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Systematic Risk Analysis of Railway Component Quality: Integration of Failure Mode & Effect Analysis (FMEA) and Fault Tree Analysis (FTA)

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ABSTRACT

Quality assurance is a critical aspect in the production systems, affecting product quality and safety. Defects and failures of manufactured components will diminish overall product quality, which could vulnerably risk consumer safety. This study focuses on quality assurance analysis of train component manufacturing systems. According to the quality control data, the number of defects recorded was about 10-12, on average, for each wagon produced. The defect mainly occurred while making the underframes, car body, and even the small components. This led to the tardiness of product delivery for 1-2 months. This study aims to analyze non-conformance report data and identify the potential failure modes, potential effects, and root causes. To do so, we integrated systematically FMEA (Failure Mode and Effect Analysis) and FTA (Fault Tree Analysis). First, RPN (Risk Priority Number) score was calculated to determine risk priority. Second, Pareto analysis was performed to select defects that most contributing to overall failures, which were then analyzed using FTA to obtain root causes. The results show that 8 defects exceed the critical RPN score of 209. Materials and personnel are identified as two major contributor failure events from three selected defects. The recommendation for further improvements is provided based on various defect categories to prevent similar defects. The findings demonstrate that the combined use of FMEA and FTA is effective in identifying failures and root causes within complex and long production cycle systems.

1. Introduction

Manufacturing comprises of multiple complex processes to produce decent quality of products. The underpinning factors significantly affecting the manufacturing process are reliability and quality control for yielding products with specific standards (Sharma & Srivastava, 2019). Products with decent standards and high quality would possibly increase the customer satisfaction and trust (Hanum, 2022). However, maintaining product quality to meet the standards is somehow arduous tasks for many manufacturing companies. The increasing number of rejected products due to defects or any production error leads to inefficient production process (Rochmoeljati & Nugraha, 2023).

Notwithstanding the company can perform rework to repair defective products, the impact of defective products is detrimental because it requires additional time and costs (Nurwulan & Veronica, 2020; Renosori et al., 2023). Rework process tend to increase waste and loss of the production (Safira & Damayanti, 2022). Moreover, defective products may reduce the service level and cause production delay, significantly undermining customer satisfaction and the company's reputation (Dinmohammadi et al., 2016; Safira & Damayanti, 2022; Signoret, et al. 2021). Renosori et al. (2023) stated that defective products should not be allowed to escape the quality control section because they can harm customers. In addition, due to defective products, the company loses time and production costs (Fibriani et al., 2023). On the other hand, when customers receive good products, they are satisfied and reuse the product. This customer satisfaction will certainly affect the company's reputation (Ridwan et al., 2023).

Additional attention must be given to the manufacturer producing consumer products (e.g. foods, beverages, drugs). Any defective products delivered to end customers will vulnerably increase the risk towards consumers' health and safety. On the other hand, manufacturers producing passenger vehicles (e.g. car, train, plane) suffered severe critiques as a consequence of low-quality products. For example, serious plane incident problems are currently faced by Boeing (Denning, 2013; Herkert et al., 2020) or recall made by car producers due to mechanical or safety issue (Chi et al., 2020). Undeniably, many companies struggle to achieve decent product quality consistently and some even did not aware of this problem, neglecting engineering ethics (Haekal, 2022; Herkert et al., 2020). More customer demand for high quality product and better service level. Once the company delivery underrated product, several issues will raise. Company's competitiveness level is also driven by product quality (Burhanuddin & Sutopo, 2022). Inevitably, improving quality control is necessary for maintaining the standard of production, increasing efficiency and productivity, and diminishing potential issues due to poor product quality (Fitriana et al., 2023; Herkert et al., 2020; Zulfikar et al., 2021).

Several studies have been conducted to investigate product defects and production failures. Ridwan et al. (2023) used the Six Sigma method to analyze defective products in manufacturing companies. An extension of so-called Lean Six Sigma is also common to maintain quality and optimize the production process (Fibriani et al., 2023; Imansuri et al., 2024). Meanwhile, Chen et al. (2017) proposed Bayesian Network for reliability analysis on high-speed trains and failure detection on a sub-system of a high-power solid-state laser. However, such methods often require substantial data, time-intensive processes, and complex interpretation, which is impractical for large-scale manufacturing companies (Shafiee et al., 2019). Other well-known methods for failures identification include FMEA and FTA. Both methods, often used in conjunction, have been implemented across various industries, including electronics (Renosori et al., 2023), automotive (Chi et al., 2020; Dinmohammadi et al., 2016; Haekal, 2022), textile (Burhanuddin & Sutopo, 2022; Fithri et al., 2020; Safira & Damayanti, 2022; Zulfikar et al., 2021), glassware and ceramics (Rachman et al., 2016; Syahtaria et al., 2018), and other types of industries (e.g. metal, rubber, timber, and paper mill) (Hidayat et al., 2018; Nurwulan & Veronica, 2020; Prasmana et al., 2023; Rochmoeljati & Nugraha, 2023). The objective of most studies can be classified in terms of elimination of failures (Fithri et al., 2020; Hidayat et al., 2018; Wardana, 2019), reducing defective products (Nurwulan & Veronica, 2020; Renosori et al., 2023; Rochmoeljati & Nugraha, 2023; Syahtaria et al., 2018), increasing quality control, reliability and productivity (Burhanuddin & Sutopo, 2022; Fitriana et al., 2023; Rahmawati & Maharani, 2023; Safira & Damayanti, 2022; Sharma & Srivastava, 2019; Zulfikar et al., 2021).

Although many studies suggest the applicability of FMEA and FTA in various industries, yet its application in the train manufacturing industry. Compared with other industries, train manufacturing has different characteristics owing to its longer production and inspection cycles. Moreover, the complexity of assembly processes, customization, and compliance with high standards may increase the challenges associated with quality control. The company used as a case study encounters problems concerning production failures, leading to delivery delays of up to two months. The failures occurred during the production of carriages or wagons, leaving 10 – 12 defects in each production. The failures include missing of bolt components, damaged panels, and leaking roofs and frames, which potentially induce lowering product quality or even increase risk safety. Accordingly, this study aims to address the problem with the application of FMEA and FTA by identifying potential causes of failures that occur in the train production processes. The findings of this study can serve as a basis for further inspection procedures or quality control improvements.

2. Method

This study employed hybrid methods of FMEA and FTA to analyze manufacturing defects in the train wagon production line. FMEA method is a systematic tool for identifying potential causes of failure and able to produce risk priority numbers for further identification (Hidayat et al., 2018). Although FMEA requires time and efforts from experts, this method is relatively straightforward, enabling intuitive interpretation of results (Min & Jang, 2021). Meanwhile, FTA enables to characterize the root cause of failures using tree structure, enabling in depth analysis. The application of both methods has been reported to be complementary and effective (Renosori et al., 2023; Shafiee et al., 2019). Fig. 1 shows the research flows performed in this study.

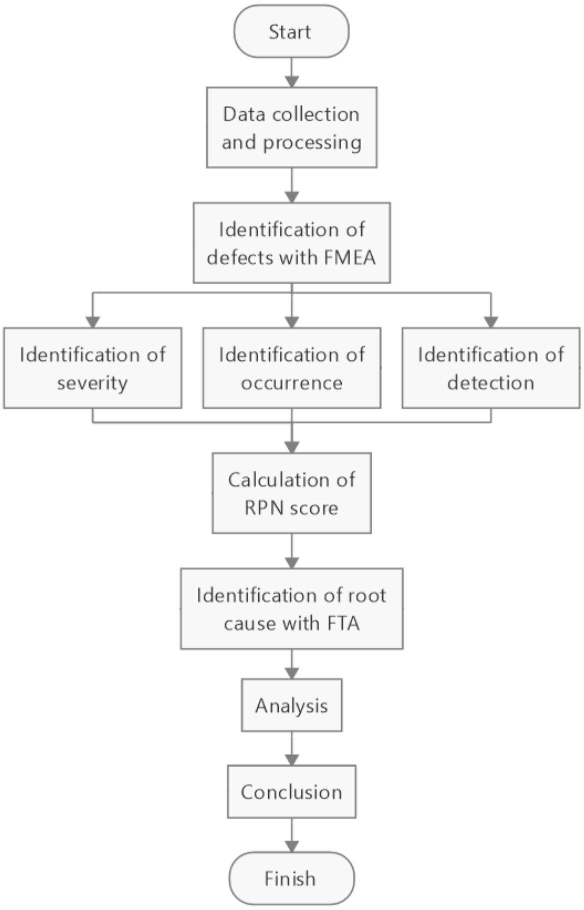

Fig. 1. Research flow diagram

3. Data Collection and Processing

The primary data was obtained through interviews and onsite observation of train production process. The interviews were conducted with the manager of POPJ (Operational Procurement and Service Provision) and employees of the railway car production process. The secondary data was obtained from the historical record of defects in the form of non-conformance report (NCR) during the period from January 2022 to March 2023.

4. Identification of Defects with FMEA

Failure Mode and Effect Analysis (FMEA) method is a method used to determine failures of operational process in the production system, aiming to achieve the certain standards of production and continuously improve operational performance (Lestari & Mahbubah, 2021). By means of FMEA, we can obtain RPN score which is calculated using three parameters including Severity (S), Occurrence (O), and Detection (D). The steps in implementing the FMEA method are as follows (Sari et al., 2018):

a) Identify the type of production process failure
b) Identify potential production process failures
c) Identify the potential effects of production process failures
d) Identify the causes of production process failures
e) Determine the rating of severity, occurrence, detection, and production RPN
f) Provide suggestions for improvements to failures that occur

Severity refers to the degree of damage caused by failure within the process. Occurrence refers to the frequency of failure, indicating the potential failure to occur. Meanwhile, detection refers to the control carried out on a failure that occurs (Lestari & Mahbubah, 2021).

Table 1 presents the severity scale used as a reference to determine to what extent the effect caused by a failure. The scale ranges from 1 to 10 and classifies into several categories. The assessment of severity was carried out along with the expert from the company. Meanwhile, the reference of failure occurrence is presented in Table 2. A failure refers to a very high occurrence when, for example, a defect is identified once out of 2 or 3 processes in component production. The stipulation of failure occurrence was determined through data analysis based on defect data provided by the company.

Table 1. Reference of severity values. Adapted from (Lestari & Mahbubah, 2021)

Scale	Effect of Failure	Categories
1	Failure No Side Effects	None
2	No Directly Effects	Minor
3	Limited Effects	Minor
4	Low Rework	Very Low
5	Requires quite a lot of reworks	Low
6	Damaged product (reject)	Mid
7	Resulting in equipment disruption	High
8	Resulting in engine failure	Very High
9	Causes engine shutdown	Dangerous Warning
10	Engine disruption and safety threats	No Warnings

Table 2. Reference of occurrence scale. Adapted from (Hidayat et al., 2018)

Scale	Occurrence	Categories
10	100 in 1000	Very High
9	50 in 1000	
8	20 in 1000	High
7	10 in 1000	
6	5 in 1000	
5	2 in 1000	Mid
4	1 in 1000	
3	0.5 in 1000	Low
2	0.1 in 1000	Very Low
1	0.001 in 1000	*Remote*

Table 3 presents a scale of failure detection used as a reference for determining the control capability once the failure occurred. Detection mechanism is very important in the production systems by which enables finding of potential mechanical causes and control measures to the damage (Nurfarizi et al., 2023). The scale of failure detection towards the defect component was determined with the confirmatory assessment from the company expert who is the manager of POPJ.

Table 3. Scale of failure detection. Adapted from (Lestari & Mahbubah, 2021)

Scale	Detection Capabilities	Categories
10	No controller	Almost impossible
9	Elusive controller	Very rare
8	Difficult to detect the form and cause of failure	Infrequently
7	Very low failure control capability	Very low
6	Low failure control capability	Low
5	Medium failure control capability	Keep
4	Very high controllability	A bit high
3	Very high failure control capability	High
2	Very high failure control capability	Very high
1	Failure control capability is almost certain	Almost certainly

1.1. Calculation of RPN score

Once the S, O, D value is determined, the subsequent step is RPN calculation using Equation (1). The critical value is calculated using Equation (2), where *n* refers to the number of defects. This calculation allows to determine the criticality limit of defects, by which the priority for improvement can be determined.

$$RPN = S \times O \times D \tag{1}$$

$$Critical\ Value = \frac{RPN}{n} \tag{2}$$

1.2. Identification of root cause with FTA

The identification of substantial defects was performed by means of Pareto principle (Hidayat et al., 2018; Renosori et al., 2023). These defects were then mapped its potential root causes using FTA method (Sari et al., 2018; Tanto et al., 2023). The following are the steps for implementing the FTA method (Sari et al., 2018):

a) Defining the top events of the system,
b) Explore each branch in every detail,
c) Resolving error trees for combinations of events related to top events,
d) Identify potential failures and transform into appropriate models,
e) Using results in decision making.

The FTA result was then confirmed with the manager of POPJ and adjusted based on the existing condition. After mapping using an error tree or FTA, suggestions for improvement are determined from the identification of problems that occur, evaluation of the causes that occur, and priority of action based on the level of problems that occur. Suggestions for improvement are given from the calculation results and elaboration of the two methods.

2. Results and Discussion

2.1. Defects Data Summary

Defect data was obtained from NCR, containing approximately 1300 records. After cleaning and pre-processing, 599 records remained. The data was then classified the defects into 4 different defect categories, including materials, personnel, visual, and document. The identification of potential failure, effects, and causes were performed carefully based on the non-conformance description in the

NCR data. The results were then confirmed to the POPJ manager through interview. Table 4 summarizes the defects data during the manufacturing process. About 22.2% (4 items of 18 defects) of the defects were caused by material. Personnel follows as a major cause of failure or defect, accounting for 44% out of 18. Personnel's capability, focus, scrupulosity are among factors contributing to failure occurrences. Visuals and documents equally contributed to the number of defects, accounting for 16.7% out of 18. Visual causes are related to the detailed activities and are often missed during the inspection, requiring the personnel to perform the job carefully. Meanwhile, incomplete, or unclear document also led to the potential failure in the manufacturing process. It is clearly seen that though the visual accounts for the minimum number of defects (3 out of 18), the frequency is the highest among the others. Particularly in the welding process that caused a crack and porosity, with occurrence accounting for 25.4%.

2.2. Defects Identification with FMEA

Table 5 shows the calculation of severity, occurrence, and detection, followed by RPN score. The score of severity and detection were determined in consultation with the maintenance technician and POPJ manager. Meanwhile, the occurrence score was calculated proportionally based on the NCR data with the reference of occurrence scale (see Table 2). For instance, defect number 15 (with 1 frequency) has an occurrence rate of approximately 0.0008 per 1300 total defects. This value falls between scale 3 and scale 4, thus in such case the lowest scale was selected.

The result indicates that the total RPN score is 3764. Visuals and documents are clearly identified as significant sources of errors, with each category contributing to two defects. For example, the defect of crack that occurs in welding has the highest RPN score with a value of 504. The possible cause is an ampere mismatch during welding which affects the porosity of the plate during the welding process. By dividing this total RPN score with total observation, which is 18 defects, a critical value of 209 was obtained. With this baseline score, 8 defects were identified as exceeding the critical score, including defect 1 – 5, 13, 14, and 16. The potential cause corresponds to these failure modes should be further observed for deriving appropriate improvements.

2.3. Root Cause Identification with FTA

Fig. 2 depicts a pareto chart illustrating the dominant defects contributing to failures in the production system. The fundamental idea of pareto 80:20 indicates that 80% of failures were caused by 20% of defects. This leads to identification of three major defects:

1. Defect 3 – Cracks in welding and porosity in the plate (25.4% of frequency)
2. Defect 1 – Component damaged and train set panel failures (15.5% of frequency)
3. Defect 13 – Scratched, striped and uneven paint (12.2% of frequency)

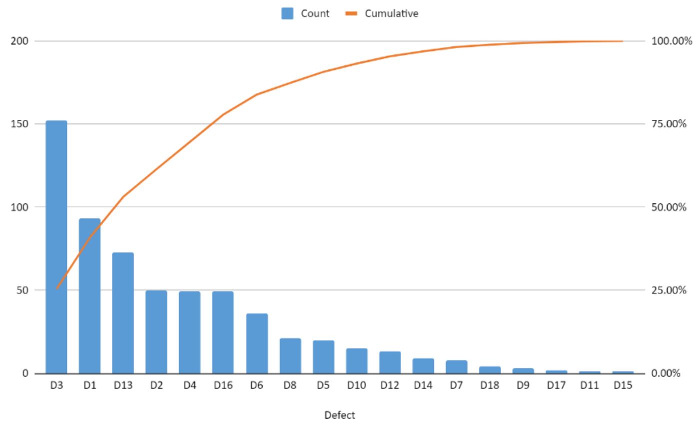

Fig. 2. Pareto chart of defects based on its occurrence

Table 4. Summary of defects data

No	Categories	Potential Failure Mode – defects	Potential Failures Effect	Potential Causes of Defect	Frequency	%
1	Materials	Component damaged and train set panel failures	Panel malfunction, risk of safety to passengers, increase repair time	Material quality, wiring interruptions, mechanical failure	93	15.5
2	Personnel	Missing or damaged interior panel and small components	Panel malfunction, untight component	Fatigue or unfocused personnel	50	8.3
3	Visual	Cracks in welding and porosity in the plate	Fracture, risk of safety to passengers	Limited visual inspection	152	25.4
4	Personnel	Loose and damaged wiring connection	Unstable or voltage malfunction, short circuit	Fatigue or unfocused personnel, limited supervision	49	8.2
5	Document	Unintended welding processes	Production delays, increase rework	No clear guidance in working order sheet	20	3.3
6	Materials	Damaged in handbrake components (tight chains, leaks and lack of bolts)	Brake malfunction, risk of injury to passengers	Error in handbrake installation, tightening not suitable	36	6.0
7	Personnel	Unpainted pipe joints	Easily exposed to corrosion of pipes	Personnel are less meticulous in the painting process	8	1.3
8	Document	Bad guidance	The occurrence of unwanted defects	Nonconformance to the standards, no guidance of personnel qualification	21	3.5
9	Personnel	Unintended crust in metal plate but welded before completely grinded	Reduce plate durability, increase rework	Personnel are less scrupulous on plate cutting process, fatigue	3	0.5
10	Personnel	Overlapping or under melting of metal on the plate	Reduce plate durability, increase rework	Limited supervision, personnel negligence	15	2.5
11	Document	Bad instruction	Increase rework, and repair time	Lack of accuracy and guidance in the production documents	1	0.2
12	Materials	Oil seepage and missing bolts at the joints	Fracture, risk of safety to passengers	Material failure, tightening not suitable	13	2.2
13	Visual	Scratched, striped and uneven paint	Increased repair time	Limited visual inspections	73	12.2
14	Materials	Leaks found during rain tests	Product release delays, passenger discomfort	Defective assembling, gaps between plate connection	9	1.5
15	Visual	Leakage in water tank	Increased repair time, passenger discomfort	Limited visual inspections, defective assembling	1	0.2
16	Personnel	Unintended collection of unused wiring materials	Unwanted defective occurrence	Less awareness of proper material handling	49	8.2
17	Personnel	Saggy bolts on the grounding panel	Resulting in panel damage	Fatigues, less careful	2	0.3
18	Personnel	No cleanliness guidance	If it is not cleaned diseases arise	Lack of awareness of hygiene	4	0.7
Total					**599**	**100**

Table 5. Calculation of SOD

No	Potential Failure Mode – defects	S	O	D	RPN
1	Component damaged and train set panel failures	8	9	4	**288**
2	Missing or damaged interior panel and small components	7	8	4	**224**
3	Cracks in welding and porosity in the plate	8	9	7	**504**
4	Loose and damaged wiring connection	8	8	6	**384**
5	Unintended welding processes	8	7	5	**280**
6	Damaged in handbrake components (tight chains, leaks and lack of bolts)	5	8	5	200
7	Unpainted pipe joints	5	5	5	125
8	Bad guidance	6	7	4	168
9	Unintended crust in metal plate but welded before completely grinded	5	4	4	80
10	Overlapping or under melting of metal on the plate	5	6	4	120
11	Bad instruction	6	3	5	90
12	Oil seepage and missing bolts at the joints	5	6	5	150
13	Scratched, striped and uneven paint	7	8	6	**336**
14	Leaks found during rain tests	5	6	7	**210**
15	Leakage in water tank	5	3	7	105
16	Unintended collection of unused wiring materials	5	8	6	**240**
17	Saggy bolts on the grounding panel	5	4	6	120
18	No cleanliness guidance	4	5	7	140
					3764

Each of the defect was then derived its potential cause of a system failure using FTA. The process of root cause identification was conducted in consultation with the maintenance technician and POPJ manager. The identification of failure factors corresponds to defect 1 is illustrated in Fig. 3. Component damaged and train set panel failures potentially occurred due to material and tools or personnel. The root causes in each intermediate event were identified carefully to the lowest level of failure, known as the basic event. The materials and tools consist of four different potential root causes, while personnel failures can be attributed to three potential causes.

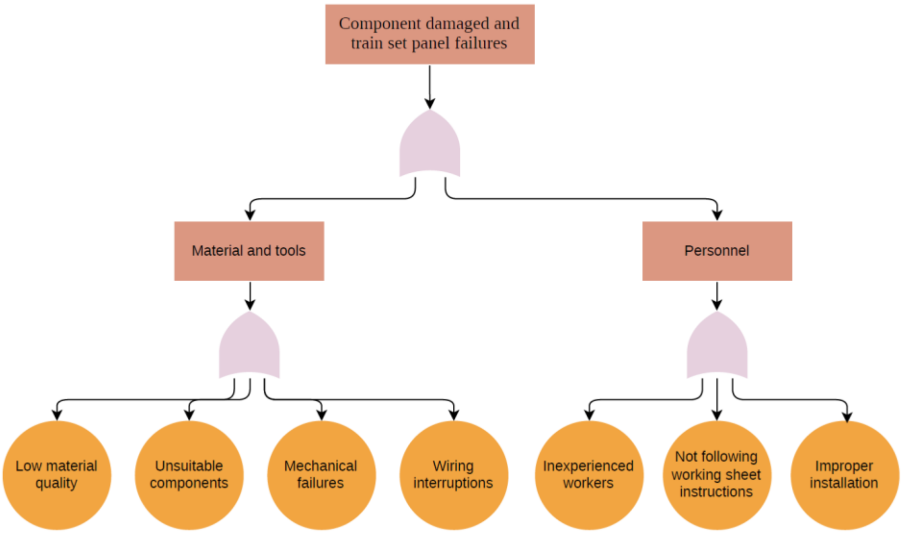

Fig. 3. FTA for defect 1 – component damaged and train set panel failures

Fig. 4 and Fig. 5 represent FTA for defects 3 and 13, respectively. We identified that both defects have the same number of intermediate failures event, involving personnel and materials. In personnel, limited visual inspection and lack of experienced workers are common issues found for both defects 3 and 13. The decrease in concentration may also be attributed to personnel issues such as fatigue and unclear communication. In some cases, the repainting process was performed immediately due to certain failures, but no documentation exists to justify this decision. Working environments can also contribute to failures due to human errors, such as hygienic issues, lack of lights and ventilation.

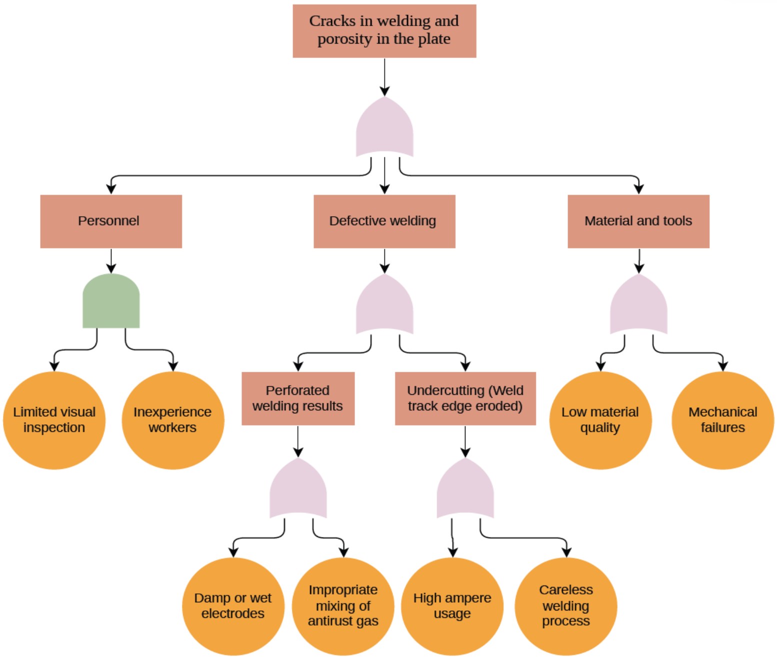

Fig. 4. FTA for defect 3 – cracks in welding and porosity in the plate

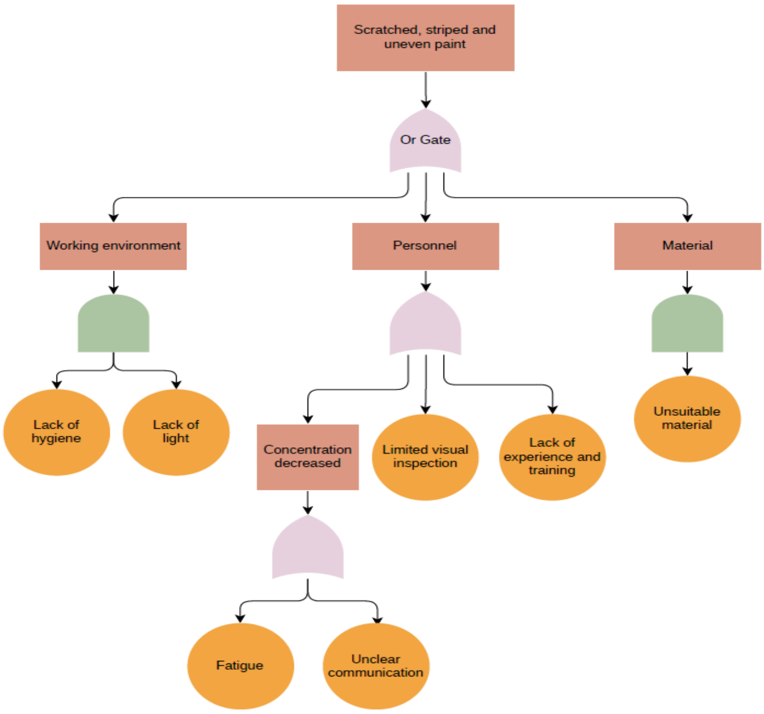

Fig. 5. FTA for defect 13 – scratched, striped and uneven paint

2.4. Discussion

Train manufacturing with its long production cycle possesses higher potential of failures. This condition may result delays and detrimental risks due to unexpected failures, imposing the necessity to conduct regular inspections (Dinmohammadi et al., 2016). The findings suggest that personnel and materials are prevalent issues, which aligns with other manufacturing sectors (Hidayat et al., 2018; Renosori et al., 2023). This study exemplifies the utilization of FMEA to properly identify failure modes, failure effects, and potential causes based on NCR records. The RPN calculation indicates that 44% (8 out of 18) defects exceeded the critical score of 209. Pareto analysis enables us to clarify which defects that contribute most significantly to overall failures. FTA is applicable to identify the potential root cause of each defect in structured manner (Shafiee et al., 2019). To prevent similar failures, the company should strive to implement comprehensive quality measures throughout production cycle. Table 6 outlines the recommendations to address each defect category.

The present study provides essential managerial implications in various perspectives. Manufacturing with extensive production cycle requires to implement potential failures modes as far as possible. FMEA work often relies on adequate data and experienced engineers (Wu et al., 2021). The combination of FMEA and FTA offers significant benefits in risk management. The findings can inform decision-making for managers, enabling them to implement appropriate countermeasures.

Table 6. Recommendation for improvements for each defect category

Defect Categories	Occurrence Frequency	Recommendations
Materials	25.2%	a. Evaluate the standard operating procedures (SOP) of welding process b. Improve material selection process that meet specific manufacturing requirements c. Implement stringent material quality inspections d. Perform periodic maintenance for welding machine and tools to prevent mechanical failures e. Take immediate countermeasures in case failures are identified
Personnel	30%	a. Increase the frequency of inspections and supervisions b. Upgrade the worker's skills through training and certification c. Implement a work-life balance schedule and safer working environment to reduce fatigue and prevent unexpected safety incidents
Visual	37.8%	a. Improve working environment with adequate lighting, ventilation, and visual aid equipment to reduce visual impediment b. Provide clear and visible working instruction c. Perform regular visual inspections
Document	7%	a. Provide clear and less complicated SOP b. Conduct regular checking to conform the document and real conditions to make necessary countermeasure c. Update the NCR document regularly to prevent rework and unnecessary work d. Communicate effectively with the workers before proceeding the operations

3. Conclusion

This study analyzes the nonconformance records data for evaluating risks associated with different component in a complex train manufacturing system. We integrate FMEA and FTA consecutively in systematic manner for identifying and prioritizing risks, by which potential root causes of failures are identified. There were 18 types of defects that occurred during the production process of driven and undriven train cars. Those defects data were then processed using the FMEA method and 8 defects were found exceeding the critical value of RPN. To determine the most contributing defects, Pareto analysis was performed and resulted three main defects each of which was further analyzed using FTA to determine the root cause of the problem. Recommendation for improvements is provided and elaborated according to different defect categories. It is expected that the present study can be used as references for company to improve its quality control and reduce production delays. This study has limitations on research data which limits interpretation or analysis performed. Future research is expected to employ various methods such as data mining or other advanced data analytics to deals with limited data analysis. Implementing simulation method, for example, may provide more realistic outcomes for evaluating various policy and quality control.

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