



Risk Mitigation and Hazard Analysis in the Battery Production Process Using the Fuzzy Fault Tree Analysis Method

Anggelia Arifa¹, Tranggono¹, Rizqi Novita Sari¹

¹Department of Industrial Engineering, Faculty of Engineering and Science, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Indonesia

*Corresponding Author: Anggelia Hayuning Ariffa Arifa

Email: hayuningariffa@gmail.com



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Abstract

Industrial Revolution 4.0 increases the demand for batteries but also increases the risk of workplace accidents in factories such as PT TMB. Production processes involving chemicals and heavy equipment cause potential hazards. In the last three years, accidents have increased, disrupting production and adding costs. Therefore, this research aims to identify risks and provide risk mitigation in the battery production process. This research uses Fuzzy Fault Tree Analysis (FFTA) to identify hazards and reduce risks, in order to improve the safety and competitiveness of the company. This research was conducted at PT TMB by combining qualitative analysis to understand general conditions and quantitative to analyze the risk of workplace accidents, such as fire, fatigue, operator injury, and worker health. The Fuzzy Fault Tree Analysis (FFTA) method was used to map and reduce potential hazards, as well as develop more effective work safety policies. The results of the research explained that there are four top events with different probabilities and impacts: fire risk (A) 26.82%, occupational fatigue (B) 11.57%, occupational injury (C) 40.58%, and occupational health (D) 21.03%. From the four top events mentioned above, mitigation is focused on the 3 highest positions based on the assessment of the matrix table, which are fire risk, occupational injury, and occupational health.

Introduction

Industrial Revolution 4.0 has driven the rapid development of batteries to support various applications, including electric vehicles and industrial equipment. As demand grows, battery factories continue to innovate to increase production capacity and efficiency. However, as the complexity of the production process increases, the potential risk of workplace accidents also increases. Factories that produce automotive batteries and VRLA (Valve Regulated Lead Acid) batteries face particular challenges related to the handling of hazardous chemicals, fire and explosion risks (Nauri et al., 2024; Zinveli et al., 2025; Dunn, 2024; Heramb, 2021). Materials such as sulfuric acid and heavy metals used in the battery production process present significant potential hazards if not handled properly (Elfidasari, 2023). In addition, the process of charging and discharging batteries can also trigger uncontrolled chemical reactions. From this, it is known that it is important for battery factories to implement a comprehensive safety management system to minimize the risk of work accidents and maintain work safety (See et al., 2022; Gabbar et al., 2021; Samarasinghe & Heenatigala, 2024).

The potential hazards that arise in the battery production process involve various stages involving hazardous chemicals such as sulfuric acid, lead, and other lead compounds

(Schismenos et al., 2021; Mrozik et al., 2021; Das et al., 2024; Khaje et al., 2025; Amusa et al., 2024). Exposure to these materials can cause skin irritation, respiratory problems, and long-term health problems (Irianti et al., 2021; Darbre, 2023; Radfard et al., 2023; Budi et al., 2024; hadi Lafta et al., 2024; Jomova et al., 2025). In battery production at PT TMB, there are three main stages, with 19 process stages shown in Figure 1, including plate preparation, assembling and formatting.

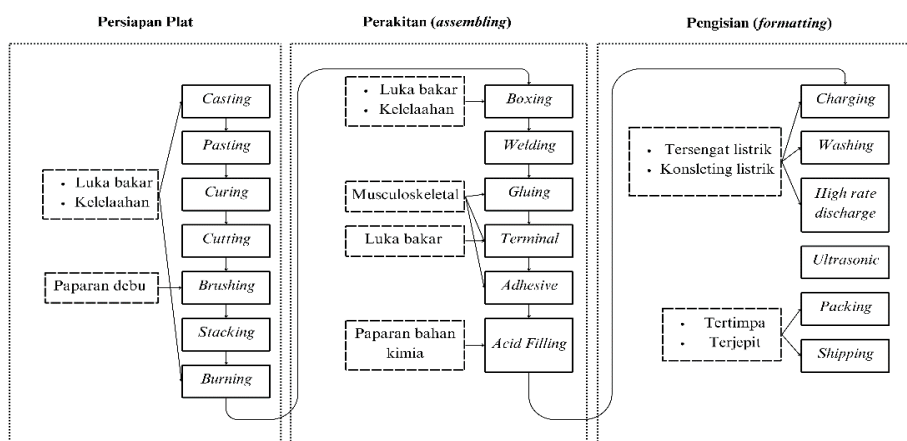


Figure 1. Battery Production Process

In the plate preparation stage, there are processes directly related to fire that can cause burns to operators. These processes include electrode casting and battery plate burning. Casting has the risk of occupational fatigue due to high temperatures while burning involves workers' interaction with fire when joining electrode plates with high potential where the burning process is shown in Figure 2. Furthermore, at the plate brushing stage, workers face the risk of exposure to dust that can damage their health and cause Occupational Diseases in the long term. In addition, high temperatures and metal dust in the air increase the risk of fire and respiratory problems.

PT TMB over the past three years found several accidents ranging from moderate to severe accidents based on the classification of the level of types of work accidents. Medium to severe accident data from PT TMB can be seen in Figure 2.

PT TMB Medium - Severe Accident Data

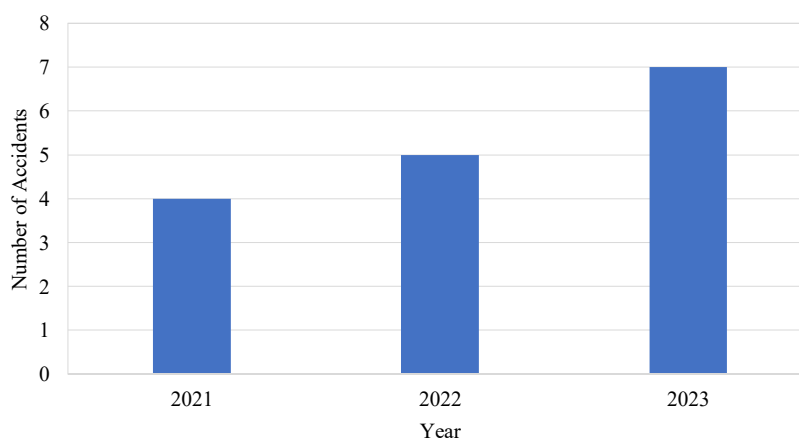


Figure 2. Medium to Severe Accident Chart

From the data shown in Figure 2, it can be seen that in 2021 there were 4 accidents, then in 2022 there were 5 accidents and in 2023 there were 7 accidents that occurred at the company.

Based on Figure 2, it can be seen that there is an increase in the number of serious work accidents. Accidents that occur include being hit by the iron doorstep when removing battery accessories, being hit when transferring the battery to the charging station, being hit by the mold when transferring, and being hit by the hand pallet when transferring the battery that has finished production.

Based on the various incidents of work accidents that occurred and their impact on the company, it can be concluded that the root of the problem lies mainly in the lack of strict implementation of work safety procedures, lack of training for workers, and unsafe working environment conditions. To prevent accidents in the future. A good and comprehensive risk management system is needed to identify and evaluate battery production (Yuantoko et al., 2022; See et al., 2022; Shukla & Shankul, 2024; Gabbar et al., 2021; Dunn, 2024). Mitigation efforts that can be carried out are regular monitoring of the application of SOPs by employees, ensuring equipment is in good condition during the production process and transfer of tools or finished goods, conducting preventive maintenance on all tools and machines, and fire management system (Indra et al., 2021; Sari & Al Faroqi, 2024; Kunanti etv al., 2024; Hardt et al., 2021). Thus, the battery industry can reduce losses efficiently and safely.

The most appropriate method used is to separate potential risks with Fuzzy Fault Tree Analysis (FFTA). The Fault Tree Analysis method is important in identifying the causes of hazards with fault tree diagrams for the highest hazard types, understanding and preventing potential hazardous events (Dianto et al., 2022; Ashraf et al., 2022; Zermane et al., 2022; Ikwan et al., 2021). Fuzzy logic combines human thinking with mathematics to handle uncertainty (Rosalinda et al., 2023). Fuzzy fault tree analysis is used when quantitative information is minimal or non-existent. This method uses the probability of an incident as a vague number because mathematical values are not available. This model utilizes vague sets and probability theory for unclear, subjective, and inaccurate data (Zaib et al., 2022; Alizadehsani et al., 2024; Bhuvaneshwari et al., 2025; Bhagat et al., 2025).

This research aims to Identify the risks and potential hazards at the stages of the production process on batteries using the Fuzzy Fault Tree Analysis (FFTA) method and Provide recommendations for mitigating risks and potential hazards at the stages of the production process on batteries based on the results of the Fuzzy Fault Tree Analysis (FFTA) analysis. Through this analysis, it is expected to identify the highest potential hazards that need to be prioritized in risk mitigation efforts. Thus, the company can prioritize effective and efficient mitigation actions, which can minimize the occurrence of work accidents, equipment damage, and financial losses. The results of this study are expected to make a significant contribution to improving occupational safety and health (OHS) performance in the company as well as improving the overall performance of the production process and product competitiveness in the global market.

Methods

This research was conducted in the battery production process at PT TMB and started in November 2024 until February 2025. This research adopts mixed methods that combine qualitative and quantitative approaches. Risk variables were obtained from the initial identification of risks and strengthened by literature studies from previous studies which were then discussed with relevant parties to obtain work accident variables which could later be used as the contents of the main survey questionnaire. Questionnaire questions were obtained from the results of fault tree analysis and identification and discussions with the K3 and production departments of PT TMB. The following is a table of work accident risks:

Table 1. Variable Risk Factors and Risk Impacts

Top Event	Factor	Source	Impact
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Fire	Electrical short circuit Battery component damage Flammable components and chemical reactions	Technical Technical Technical - Environment	Fatalities and injuries Damage to production materials and equipment Damage to facilities
Occupational Fatigue	Standing for too long Hot temperature Workload	Organizational Environment Organizational	Loss of focus Work injury
Occupational Injury	1. Pinched pallet/iron 2. Being crushed by goods 3. Scratched during repair 4. Electric shock 5. Burned Mold	1. Technical – Human 2. Technical 3. Human 4. Technical 5. Technical	1. Injury 2. Disability 3. Employee absence 4. Decreased productivity
Occupational Health	1. Chemical exposure 2. Chemical spill	1. Environment 2. Technical - Human	1. Occupational disease 2. Chemical irritation

The selection of important events related to fire risk, occupational fatigue, occupational injuries, and occupational health in the production process of lead-acid and VRLA batteries at PT TMB is crucial for identifying potential hazards in future production processes. The selection of these key events is based on the company's historical data and industry incident data from 2020 to 2023 in the same industry sector.

Data collection is done by observation by observing the battery production process to find out the potential hazards that may occur during production. Furthermore, interviews were conducted with experts with 1 K3 staff and 4 production staff. Interviews are conducted to find out the risks that have and may occur and their causes and the results of the interview will be used in the preparation of Fault Tree Analysis. The next stage is the distribution of questionnaires to 5 experts related to the potential hazards and risks of work accidents in the production process. In addition, the selection of experts in the production section is an expert who understands work safety and battery production SOPs. The questionnaire will contain the causes and risks that have been obtained from the preparation of FTA which will be assessed for their probability value with fuzzy linguistic variables as follows:

Table 2. Linguistic Variables and Fuzzy Numbers

Grade	Likelihood	Membership Function
1	Very Low (VL)	(0.00, 0.00, 0.25)
2	Low (L)	(0.00, 0.25, 0.50)
3	Medium (M)	(0.25, 0.50, 0.75)
4	High (H)	(0.50, 0.75, 1.00)
5	Very High (VH)	(0.75, 1.00, 1.00)

Source: Sejati et al. (2023)

Table 3. Expert Criteria Weights

Constitution	Klasifikasi	Score
Professional Position	Production Manager	5
	OHS Officer	4
	Production Technician	3
	Production Operator	2
	New Employee	1

Education / Competency Level	Doctorate / Expert	5
	Technician	4
	Master/Engineering Manager	3
	S1/Project Technician	2
	Diploma/Technician	1
Professional Experience / Length of work at the company	SMA/SMK/Operator	1
	More than 20 years	5
	15 to 20 Years	4
	10 to 15 Years	3
	5 to 10 years	2
	Less than 5 years	1

Source: Li et al. (2021)

Data analysis was conducted using the Fuzzy Fault Tree Analysis (FFTA) methodology. Fuzzy Fault Tree Analysis (FFTA) is a risk analysis technique that quantifies the probability of failure in the Fault Tree Analysis (FTA) fault tree structure to determine the greatest probability on one of the branches or basic events that are the main cause of a hazard risk or cause of work accidents at PT TMB. The fuzzy method is used to handle the complexity and uncertainty of the cause of risk and is used because the documentation of work accidents is still not done properly (Simanjuntak et al., 2022). Fault Tree Analysis is a method to describe in detail the cause-and-effect relationship of an event, which is described in the form of a fault tree model. Fault Tree Analysis (FTA) will help solve the problem as the top event on the Fault Tree to identify, evaluate, and mitigate the risks that have been identified (Suseno & Kalid, 2022).

Results and Discussion

The analysis process involves inputting basic event data obtained from interviews and questionnaires given to respondents. Furthermore, a well-structured FTA diagram was prepared. The following is the resulting FTA diagram:

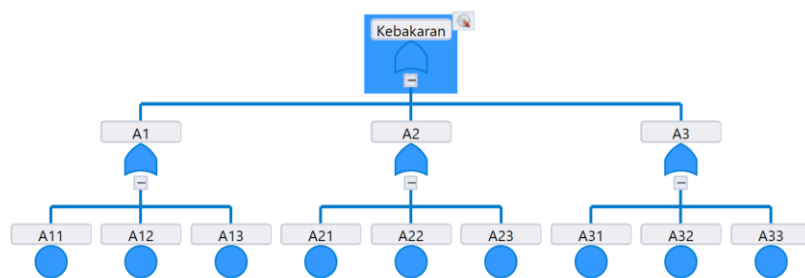


Figure 3. Fault Tree Fire

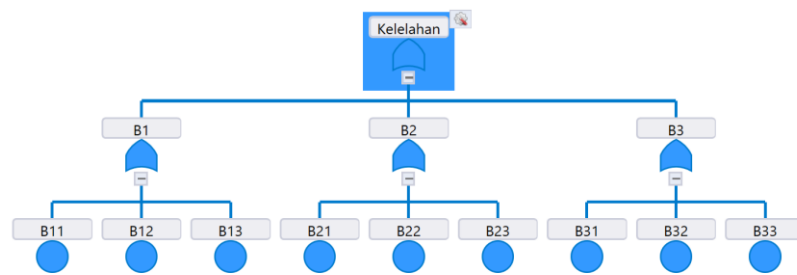


Figure 4. Fault Tree Occupational Fatigue

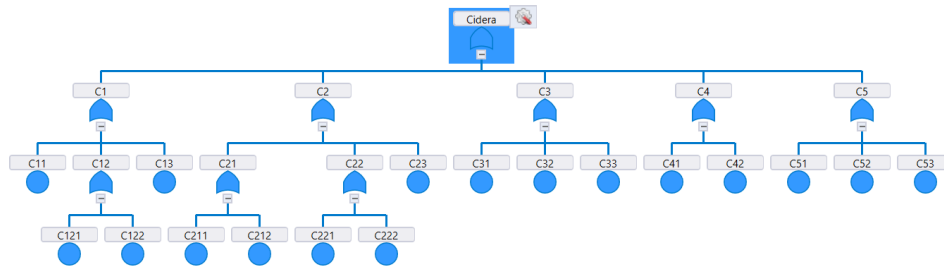


Figure 5. Fault Tree Occupational Injury

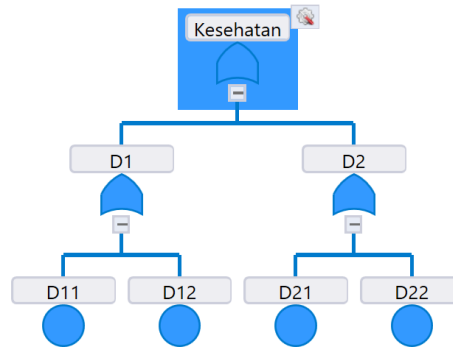


Figure 6. Fault Tree Occupational Health

From the Fault Tree analysis carried out in Figures 3, 4, 5, and 6 the identified basic events are listed in Table 4:

Table 4. FTA Basic Event Diagram

No.	Code	Event Name
Fire Risk		
1	A11	Use of cables that do not meet the standards
2	A12	Electrical equipment is obsolete
3	A13	Poor electrical installation at the production site
4	A21	Damage to battery raw materials
5	A22	Low quality of raw materials
6	A23	Improper battery assembly process/not according to SOPs
7	A31	Unsafe storage of battery chemicals
8	A32	Lots of combustible metal dust in the work area
9	A33	The presence of a fire source around flammable materials
Occupational Fatigue		
10	B11	Unergonomic workplace design
11	B12	Duration of sitting time that exceeds safe limits
12	B13	Long working hours without sitting
13	B21	Inadequate workplace ventilation system
14	B22	Production processes that generate heat
15	B23	Work environment temperature exceeds comfortable limits
16	B31	High production volume
17	B32	Task load on employees exceeds physical or mental capacity
18	B33	Lack of training and skills
Occupational Injury		

19	C11	Lack of supervision when moving goods
20	C121	Narrow work area
21	C122	Unsafe work area
22	C13	Unsafe pallet arrangement
23	C211	Moving goods is done without safety
24	C212	Placement of goods on an inclined plane
25	C221	Operators are not properly trained in moving techniques
26	C222	Operators do not follow moving SOPs
27	C23	Instability when using moving equipment
28	C31	Lack of protective cover on the conveyor
29	C32	Technician operators do not use PPE when repairing conveyors
30	C33	Technician operator inaccuracy when performing repairs
31	C41	Direct contact with parts that conduct electricity
32	C42	Electrical equipment that is not maintained
33	C51	Not using PPE when applying mold
34	C521	Sensor switch damage
35	C523	Direct contact with tools that produce fire
Occupational Health		
36	D12	Use of chemicals
37	D22	Not using PPE when in contact with chemicals
38	D21	Spills occur during transportation of materials
39	D22	Chemical spills are not handled properly

Table 5 is the result of a questionnaire using fuzzy linguistic variables:

Table 5. Basic Event Diagram FTA

Code	Basic Event	Respondent				
		1	2	3	4	5
Fire Risk						
A11	Use of cables that do not meet the standards	VL	L	L	VH	H
A12	Electrical equipment is obsolete	VL	VH	L	H	VL
A13	Poor electrical installation at the production site	VL	H	M	H	H
A21	Damage to battery raw materials	L	VH	L	M	L
A22	Low quality of raw materials	L	L	L	L	L
A23	Improper battery assembly process/not according to SOPs	L	M	H	M	M
A31	Unsafe storage of battery chemicals	VL	VL	H	L	L
A32	Lots of combustible metal dust in the work area	VL	H	L	L	H
Code	Basic Event	Respondent				
		1	2	3	4	5
A33	The presence of a fire source around flammable materials	VL	VH	H	VH	H
Occupational Fatigue						
B11	Unergonomic workplace design	VL	VL	L	M	L
B12	Duration of sitting time that exceeds safe limits	VL	VL	L	M	L
B13	Long working hours without sitting	VL	L	L	H	M
B21	Inadequate workplace ventilation system	VL	M	M	M	M
B22	Production processes that generate heat	VL	L	M	H	L

B23	Work environment temperature exceeds comfortable limits	VL	L	M	M	L
B31	High production volume	L	H	M	M	M
B32	Task load on employees exceeds physical or mental capacity	VL	VL	M	M	L
B33	Lack of training and skills	L	L	L	H	VH
Occupational Injury						
C11	Lack of supervision when moving goods	L	M	L	H	L
C121	Narrow work area	VL	VL	L	M	VL
C122	Unsafe work area	VL	L	M	H	L
C13	Unsafe pallet arrangement	VL	VL	L	H	M
C211	Moving goods is done without safety	L	L	L	VH	M
C212	Placement of goods on an inclined plane	VL	L	M	M	H
C221	Operators are not properly trained in moving techniques	VL	VL	L	H	L
C222	Operators do not follow moving SOPs	L	VL	L	H	L
C23	Instability when using moving equipment	L	L	M	VH	M
C31	Lack of protective cover on the conveyor	L	H	L	M	VL
C32	Technician operators do not use PPE when repairing conveyors	L	VH	L	M	H
C33	Technician operator inaccuracy when performing repairs	L	VL	L	H	H
C41	Direct contact with parts that conduct electricity	L	VH	H	VH	H
C42	Electrical equipment that is not maintained	L	L	M	H	L
C51	Not using PPE when applying mold	L	L	H	VH	M
C52	Sensor switch damage	L	L	M	M	VL
C53	Direct contact with tools that produce fire	L	L	H	VH	L
Occupational Health						
D11	Lack of supervision when moving goods	L	VH	H	H	H
D12	Narrow work area	L	VH	H	H	M
D21	Unsafe work area	VL	VL	M	H	L
D22	Unsafe pallet arrangement	L	M	M	M	L

Source: Data processing

The calculation of possibility in this final project uses fuzzy logic, namely triangular fuzzy numbers with 3 fuzzy numbers, using numbers from linguistic variables that produce possibility, obtained from respondents. The following is the calculation of respondent weighting for respondent 1:

Weight of Expert 1

$$\begin{aligned}
 SCO_1 &= SPP_1 + SEC_1 + SPE_1 & (1) \\
 &= 4 + 3 + 3 \\
 &= 10
 \end{aligned}$$

$$\begin{aligned}
 W_j &= \frac{\text{weight expert}}{\sum_{i=1}^n \text{weight expert}} & (2) \\
 &= \frac{10}{37} \\
 &= 0,27
 \end{aligned}$$

Table 6 weighting results of 5 respondents that have been obtained:

Table 6. Respondent Weighting

Respondent	Score
1	0,27
2	0,22
3	0,16
4	0,16
5	0,19

The next step is the calculation of Possibility (FPs). Table 7 is the possibility calculation for the basic event with code A11:

Table 7. Basic Event A11 Questionnaire Results

Respondent				
1	2	3	4	5
VL	L	L	VH	H

Based on the linguistic variables that have been determined, the next step is to apply the multiplication operation between fuzzy numbers and the weights of each respondent, resulting in the following calculation:

$$\text{Respondent 1} = (0.00; 0.00; 0.25) \times 0,27$$

$$= (0,00; 0,00; 0,07)$$

$$\text{Respondent 2} = (0.00; 0.25; 0.50) \times 0,22$$

$$= (0,00; 0,05; 0,11)$$

$$\text{Respondent 3} = (0.00; 0.25; 0.50) \times 0,16$$

$$= (0,00; 0,04; 0,08)$$

$$\text{Respondent 4} = (0.75; 1.00; 1.00) \times 0,16$$

$$= (0,12; 0,16; 0,16)$$

$$\text{Respondent 5} = (0.50; 0.75; 1.00) \times 0,19$$

$$= (0,09; 0,14; 0,19)$$

From the results of the addition operation on each fuzzy number generated, a fuzzy number is obtained as follows:

$$M = (0,00 + 0,00 + 0,00 + 0,12 + 0,09);$$

$$(0,00 + 0,05 + 0,04 + 0,16 + 0,14);$$

$$(0,07 + 0,11 + 0,08 + 0,16 + 0,19)$$

$$= (0,216; 0,399; 0,608)$$

To get the probability value of the fuzzy number, the average calculation is done by summing the three values and dividing by three, with the following calculation:

$$\text{FPs} = \frac{(0,216 + 0,399 + 0,608)}{3}$$

$$= \frac{1,223}{3}$$

$$= 0,408$$

The transformation of fuzzy possibility values (FPs) into fuzzy probability values (FPr) requires converting the possibility value into probability. The probability calculation process

begins with determining the value of K, which is clarified through the following code example A11:

$$\begin{aligned}
 K &= \left[\left(\frac{1-FPs}{FPs} \right) \right]^{\frac{1}{3}} \times 2,301 & (3) \\
 &= \left[\left(\frac{1-0,408}{0,408} \right) \right]^{\frac{1}{3}} \times 2,301 \\
 &= 2,6
 \end{aligned}$$

After determining the K value, the next step is to calculate the probability (FPr), as follows:

$$\begin{aligned}
 FPr &= \frac{1}{10^k} & (4) \\
 &= \frac{1}{10^{2,6}} \\
 &= 0,00251
 \end{aligned}$$

After calculations 3 and 4, the FPr from the calculation of a single basic event (e.g., A11) cannot yet be used as a definitive reference in determining risk mitigation priorities. Because this study involves more than one top event, the probability of a single basic event does not fully represent the risk. Therefore, it is necessary to aggregate the probabilities of all basic events that make up a top event to obtain a top-event probability that approximates OSHA's tolerance limit of 0.001. The probability value of each basic event is shown in Table 8:

Table 8. Fuzzy Probability (FPr) Calculation Results

Kode	FPs	K	FPr
A11	0,408	2,6	0,00251
A12	0,399	2,64	0,00229
A13	0,529	2,21	0,00617
A21	0,435	2,51	0,00309
A22	0,250	3,32	0,00048
A23	0,473	2,39	0,00407
A31	0,250	3,32	0,00048
A32	0,408	2,61	0,00245
A33	0,633	1,92	0,01202
B11	0,209	3,59	0,00026
B12	0,209	3,59	0,00026
B13	0,333	2,9	0,00126
B21	0,387	2,68	0,00209
B22	0,327	2,93	0,00117
B23	0,286	3,12	0,00076
B31	0,486	2,34	0,00457
B32	0,250	3,32	0,00048
B33	0,457	2,44	0,00363
C11	0,385	2,69	0,00204
C121	0,178	3,83	0,00015
C122	0,327	2,93	0,00117
C13	0,297	3,07	0,00085
C211	0,405	2,62	0,00240
C212	0,381	2,71	0,00195
C221	0,250	3,32	0,00048
C222	0,295	3,08	0,00083

C23	0,486	2,34	0,00457
C31	0,367	2,76	0,00174
C32	0,529	2,21	0,00617
C33	0,390	2,67	0,00214
C41	0,678	1,8	0,01585
C42	0,372	2,74	0,00182
C51	0,486	2,34	0,00457
C521	0,300	3,05	0,00089
C523	0,439	2,5	0,00316
D12	0,651	1,87	0,01349
D22	0,604	2	0,01000
D21	0,291	3,1	0,00079
D22	0,385	2,69	0,00204

To determine the probability of a Top Event, we examine each cut set for each top event. A cut set is a combination of failures that causes the top event to occur, while a minimal cut set is the smallest combination of events that leads to the undesirable event. The following are the probabilities for each top event:

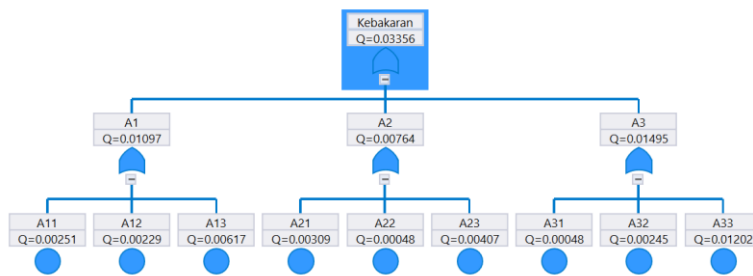


Figure 7. Minimum Cut Set Results Fire Risk

It can be seen that the minimum cut set for the top fire event is A1 with a probability of 0.01097, A2 with a probability of 0.00764, and A3 with a probability of 0.01495. The total probability of the minimum cut set for the top event is 0.03356.

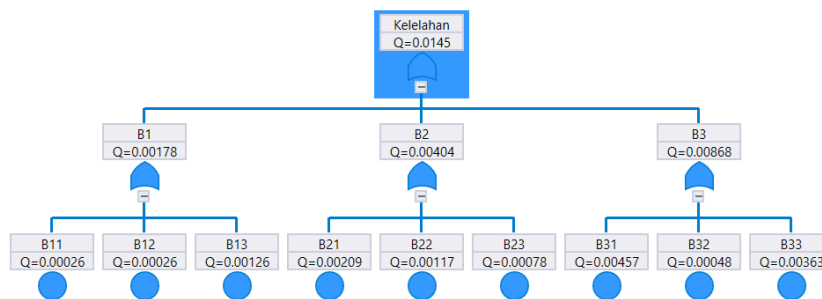


Figure 8. Minimum Cut Set Results Fire Risk

It can be seen that the minimum cut set for the top event of work fatigue is the minimum cut set B1 with a probability of 0.00178, B2 with a probability of 0.00404, and B3 with a probability of 0.0088. The total probability of the minimum cut set for the top event is 0.01448.

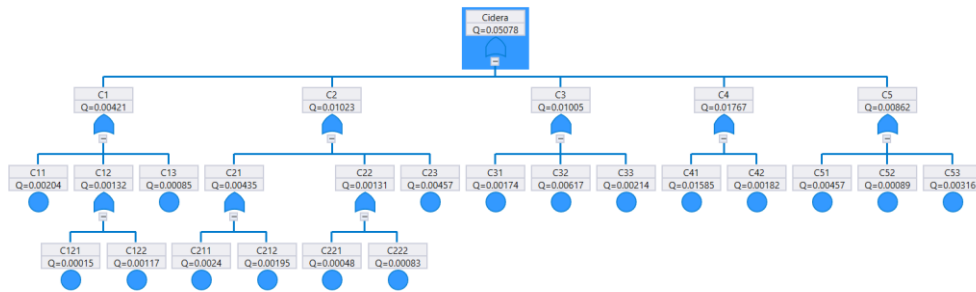


Figure 9. Minimum Cut Set Results Occupational Fatigue

It can be seen that the minimum cut set for the top event of work fatigue is the minimum cut set B1 with a probability of 0.00178, B2 with a probability of 0.00404, and B3 with a probability of 0.0088. The total probability of the minimum cut set for the top event is 0.01448.

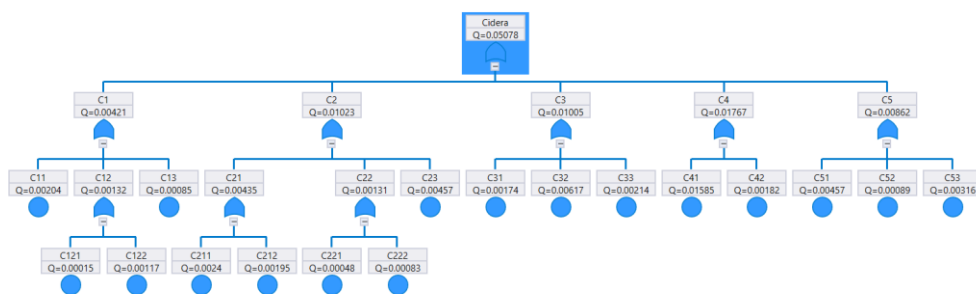


Figure 10. Minimum Cut Set Results Occupational Injury

It is known that the minimum cut set for the top event Operator Injury is the minimum cut set C1 with a probability of 0.00421, C2 with a probability of 0.01023, C3 with a probability of 0.01005, C4 with a probability of 0.01767, and C5 with a probability of 0.00316. The total probability of the minimum cut set for the top event is 0.05078.

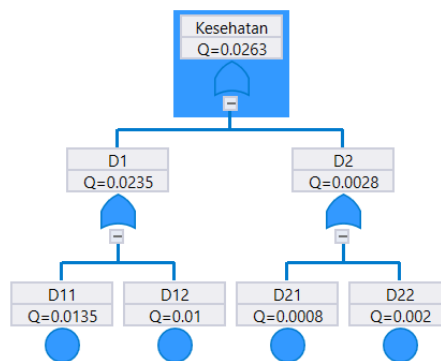


Figure 11. Minimum Cut Set Results Occupational Health

It is known that the minimum cut set for the top worker health event is D1 with a probability of 0.0235 and D3 with a probability of 0.0028. The total probability of the minimum cut set for the top event is 0.0263.

Probability Intermediate Event

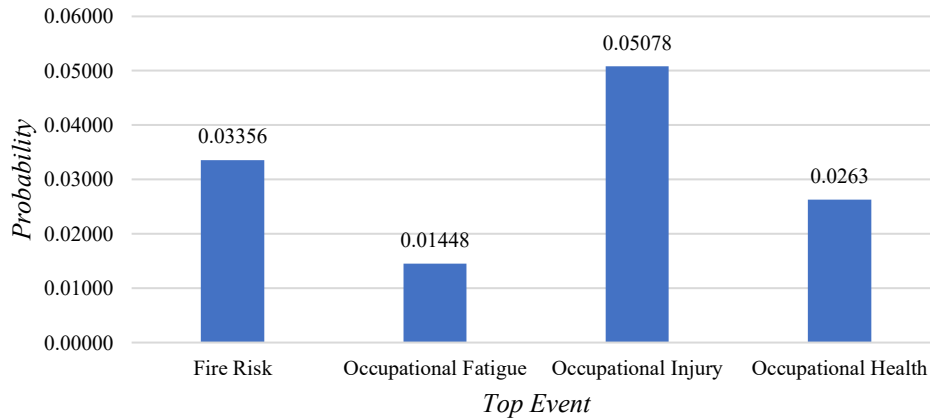


Figure 12. Comparison Chart of Top Event Probability

Figure 12 shows that causes operator injury has the highest probability, followed by the risk of fire, risks that affect worker health, and the lowest probability is the risk of work fatigue. The risk that causes operator injury is often caused by carelessness when assembling batteries, and the frequency of this risk occurring is quite high during battery production..

Then the results are entered into the risk matrix used by dividing 3 levels of probability namely Low (L), Medium (M), and High (H) with the level of impact of lost work time divided into 3 namely minor accidents, moderate accidents and severe accidents.

Table 9. Top Event Categories in the Risk Matrix

Code	Top Event	Probability	Percentage Probability	Impact
A	Fire Risk	0,03356	26,82%	High
B	Occupational Fatigue	0,01448	11,57%	Medium
C	Occupational Injury	0,05078	40,58%	High
D	Occupational Health	0,0263	21,03%	High

Table 1.9 shows the provisions for probability, which are carried out by discussing with the company's OHS with a percentage of 0 - 33.33% categorized as low (L), 33.33% - 66.67% categorized as medium (M), and 66.67 - 100% categorized as high (H). With a mild impact of healing on the same day or resting < 2 days, moderate work accidents that require healing and need to rest for > 2 days, and severe impact of work accidents that experience amputation and body function failure. The following is the risk matrix of each top event:

		Impact		
		Ringan	Sedang	Berat
Probability	Tinggi (H)	III	IV	V
	Sedang (M)	II	III	C IV
	Rendah (L)	B I	II	A, D III

Figure 13. Risk Matrix

Based on Figure 13, the position of each top event is known, from the matrix it is known that top event C (Occupational Injury) is classified in the high-risk category, for top events A (Fire Risk) and D (Occupational Health) are classified in the medium risk category and top event B (Occupational Fatigue) is classified in the low-risk category.

Based on the risk matrix in Figure 13, it can be seen that there are 2 top event risks in the medium risk position and 1 top event in the severe risk position. Based on these findings, preventive recommendations are then given to overcome the risks that occur. Table 1.10 is a risk mitigation table for each moderate to severe risk:

Table 10. Moderate to Severe Risk Mitigation

No	Code	Basic Event	Consequences	Preventive Action
Fire Risk				
1	A11	Use of cables that do not meet the standards	Risk of fire due to short circuit	Use SNI standard cables and conduct regular inspections
2	A12	Electrical equipment is obsolete	Electrical short circuit that causes fire	Replace obsolete equipment and perform maintenance
3	A13	Poor electrical installation at the production site	Potential electrical fires and accidents	Make sure electrical installations are carried out by experts
4	A21	Damage to battery raw materials	Explosion or fire due to chemical reaction of raw materials	Check the quality of materials before use and a good storage system on raw materials
5	A22	Low quality of raw materials	Risk of product non-conformity	Use high quality standard raw materials from the company
6	A23	Improper battery assembly process/not according to SOPs	Potential short circuit in the final product	Provide training to employees and conduct regular supervision
7	A31	Unsafe storage of battery chemicals	Risk of fire and environmental contamination	Use appropriate storage containers and keep away from fire sources
8	A32	Lots of combustible metal dust in the work area	Potential explosion or fire due to sparks	Use a good ventilation system
9	A33	The presence of a fire source around flammable materials	Risk of major fire	Limit the use of fire sources around flammable materials (provide separate and spaced work areas)
Occupational Injury				
10	C11	Lack of supervision when moving goods	Risk of accidents due to incorrect procedures	Add a supervisor in the moving area
11	C121	Narrow work area	Potential accidents due to limited space	Organize a more flexible workplace layout
12	C122	Unsafe work area	Risk of falling or being hit by goods	Make sure the work area is well organized and safe
13	C13	Unsafe pallet arrangement	Goods fall and injure workers	Arrange pallets correctly and use tools
14	C211	Moving goods is done without safety	Risk of operator injury	Use personal protective equipment and safety systems when moving goods
15	C212	Placement of goods on an inclined plane	Goods slip and fall	Ensure flat storage surfaces or additional friction flow for inclined planes

16	C221	Operators are not properly trained in moving techniques	Wrong procedure for moving goods	Provide training on shifting techniques
17	C222	Operators do not follow moving SOPs	Potential injury due to negligence	Supervise and ensure SOPs are followed
18	C23	Instability when using moving equipment	Goods fall or roll over	Ensure removal equipment is stable before use
19	C31	Lack of protective cover on the conveyor	Risk of hand being caught in machine	Install guards on the conveyor
20	C32	Technician operators do not use PPE when repairing conveyors	Injury due to work accident	Require the use of PPE when making repairs
21	C33	Technician operator inaccuracy when performing repairs	Risk of tool damage or worker injury	Increase training and vigilance for repairs
22	C41	Direct contact with parts that conduct electricity	Risk of electric shock	Use electrical isolation devices and PPE
23	C42	Electrical equipment that is not maintained	Risk of short circuit and fire	Perform routine maintenance on electrical equipment
24	C51	Not using PPE when applying mold	Risk of skin or respiratory irritation	Use PPE according to work standards
25	C52	Sensor switch damage	Risk of accident due to sensor failure	Check and replace sensors regularly
26	C53	Direct contact with tools that produce fire	Risk of burns	Use proper protective equipment and SOPs
Occupational Health				
27	D11	Use of chemicals	Risk of poisoning and irritation	Use chemicals according to procedures and PPE
28	D12	Not using PPE when in contact with chemicals	Risk of accidents and environmental contamination	Ensure containers are tightly closed when transporting
29	D21	Spills occur during transportation of materials	Risk of poisoning and skin reactions	Require the use of PPE according to standards
30	D22	Chemical spills are not handled properly	Risk of pollution and health hazards	Prepare emergency response procedures for chemical spills that can be handled on the MSDS.

According to this study, the most acute risk in the battery production process is occupational injury, which further confirms the findings of previous studies, which have shown that such accidents often appear when no supervision and discipline of the procedure are observed when working with manual handling and machine operation (Dianto et al. 2022; Suseno and Kalid 2022). Numerous studies highlight the fact that the small operational mishaps, including the misuse of pallets, or electrical equipment touch, frequently escalate to larger accidents, especially when the workers have not been adequately trained or when the industrial protection devices are not always implemented (Zaib et al. 2022; Simanjuntak et al. 2022). These results highlight the fact that improving competency and operation management is still central to the minimization of incidence of injury.

The next most prevalent threat is fire risk, which makes sense when considering the fact that the production line has electrical elements, combustible metal dust, and chemical reactions as part and parcel of the process. As described in the previous research, the risk of ignition and fire propagation in battery-based industries increases due to unsteady raw materials, outdated electrical systems, and inadequate storage procedures (Elfidasari 2023; Nauri et al. 2024). The comparative study among energy and metallurgical plants also proves that preventative

engineering, routine inspection procedures, and strict separation of flammable materials comply better with the prevention than with the emergency intervention when the incident has already taken place (Li et al. 2021). As a result, it is apparent that PT TMB should have a well-organized fire-prevention systems supported by regular maintenance and monitoring.

The field of occupational health risks also deserves to be mentioned, as the long-term effects of such exposures as toxic compounds, including lead and acid fumes, gradually reduce respiratory and dermal health conditions without any immediate symptoms (Irianti et al. 2021; Indra et al. 2021). The presence of chemical risks is often referred to by scholars as silent risks, which accumulate over the time, which explains why personal protective equipment and environmental surveillance enforcement are necessary to maintain the wellbeing of workers (Rosalinda et al. 2023). Though fatigue is also linked to having a reduced likelihood of incident, it nevertheless provides an indirect contribution to the risk of accidents due to reduced attention and worse decision-making, which has also been validated by the current researches on operational ergonomics (Yuantoko and Djunaidi 2022; Sejati et al. 2023).

The Fuzzy Fault Tree Analysis strengthens the analytical framework of the given research study because the approach allows measuring the subjective expert judgment and helps to establish priorities on mitigation when the historical data are unavailable (Li et al. 2021; Zaib et al. 2022; Simanjuntak et al. 2022). These insights would ensure that mitigation activities center on injury control as the main intervention area and the second area of intervention is fire risk management and reduction of chemical exposure. It is supported in literature that a combination of engineering control, procedural adherence, maintenance, and safety awareness, which is integrated prevention, is the most sustainable way to decrease accidents in the industrial environment (Indra et al. 2021; Dianto et al. 2022; Suseno and Kalid 2022). In this regard, the current research will offer a solid ground upon which PT TMB can use to formulate evidence-based safety measures that may be implemented in the future.

Conclusion

this study analyzed the risks in the battery production process using the Fuzzy Fault Tree Analysis (FFTA) method, which resulted in four top events with different probabilities and impacts: fire risk (A) 26.82%, Occupational fatigue (B) 11.57%, Occupational injury (C) 40.58%, and occupational health (D) 21.03%. Top events A and D have a low probability of severe impact, top event B has a low probability and low impact, while top event C has a medium probability and severe impact. Risk mitigation focused on fire prevention, operator injury reduction, and worker health protection. Research suggestions include using other methods such as HAZOP and Chemical Exposure Risk Assessment, as well as assessing the impact of risks on company finances and testing the effectiveness of mitigation.

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