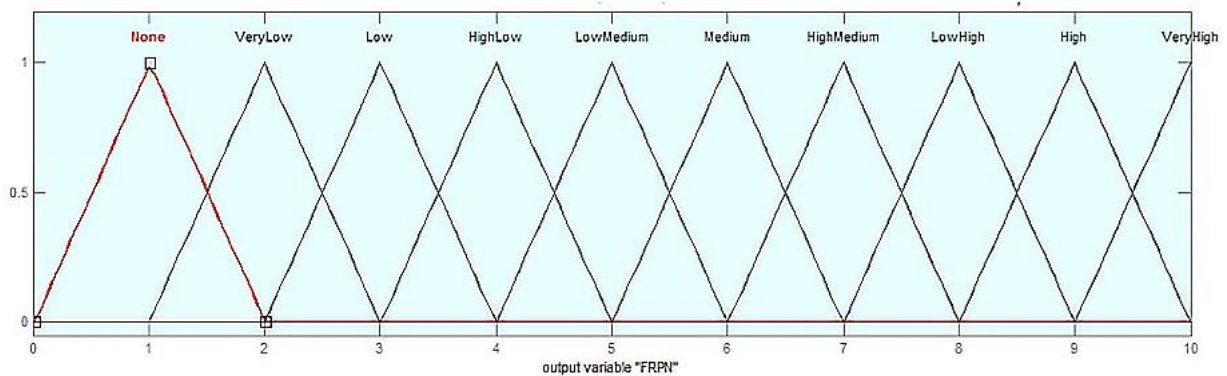| Fuzzy Set	Domain
Very Low	(0, 2)
Low	(1, 2.5, 4)
Medium	(3, 5, 7)
High	(6, 7.5, 9)
Very High	(8, 10)

Figure 3. Membership function for input variables: S, O, and D.

As input variables, output variables membership function was also used to describe the graph that corresponds to the fuzzy membership function domain. Table 4 was the domain of fuzzy output variable (FRPN). The domain of the output variable was then described in the form of a graph of the

membership function of the output variable. The graph of membership function for the output variable is shown in Figure 4.
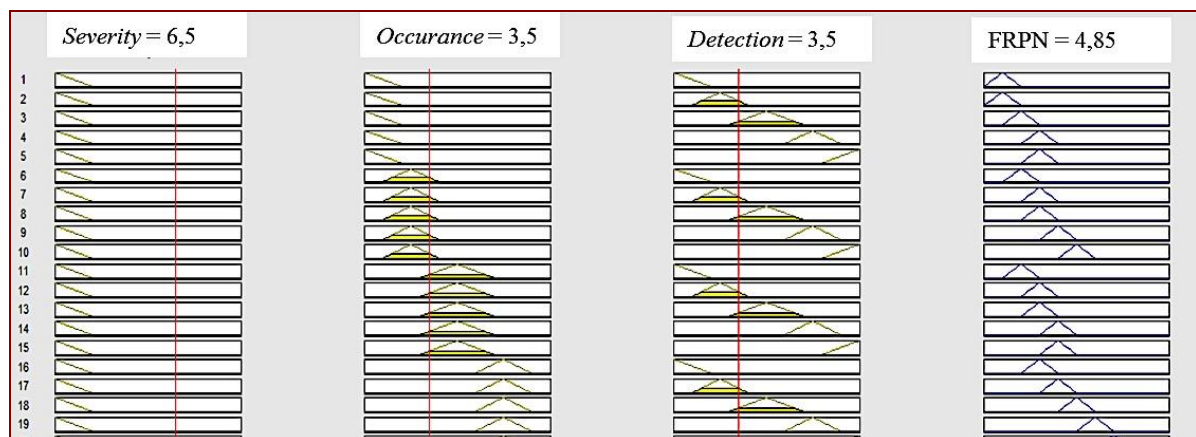
Table 4. Fuzzy Output Variable Domain (FRPN)

Fuzzy Set	Domain
None	(0, 1, 2)
Very Low	(1, 2, 3)
Low	(2, 3, 4)
High Low	(3, 4, 5)
Low Medium	(4, 5, 6)
Medium	(5, 6, 7)
High Medium	(6, 7, 8)
Low High	(7, 8, 9)
High	(8, 9, 10)
Very High	(9, 10)

Figure 4. Membership function for output variable: FRPN.

The next phase was to determine the rules where the three variables: S, O, and D, each had 5 categories of membership functions, so the comparison results could produce 5 x 5 x 5 = 125 rules. These rules were used in the min-max inference process in MATLAB. In R1, only 8 rules were used, because in the previous calculation for each input variable (S, O, and D) only had 2 possibilities. The scores of S, O, and D for each risk that had been obtained previously were entered in MATLAB. Figure 5 was an example of the MATLAB output result for R1.

Figure 5. MATLAB output result for R1.

After each risk had FRPN, then FRPN was sorted by the largest to the lowest score. The higher of FRPN score, the higher the priority of handling the risk. FRPN calculation results showed the risk with the highest priority was R13, the container failed to be lifted during the loading and unloading process, with a score of FRPN was 7 and was categorized as "high medium". On the contrary, the risk with the lowest priority was R2, the ship's bridge lights are broken, with a score of FRPN was 3.88 and was categorized as "low - high low". The priority of this risk could help the port to found out which risks needed more attention and handling. Table 5 is the result of each FRPN risk and sorted from highest to lowest.

Table 5. Fuzzy Risk Priority Number (FRPN) Results

Code	FRPN	Category
R13	7	High Medium
R5	6.43	Medium – High Medium
R8	6.43	Medium – High Medium
R11	6.12	Medium – High Medium
R3	6	Medium
R14	5.88	Low Medium - Medium
R16	5.88	Low Medium - Medium
R4	5.36	Low Medium - Medium
R7	5	Low Medium
R9	5	Low Medium
R10	5	Low Medium
R12	5	Low Medium
R17	5	Low Medium
R18	5	Low Medium
R1	4.85	High Low – Low Medium
R15	4.43	High Low – Low Medium
R19	4.43	High Low – Low Medium
R6	4	High Low
R2	3.88	Low – High Low

3.4. Risks response planning

Risk response planning or risk action planning was arranged based on the priority order of risk. The response chosen in this planning was risk mitigation, where this action was intended to the severity of risks negative impact, the possibility of risks occurrence, and the certain action to reduce risk [22]. Based on the results of the analysis, plans for handling the risk of occupational accidents on the dock were obtained. Table 6 is plan for handling the three highest risks. The risk that occupies the first priority is R13 with the score FRPN was 7, which included in the high medium level. Risk management plans required for the highest-priority risks because it had a significant impact on the port.

Table 6. Risk Response Planning

Code	Risk	Response Planning
R13	The container failed to lift during the loading and unloading process	Make efforts to reduce the cause of risk and increase the motivation of workers to minimize human error.
R5	Doors ship damaged (broken window)	Make improvements by doing coordination with STS and crane operator. The company also can make requirement the appropriate type of ship according to company standards and make it more safe and sound in the process of loading and unloading.

Code	Risk	Response Planning
R8	CTT stops functioning when carrying loads (breaking down)	Repairs on damaged CTT machines and regular maintenance of CTT. In addition, early detection if there is an engine failure, so it does not jam when operating.

The cause of the risk of container fails raised during the loading and unloading process was that the STS operator did not replace the twin lift mode when carrying out double handling in a 20ft container. This was due to the human error, i.e. the operator forgets to change the mode. Therefore, risk improvement recommendations aimed at preventing the operator negligence in doing the job.

In the planning stage of risk management, it was recommended to make efforts to reduce the causes of risk, human error, as well as made efforts to increase the motivation of workers to avoid the human error. Technical recommendations as handling measures for priority risk were routine briefings at the beginning and end of work shifts, the daily report form, safety signs, regular training, and reward systems as work motivation.

Briefing was briefed by the shift manager who is usually given to employees at the beginning and end of the shift. The briefing at the beginning of the work shift aimed to discuss the work plan and targets to be achieved, while the briefing at the end of the work shift aimed to evaluate the work and achievement of the targets that had been made. Each briefing should also be provided with an official report form as documentation and a daily journal that can be used as an activity control.

The lack of information in the STS operating area made operators often forget to change the lift mode, especially when the operator was on the job training. Safety sign was used to provide information and remind operators not to forget to change the lifting mode in the container.

Training was conducted regularly, not only when at the beginning of the recruitment, but every 3-5 years, so the operator fully understood the operating procedures of the appliances. In addition to improving operator skills and skills in the operation of STS, training also conveyed occupational health and safety (OHSA) to broaden the knowledge and insights of workers regarding OHSA on their work.

The implementation of the reward system as work motivation was the last recommended risk action plan. Many reasons could cause human error, one of which was bad motivation [6]. By implementing a reward system every year, it would provide challenges for every worker to always do his best, increase work motivation, apply a work culture that supports each other, and motivates each other both vertically and horizontally to reduce the existence of human error done by workers.

With risk management planning, it was expected to minimize the level of risk that had a negative and detrimental impact, so the port's vision and mission as green port could be implemented as well. These response plans should be conducted and monitored by managerial and all related elements to carry out continuous improvement at the port.

4. Summary

At the risk identification stage, there were 19 risks of occupational accidents in the green port, especially in the container dock. The results of data analysis performed by one of the quantitative risk approaches, fuzzy FMEA, obtained the priority of occupational accident with the highest risk was containers failed to be lifted during the loading and unloading process, while the lowest risk was the bridge lights were broken. The risk mitigation plan for the highest risk was by conducting regular briefings at the beginning and end of the operator's work shift, as well as making an official report form. In addition, the safety signs were intended for operators to increase their awareness, so the changeover of the twin lift mode while performing double handling will not be forgotten. Regular training and implementation of reward systems were also recommended as operator motivation.

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