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Application of Failure Mode Effect and Critical Analysis for Risk Management: A Case of Road-rail Transport at the Thai-Lao PDR Cross Border

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Abstract: Globalization is the process of increased interconnectedness among countries, resulting in the growth of international trade, investment, and cultural exchange. Transport and Logistics are important for economic growth and development, allowing industries to enter potential customers, reduce costs, and enhance efficiency. The cross-border trade requires good transportation and logistics systems to move products and services across borders through road, rail, air, and water transport. As the railway is an environmentally friendly and sustainable mode of transport, but cannot provide transportation service alone without other modes of transport, this study focuses on risk management in road-rail freight transport. The objectives of the study are to identify risks with respect to road-rail freight transport at the cross border between Thailand and Laos PDR and to provide a guideline for risk management for the case study. The risks were prioritized based on the Failure Mode Effects and Criticality Analysis (FMECA) concept. Findings from this research present that the technology risk, the equipment and operations risk, and the organization and personal risk are among the top priorities in need of risk management. Lastly, this research suggests proper risk mitigation guidelines to manage those risks.

Keywords: Risk Management; Risk Assessment; Road-Rail Transport; Failure Mode and Effects Analysis (FMEA); Failure Mode Effects and Criticality Analysis (FMECA)

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1. Introduction

No one can discard the fact that rail transportation for freight service is the cheapest mode, especially for international freight transport and it is another option to diversify transportation risks. Comparing the transportation costs between the four routes from China to Thailand, it was found that the estimated transportation costs via train is much cheaper than the truck-only transport [1]. Therefore, many countries have issued their national policy to support the shift to rail in order to reduce the transport cost. In addition, rail transport is the most eco-friendly mode among the land transports and good for sustainability.

However, despite the benefit of the rail transport, the operations of international rail freight transport are challenging. Challenging for international rail includes the infrastructure, the missing link, the international cooperation, and the technical problems. Cross-border trains are complicated due to different gauges and interoperability of signaling and electrification systems between neighboring countries. The challenges for rail freight include economy, intermodal, modal shift, consolidation, the last mile, liberalization, access charge, and capacity [2]. According to the fact that rail freight transport cannot run alone, the other mode of transportation like road is needed to complete the service from the suppliers to the customers. Hence, it is interesting to explore the challenges and the associated risks with respect to the road-rail freight transport. As the Bilateral Agreement between Thailand and Lao PDR on 'Joint Traffic Working Over Railway' had been signed several years ago and the Thailand-Laos cross border in Nong Khai province is in operations, this research chose this cross border as the case study. The research questions are:

RQ1: What are the risks related to road-rail freight transport?

RQ2: How to manage the risks?

Multimodal transportation refers to logistics transport and freight processes that require two or more modes of transport including road, air, marine and railway transport. These days, multimodal transport is the dominant mode for the global supply chain and logistics. It requires the coordination of multiple modes of transport. In this study, the focus is only on the road-rail transportation which is a kind of multimodal transportation. The road-rail process for cargo transport of the case study is illustrated in Fig. 1.

From Fig.1, the process shows a combination of Road-Rail transport starting from the containers were shipped by truck to freight station in Thailand, then the unloading and loading process was performed, the containers were shipped by train to the borders and cross the borders to Lao PDR and unloaded at the terminal station before being shipped by truck to the destinations. However, the

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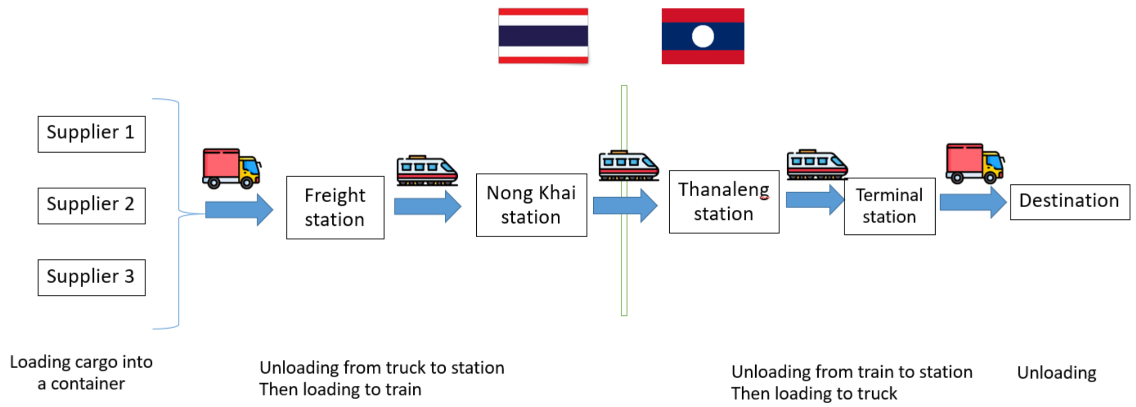

Fig. 1 The road-rail cargo transport process of the case study

container transport may face a number of uncertainties during the process and may result in the delay of shipments.

The case study at Nong Khai station was used as a case for identifying failure modes with respect to Road-Rail transportation for freight From observation during preliminary study, during the process of cargo shipment by truck to freight station, sometimes problems occur due to insufficient number of trucks, rise of energy cost, delay from road accidents, etc. For the loading cargo process at the station, problems related to technology, equipment, labor staff, container/packaging, and storage of hazard materials may be found. For railway transport, the failures are from the technology for handling cargoes and the delay in transport. The problems for unloading process are similar to the loading process. Lastly, the last-mile connection to the customers may concern transport risk.

Therefore, the objective of this study is to identify risks in the road-rail transportation at the cross border between Thailand and Laos PDR as a case study and to suggest the guidelines to manage the risks.

2. Risk management and Risk factors related to international rail freight

Risk management is a set of activities within an organization undertaken to carry the most positive outcome and decrease the volatility of that outcome. Wei [3] studied the risk and found that technology, equipment, operations, environment, and transport risks are the major concern for multimodal transport. In 2013, safety, technology, transport, and time are the most important risks for transportation in Chiang Rai and Kunming [4]. These risks were confirmed later in 2020 for the import-export logistics of agricultural products from Thailand to China [5].

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Another research, Reis et.al. [6] concluded that operation, environment, and personnel are the key issues for multimodal transport. Later in 2019, Liebchen and Schülldorf [7] confirmed that the operation, personal, organization, and business strategy are among the important risks for railway transportation. In 2014, Shi and Zhou [8] has conducted research with respect to railway freight transport market. The authors conducted a study to analyze the factors influencing market share of the railway and found the means to increase competitiveness of the rail freight comparing to other modes of transport. The results of the study provided an avenue to increase the railway freight transport services and the market share.

Therefore, from the review of literature, it can be concluded that the initial risks associated to multimodal transportation include technology, equipment, operations, environment, transport, safety, time, personal, organization, and business strategy.

The concept of risk management can be applied in the Road-Rail freight transport as it is a way to assess the specific risks and suggest strategies to deal with those risks. The risk management process starts from Risk identification, Risk mapping, Risk analysis, and Risk treatment. it is challenging for any freight transportation service to ship their cargoes to the destination safely, efficiently and on time due to uncertainty in the shipment process. Hence, this study applied the risk management concept to identify risks, map the risks, analyze the risk and suggest mitigation strategies.

The failure mode and effects analysis (FMEA) is a method of analysis that identifies failure modes. An extension of failure mode and effects analysis (FMEA) by including a criticality analysis which quantifies the level of risks associated with failure modes against the severity is called the failure mode effects, and criticality analysis (FMECA). The critical analysis might be based on the failure mode probability. The result can be summed up to quantitative data which is able to measure and then it can be improved. The benefits of FMECA are increase quality and reliability during the development, reduce wastes in the operations, and minimize cost. The risk evaluation of each failure is determined by three factors namely severity, occurrence, detection. Severity (S) is failure consequences. Occurrence (O) is the failure probability. Detection (D) is the failure probability which can be found before a bad result happens. The risk priority number, called RPN, will be determined by occurrence x severity x detection. Occurrence (O) came from data driven, but severity (S) and detection (D) was by expert driven. Firstly, the highest RPNs should be managed and then all failure modes should continuously improve till result will be at an acceptable level. Certainly, the aim is process and product problem prevention before they

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happen. Company, which used FMEA in both the design and manufacturing process, can decrease cost and become more robust process due to the reduced or eliminated crises. On the other hand, if they focused on wrong failure modes that become the biggest problem and opportunities missing to improve the failure modes [11].

In 2021, Filz, et.al. applied FMEA with data-driven tools such as deep learning models using data from the usage of industrial investment goods. This method deepens learning models on historical and operational data [12]. In 2022, FMEA also applied when designing a bicycle brake cable [13].

In 2022, Sakly, et.al. applied FMECA for the pharmaceutical process for medicines which sensitive to temperature at a hospital and the results were interesting [14]. Two rounds of FMECA were performed. The first round showed the prioritized areas for further improvement including the documentation, human resource development, and procurement. For continuous improvement process, a second FMECA had been done to detect other remaining risks and identify new potential risks.

3. Research Methodology

The steps of research methodology are shown in Fig. 2.

3.1 Step 1: Risk identification

The first step includes identification of risks associated to multimodal transportation from literature review followed by expert opinion to narrow down the risks to specific to road-rail transportation. Three experts who have experience in multimodal transportation were asked to give inputs. The experts are the persons who have at least three year experience with relevant to the Road or Rail freight transport which include a professor in logistics services, a specialist in multimodal transport, and a specialist in railway services. This study used the convenience sampling method to select participants based on their accessibility and availability to the researcher during the study period.

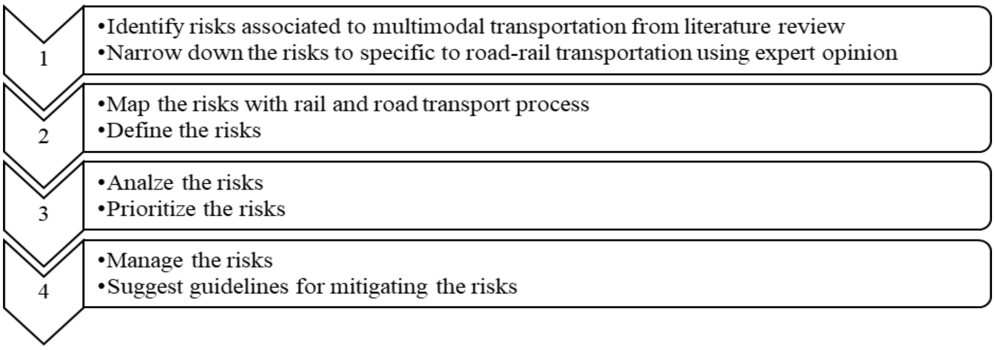

Fig. 2 Steps of Research methodology

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3.2 Step 2: Risk mapping

This step includes mapping of the risks with road and rail transport processes and defining the risks. The disruption of multimodal transport and the risks associated with each process are identified and mapped. Then the risks are defined properly.

3.3 Step 3: Risk analysis

This step starts from analyzing the risks. Then the risks are prioritized based on failure mode effects and criticality analysis (FMECA) concept. For the FMECA, a criticality analysis which quantifies the level of risks associated with failure modes against the severity of their consequences is added to the common FMEA.

The FMECA contains two main activities: 1) to create the FMEA and 2) to perform the criticality analysis. At the beginning, the FMEA explores the likelihood of product failures or not function properly, shorten product life cycle, and detection of unsafety process. Then the criticality analysis is based on failure mode probability, which can be summed up to quantitative data [10]. The analysis consists of four levels: catastrophe, critical, marginal, and negligible, respectively. The severity and the probability matrix for risk assessment is shown in Table 1.

From Table 1, FMECA analyzes risk, which is measured by the combination of severity and probability to determine criticality in order to provide a priority way to reduce the possibility of failure.

‘Catastrophic’ refers to the extremely severe risk which could cause death or permanent total disability. In term of financial amount, it refers to the loss of more than $1 million. It also causes irreversible severe environmental damage and illegal matters.

‘Critical’ refers to the high risk that cause injuries or permanent partial disability and 3 or more persons got admitted to hospital. In term of financial amount, it refers to loss of more than $200,000 but less than $1 million. It also causes environmental damage and illegal matters.

‘Marginal’ refers to the risk that results in minor injuries which requires at least 1 day leave from work. In term of financial amount, it refers to the loss between $10,000 and $200,000. It also causes some environmental damage without violation of law.

Table 1 A risk assessment matrix adapted from MIL-STD-882E [9]

Severity / Probability		Catastrophic 1	Critical 2	Marginal 3	Negligible 4
Frequent	A	High	High	Serious	Medium
Probable	B	High	High	Serious	Medium
Occasional	C	High	Serious	Medium	Low
Remote	D	Serious	Medium	Medium	Low
Improbable	E	Medium	Medium	Medium	Low
Eliminated	F	Eliminated			

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'Negligible' refers to the minor risk that results in minor injuries which do not require any leave from work. In term of financial amount, it refers to the loss between $2,000 and $10,000. It may also causes a little environmental damage [15].

The questionnaires were distributed to two main groups of stakeholders: one is the customers, and the other is the transport providers. The customers are the persons who have products to be transported using Road-Rail transport and the providers include the staff of the State Railway of Thailand and the logistic service providers. In total, six respondents answered the survey with three participants from each group.

The survey consists of two parts. The first part is the information on personal characteristics of the respondents and the second part includes their opinions on the Occurrence (O), Severity (S), and Detection (D) of each risk. Occurrence (O) refers to the probability of failure or problem occurrence; Severity (S) refers to the degree of impact and consequences of failures; and Detection (D) is the probability of the failure being detected before the impact of the failure to the system. The Likert scale of 1-5 which 1 refer to the lowest score and 5 is the highest score is used in this study. Then the risk priority number based on the FMEA is calculated by multiplying O by S by D. Then the criticality analysis was applied further by asking experts' opinions.

3.4 Step 4: Risk management

This step includes suggestions on how to manage the risks and a guideline for mitigating the risks for improving road-rail transportation.

4. Findings

After completing the research Steps 1-4, the results are as follows.

4.1 The risk factors

The risk factors for Road-Rail transportation identified from literature review were considered and selected by experts for the cross border risks. In total, six risk factors including Transport risk, Technology risk, Equipment and operations risk, Organization and personal risk, Packaging hazard risk, and Storage hazard risk were identified. Then the risks were mapped with the process flow of the Road-Rail transportation starting from transport by truck, loading at freight station, transport by railway, unloading at terminal station, and lastly transport by truck to the customers. The result of the failure mode and process mapping is shown in Table 2. Then the relevant risks were defined as shown in Table 3.

4.2 The application of FMECA

The application of FMECA helps to prioritize the risks based on failure mode effects and criticality analysis (FMECA) concept. The initial finding shows FMEA result in Tables 4 and 5. Customers think the FM2: Technology risk is the most

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important risk followed by FM1: Transport risk and FM6: Storage hazard risk.

Providers have the same idea that FM2: Technology risk is the most important risk, but they think FM5 Packaging hazard risk and FM3 Equipment and operations risk are also important.

Referring to Table 1, FM3 Equipment and operations risk got the '2' in term of severity and 'C' in term of probability. FM4 Organization and personal risk got the '2' in term of severity and 'C' in term of probability. Therefore, FM3 and FM4 were considered as 'serious' risks. The other like FM1 Transport risk got the '3' in term of severity and 'C' in term of probability, hence it is classified as 'medium' risk. For other factors, the results are also 'medium' that shown in Table 6.

4.3 The findings from this research

The findings from this research show that from both the customer's and provider's views, the FM2: Technology risk is the top priority in need for risk management. Road-Rail transportation involves the cargo handling equipment and the technology helps to make efficient handling and shipment. In addition, traceability is important and a good cargo tracking system is in need. The Artificial Intelligence and cloud-based freight management systems will also help smooth operations for Road-Rail transportation.

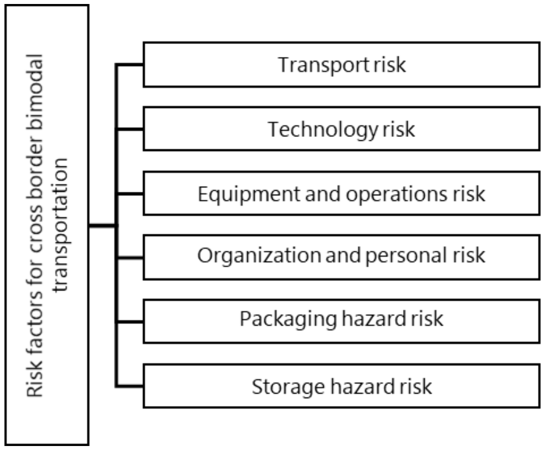

Fig. 3 Risk factors for cross border transportation

Lastly, due to the issue of international connectivity at the cross borders, the challenge is in the technical specifications for managing the difference in the gauging system.

For customers, they are aware of their cargoes whether or not they will be delivered as planned without any disruption or delay. The FM1: Transport risk is the second concern for them. Also, the quality of the merchandise inside the containers is important. Some goods like fresh agricultural products, seafood and pharmaceuticals need special temperature-controlled containers in order to keep the quality of the products. Hence, the FM6: Storage hazard risk with relevant to the cold storage is also significant for them.

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Table 2 Failure mode (FM) identified in this study

No.	Process	Failure mode
1	Cargoes are transited to freight station by truck	• Transport risk
2	Cargoes are loaded in the freight station	• Technology risk • Equipment and operations risk • Organization and personal risk • Packaging hazard risk • Storage hazard risk
3	Cargoes are transported by railway	• Technology risk • Transport risk
4	Cargoes are unloaded in terminal station	• Technology risk • Equipment and operations risk • Organization and personal risk • Packaging hazard risk • Storage hazard risk
5	Cargoes are transported to destination	• Transport risk

Table 3 Definition of risk factors

Failure mode	Risk factor	Definition
FM1	Transport risk	Risk related to transportation capacity, cost, and delivery of the cargoes as well as the transport mode change.
FM2	Technology risk	Risk related to technology failure to disrupt a business due to cyber-attack, service outages, old equipment, and others.
FM3	Equipment and operations risk	Risk related to availability and efficiency of equipment and operations.
FM4	Organization and personal risk	Risk related to organization culture and staff performance.
FM5	Packaging hazard risk	Risk related to the packaging of goods.
FM6	Storage hazard risk	Risk related to the storage of goods, especially the one requiring special storage facilities and management

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From Table 4, for the customers of fright transport service, the average RPNs are calculated for each failure mode. For customers, they are aware of their cargoes whether or not they will be delivered as planned without any disruption or delay. The FM2: Technology risk is their priority. The FM1: Transport risk is the second concern for them. Also, the quality of the merchandise inside the containers is important. Some goods like fresh agricultural products, seafood and pharmaceuticals need special temperature- controlled containers in order to keep the quality of the products. Hence, the FM6: Storage hazard risk with relevant to the cold storage is also significant for them.

From Table 5, for freight transport providers, the average RPNs for each failure mode is calculated. For freight providers, the FM2: Technology risk is shown to be the priority. The FM5: Packaging hazard risk is the second concern. In order to win the customers' mind, their service must be professional, and the quality of the shipment must be in the high priority. They have to be aware of the fragile goods and handle the goods with special care during the shipment. Hence, the packaging is of their concern. In addition, the modern equipment and the efficient operation process are essential for the service at the cross border. It confirms the importance of FM3: Equipment and operations risk.

Table 4 Risk priority numbers from Customer's perspective.

Failure mode	Customer's perspective			
	Avg. S	Avg. D	Avg. O	RPN
FM1	3.00	3.67	3.00	**33.03**
FM2	2.67	4.33	3.00	**34.68**
FM3	2.67	3.67	3.00	**29.40**
FM4	3.00	3.33	3.00	**29.97**
FM5	3.00	3.67	2.67	**29.40**
FM6	3.67	3.33	2.67	**32.63**

Table 5 Risk priority numbers from Provider's perspective

Failure mode	Provider's perspective			
	Avg. S	Avg. D	Avg. O	RPN
FM1	3.00	3.67	2.00	**22.02**
FM2	2.67	4.67	3.33	**41.52**
FM3	2.67	3.33	3.67	**32.63**
FM4	3.00	3.00	3.00	**27.00**
FM5	3.00	4.33	2.67	**34.68**
FM6	3.67	3.67	2.33	**31.38**

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After the FMEA, the Criticality Analysis was performed and the result is shown in Table 6. The table illustrates that for the risks related to the cross border freight transportation, FM3: Equipment and operations risk and FM4: Organization and personal risk are in the 'serious' zone while the others are in the 'medium' zone.

Table 6 Criticality analysis

Failure mode	Risk factor	Criticality analysis
FM1	Transport risk	medium
FM2	Technology risk	medium
FM3	Equipment and operations risk	serious
FM4	Organization and personal risk	serious
FM5	Packaging hazard risk	medium
FM6	Storage hazard risk	medium

5. Risk management

Guidelines for risk management is based on the concept of Treat, Transfer, Take and Terminate (4T) and made by experts. The concept of 4T is the key components for effective risk management.

Treat: To manage the impact and possibility of the risk or reduce the risk by several measures including adding precautions, initiating contingency plans, diversifying resources, or training staff.

Transfer: To transfer risk by moving the risk to another person through insurance policies, contracts, or outsourcing agreements.

Take: To take risk by accepting the possible impact which is relatively minimal, but still monitoring the risk.

Terminate: To eliminate risk by the removal of the activity, task, or process which may cause risk.

Organizations or Industries wish for risk management should follow the 4T concept of risk management including tolerate, terminate, treat, and transfer. However, these risk management tactics are not mutually exclusive. It is a guideline and the actual implementation requires a combination of strategies depending the risk. To manage the risk effectively, involved stakeholders should be aware of the risks, evaluate the risks and choose the suitable mitigation alternatives to manage the risk.

5.1 Technology risk

The failure effect from technology risk is the mal-function and inefficiency. The suggested risk mitigation strategies are as follows.

a. Treat: Treating or controlling risk can be done by reducing the likelihood of the risk occurring or minimizing its impact. The update and implementation of new technology is necessary as well as the proper and continue maintenance of the system. The availability of the equipment and technology should be monitored.

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Once the failure occurs, the malfunction or errors must be treated immediately.

b. Transfer: Allocating or transferring risk can be performed by purchasing insurance policies, or hiring third parties to do the tasks and take the risk instead of the organization. The risk can be transferred to the consulting companies who own the technology and offer maintenance service.

c. Take: Admitting or taking risk means do nothing to mitigate the risk. If it happens, let it be. Advanced technology is costly and needs a big capital investment. Sometimes, the operators need to accept the failure and do corrections afterwards.

d. Terminate: Stopping or terminating risk can be another measure to ensure the discontinuing of the processes and activities that create risks. In case the technology risk has a severe impact on the organization, it may be the time to terminate such technology and implement the new one.

5.2 Equipment and operations risk

The equipment and operations risk may affect the quality of the products in the containers. The risk mitigation is suggested as follows.

a. Treat: The availability and quality of the equipment should be checked regularly. The equipment should be standardized in order to avoid mistakes. The operations process should also be reviewed and improved. Once a failure occurs, immediate corrective action is needed.

b. Transfer: The risk can be transferred to the suppliers of the equipment, and they must guarantee the quality and offer corrective action.

c. Take: Sometime the operator needs to take risk of the failure and solve the problems.

d. Terminate: Some equipment is too old and should be terminated and replaced with new ones in order to provide good and continue operations.

5.3 Organization and personal risk

The organization and personal risk may affect the efficiency of the entire process. The risk mitigation is suggested as follows.

a. Treat: As Road-Rail transportation involves different organizations and people with different backgrounds, the risk of failure in terms of organization and human resources should be treated with care and confidentiality. This action may include fair treatment for all employees and the appropriate income and fringe benefits.

b. Transfer: The risk can be transferred to the experts by outsourcing. Also, the system for inspection and the quality-concern organization culture may help to re-duce human error.

c. Take: The risk from human error may happen. The service providers may take risks and prepare for action as soon as possible. Put the right man in the right job may help.

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d. Terminate: In case the above effort to mitigate the risk is not possible, the termination of the staff who is responsible on the malfunction may be a good option.

6. Conclusion

For Road-Rail transportation, using road transport for short distance and rail service for long distance is often more efficient than other modes of transport. Trucks are essential for the last mile of local pickups and deliveries. Rail terminals with technical equipment of the transshipment systems to transfer loading units between two modes of transport is needed. This research has explored the challenges of Road-Rail transportation and suggests avenues for development.

Findings from this research give answers to the research questions. The answer for RQ1: What are the risks related to Road-Rail freight transport? is the six risks including Transport risk, Technology risk, Equipment and operations risk, Organization and personal risk, Packaging hazard risk and Storage hazard risk. Then the priority has been analyzed using the FMECA method.

The answer for RQ2: How to manage the risks? is focused on the priority risks which are Technology risk, Equipment and operations risk, and Organization and personal risk. The 4T measures are suggested for mitigating the risks. Overall, efficient transportation and logistics operations using proper technology and equipment which provides quality, safety and reliability service are the major concern for decision making. Standardization should be implemented. Organizational culture and human resource development must be in place. Lastly, the risks causing the delay in transportation and the damage of the cargoes and products must be managed properly.

The contribution of this study is the application of FMECA in assessing the risks of Road-Rail Transportation for Freight service. The risks, which are identified ‘severe’, will be of concern as priority to find recommendations to mitigate the risks. The FMECA has some advantages as it begins with FMEA and follows by the critically analysis. FMEA considers only qualitative information while FMECA considers both qualitative and quantitative information. In addition, FMECA measures criticality level for the failure modes and classify them based on the importance. The criticality level is the combination of severity and probability and contains Catastrophic’, ‘Critical’, ‘Marginal’, and ‘Negligible’ levels.

The result from this research provides a guideline for Road-Rail Transport improvement using the FMECA approach to identify the risk priority and risk management approach to mitigate the risks. Among all risks, the Technology risk, Equipment and operations risk, and Organization and personal risk are priorities.

วารสารวิชาการเทคโนโลยีอุตสาหกรรม (The Journal of Industrial Technology)
ISSN (online): 2697-5548
DOI: 10.14416/j.ind.tech.2024.08.007

The technology risk involves the information flow of the freights from the suppliers along the way to the customers and the technology used for cargo handlings to load and unload at stations. It is suggested that the implementation of new technology should be in the plan in order to treat the risk. For Equipment and operations risk which may cause delay in transportation or affect the quality of the products in the containers, it is suggested that the risk should be transferred to the suppliers or the insurance companies. For the Organization and personal risk, it may affect the entire Road-Rail transportation process as it involves several stakeholders and the staff is an important factor for operations. In this case, the take strategy is suggested as miscommunications and human errors may be difficult to prevent and may probably does not cause major disruptions.

This research is limited to the study of the customers and providers at the cross border in Nong Khai province only. Exploration of the same methodology at stakeholders at other cross borders may result in different perspectives. Other international cross border comparisons are recommended for future research as the national context will be considered. Finally, other risk management tools and strategies can also be implemented to provide different results and improvement plan.

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