

EMERGENCY FUEL DISTRIBUTION STRATEGY IN CONDITIONS OF TRANSPORTATION ACCESS DISRUPTION DUE TO FLOODING: A CASE STUDY OF THE SUMATRA REGION

Revika Shintha Mustika¹, Melia Eka Lestiani²

¹ University of Logistics and International Business, Bandung, Indonesia

² Lecturer, University of Logistics and International Business, Bandung, Indonesia

Email : revikastuv@gmail.com¹; meliaeaka@ulbi.ac.id²

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Abstract

Transportation disruptions caused by flooding in the Sumatra region often lead to the paralysis of fuel distribution, impacting economic stability and emergency services. This study aims to develop a resilient emergency distribution strategy by identifying critical risks and root causes of failure. The methods used are the integration of Failure Mode and Effect Analysis (FMEA) to determine risk priorities through Risk Priority Number (RPN) and Fault Tree Analysis (FTA) to track the root causes of technical and managerial failures. The results of the study show that seven risk indicators exceed the Critical Value of the average Total RPN Value of 186,89, with the highest risks being in the Fuel Distribution Infrastructure (252.93) and Main Line Vulnerability (226.38). FTA analysis confirmed that dependence on satellite connections in blank spot areas and bureaucratic obstacles were the main factors hindering distribution. As a solution, a Risk Response Plan was developed, which includes: 1) Preventive Action through automatic data synchronization (Digital Ground Checking) and a Green Route MoU; 2) Mitigation through the provision of an alternative fleet (4x4 and ships) with a standby contract system; and 3) Corrective Action in the form of mobilizing heavy equipment and a rapid recovery team. This study provides a strategic framework for maintaining regional energy security even when land infrastructure is completely disrupted.

Keyword: Fuel Distribution; Sumatra Floods; FMEA; FTA; Risk Response Planning

1. Introduction

Natural disasters, such as flash floods and landslides that hit the Sumatra region, routinely test the resilience and adaptability of the national energy supply chain. These disasters not only cause physical infrastructure damage, but also directly create critical supply chain disruptions that trigger fuel shortages. The scarcity of fuel oil after a disaster has a double impact: first, it hinders the mobility of residents for evacuation and meeting basic needs; second, it disrupts the operations of rescue teams, hospitals, and heavy equipment that are crucial for infrastructure recovery.

The fuel shortage that occurred after the disaster in Sumatra was not only a problem of stock availability at fuel terminals, but also a problem of distribution and accessibility. Tanker trucks cannot reach isolated gas stations, causing stock shortages at the retail level. This situation is exacerbated by panic buying, which triggers a sudden surge in demand, depleting remaining stocks. As a result, vital activities such as rescue operations, medical and food aid deliveries, and citizen evacuations are hampered.

This case study was compiled as a strategic solution to overcome fuel shortages after flooding in order to minimize greater losses, both economically and in terms of other emergency service operational failures, by ensuring the smooth running of emergency distribution. Risk identification was conducted comprehensively using the Failure Mode and Effect Analysis (FMEA) method to determine the Risk Priority Number (RPN) and Fault Tree Analysis (FTA) to track the root causes of failure, ranging from extreme weather factors to technical constraints. As an anticipatory measure, a Risk Response Plan was developed, covering preventive action, mitigation, and corrective action.

To date, most disaster management literature has focused on general flood mitigation or population evacuation. However, specific aspects of disaster management have not yet addressed fuel distribution strategies during disasters. This study aims to fill this gap in the literature, particularly by taking a specific case study in the Sumatra region, which has unique geological challenges, such as

landslide-prone areas and extreme regional isolation. Therefore, this study will add to the knowledge of disaster mitigation, especially from the aspect of fuel distribution.

The novelty of this research lies in the integration of FMEA and FTA in the context of post-disaster fuel distribution, which not only identifies priority risks but also maps the causal relationships of failures down to the *basic event* level as a basis for formulating strategic responses.

2. Research Method

The steps in the research are a systematic description that will be used as a reference in conducting the research. The following are the steps taken in this study:

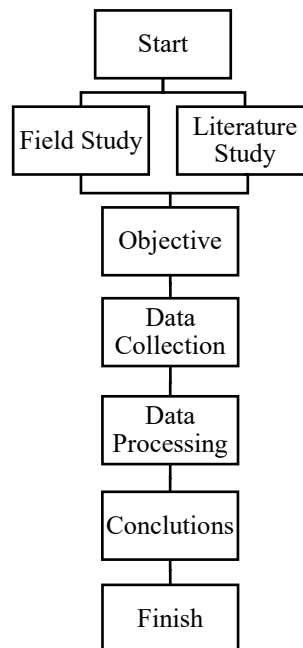


Figure 1. Research Flow Chart

- 2.1. Field Study: Field studies aim to obtain primary data and real-time information about practices, challenges, and risk assessments from field practitioners.
- 2.2. Literature Study: The literature study was conducted using sources such as books, scientific journals, and supporting data related to operational risks.
- 2.3. Research Objectives: This study aims to identify, analyze, and formulate responsive solutions to the risk of fuel distribution delays after flooding in the Sumatra region.
- 2.4. Data Collection: Data was collected qualitatively through field observations and assessments of actual conditions to support the analysis of the risk of fuel distribution failure due to flooding in the Sumatra region. The information collected included descriptions of the physical conditions of the main distribution routes, overviews of seasonal rainfall patterns, and the geological characteristics of the Sumatra region. Risks were identified by compiling a list of potential failures based on field findings.
- 2.5. Data Management: Risk data was processed in three stages. The first stage was critical risk analysis using the Failure Mode Effect Analysis (FMEA) method, which involved calculating the RPN. The second stage was risk analysis using the Fault Tree Analysis (FTA) method. The third stage was a preventive measure, namely Risk Response Planning.
- 2.6. Conclusion: The conclusion is the final stage of this study, which contains conclusions obtained from the results of data collection, processing, and analysis that answer the research objectives set.

3. Result and Discussion

3.1 Data Collection

Information collection was carried out systematically and comprehensively to examine the conditions, facts, and events that occurred. This stage aims to identify risk indicators used as a basis for preparing statements of potential risks in the fuel distribution supply chain in the Sumatra region due to disruption of transportation access caused by flooding. Risk indicators are determined through a breakdown process of each risk variable based on related operational activities.

Table 1. Summary of Risk Variables

Risk Variable	Risk Indicators Compiled
Failure of Land Transportation Access	Vulnerability of main routes Availability of real-time data
Failure of Alternative Resources	Alternative Fleet Readiness Sufficiency of Reserve Stocks
Last-Mile Logistics Failures	Access to fuel distribution points Fuel distribution infrastructure Rapid Decision Making
Failure of Coordination and Regulation	Permits and bureaucracy Standard Operating Procedures and Communication
Failure of Non-Physical External Factors	Consumer Response Market Stability

Next, all identified risks are analyzed for their impact using the Failure Mode and Effect Analysis (FMEA) method.

3.2 Risk Analysis Using The Failure Mode Effect And Analysis (FMEA) Method

At this stage, the identified risk indicators are analyzed using the Failure Mode and Effect Table to assess the possible causes and impacts of each potential failure.

Table 2. Land Transportation Access Failures

Access Failure Land Transportation Main Route Vulnerability	Failure Effect	Possible Mode	Controls Implemented
Critical road closure due to flooding	Total distribution stoppage to one region	Frequently occurs in Sumatra during the rainy season	Easily detected via police/driver reports
Gas stations that can only be accessed by a single distribution route single	no backup route if the road is cut off	Many remote areas in Sumatra only have one proper access	This has been clearly recorded on the logistics map
Access- prone/disrupted areas	risk of trucks getting stuck or accidents	Sumatra is prone to landslides and road collapses	The locations are known, but the timing of the collapses is difficult to predict
Availability of real-time data	Effect failure	Possible modes	Control measures implemented
Accuracy of real-time GIS mapping with field conditions during disaster	Incorrect data renders emergency routes useless	Dependent on satellite connection in blank spot areas	Difficult to know the exact GIS data until the truck arrives at the location

Table 2 shows the sub-indicators for each indicator related to land transportation access. The vulnerability of main routes has three sub-indicators that describe potential risks that may occur. Meanwhile, the second indicator, real-time data availability, has one sub-indicator.

Table 3. Failure of Alternative Resource Access

Failure of Alternative Resources Alternative Fleet Readiness	Effect of Failure	Possible Mode	Controls Implemented
No standby contracts for modes that require a long time to load fuel at alternative ports	Delays in activating ships/barges for days	Often overlooked due to routine cost considerations	Can be detected through administrative audits
Security risks / conditions of new alternative roads	Risk of looting or truck rollovers on back roads	Alternative routes in Sumatra are often narrow/unsafe	Security disturbances on roads are often unpredictable
Sufficiency of reserve stocks	Effect failure	Possible Mode	Controls implemented
Buffer stock at TBBM is	Total stock depletion	Sudden spikes in	Fuel stock levels

insufficient to meet surge in demand / long road closure duration	before access is restored	demand often exceed stock	are monitored by the system every hour
Delays in activating emergency fuel stock management	Internal bureaucracy hindering swift action	Depends on the maturity of SOPs of the company	Delays in response are often only noticed after it is too late
Failure to load fuel at the depot	The main source fails, the entire downstream is paralyzed	Depots usually have stronger flood protection	Detected immediately by depot operators

Table 3 The relationship between alternative resources and disaster management is at the core of emergency logistics strategies, especially in the case of fuel distribution in Sumatra, which is prone to flooding. The table shows two sub- indicators of risk in the readiness of alternative fleets and three sub-indicators of risk in the adequacy of reserve stocks.

Table 4. Last-mile Logistics Failures

Logistics Failure Last-Mile Access to fuel distribution points	Failure Effect	Possible Modes	Controls implemented
Number of partially isolated gas stations	Fuel is in the tank but consumers' vehicles cannot enter	Although the main road has receded/is passable, there is still standing water in the gas station area	Manual reports are required from gas station managers
Fuel distribution infrastructure	Effect failure	Possible Mode	Controls implemented
Gas stations in vulnerable areas that do not have loading and unloading facilities for drumming units or 4x4 tanks	Small tanker trucks arrive but cannot be drained into underground tanks	Infrastructure limitations at gas stations that are not flexible enough to receive supplies from non-standard vehicles non-standard vehicles.	Can be surveyed before the flood season arrives

Table 4 shows the sub-indicators of risk included in the Last-Mile Logistics Failure variable. The fuel access indicator has one sub-indicator, as does the fuel distribution infrastructure indicator, which consists of one sub-indicator.

Table 5. Coordination and Regulation Failures

Failure of Coordination and Regulation Rapid Decision Making	Effect Failure	Possible Mode	Controls implemented
The time required for regional management to decide on an emergency route	Hesitation causes gas stations to run out of fuel faster	Rigid decision- making hierarchy	Difficulty detecting systemic managerial hesitation
Permits and bureaucracy	Failure Effect	Possibility Mode	Controls implemented
Time required to obtain permits from BPBD/TNI/POLRI for tank trucks to pass through disaster zones	Trucks are held at temporary posts while gas station tanks are empty	Number of permit gates at the regional level	The progress of the permit process can be monitored
SOP and Communication	Effect failure	Possible Modes	Controls implemented
Number of vital communication	Loss of control over fleet position	Telecommunications infrastructure is often	Only discovered after the fleet cannot

interruptions (radio/satellite) between the fleet in the field and the emergency control center during operations		damaged during disasters	be contacted
Number of revisions required to the emergency distribution SOP	Confusing for personnel, but the physical impact is low	SOPs should be stable if they have been tested in emergency conditions	Clearly visible in administrative documents

Table 5 shows the sub-indicators of risk found in the variables of Coordination and Regulatory Failure. The rapid decision-making indicator has 1 sub-indicator, the licensing and bureaucracy indicator consists of 1 sub-indicator, while the SOP and communication indicator has 2 sub-indicators.

Table 6. Non-Physical External Factor Failures

Failure Non- Physical External Factors Consumer Response	Failure Effect	Possible Modes	Controls implemented
Surge in demand/panic buying due to supply uncertainty	Emergency stocks depleted 3 times faster than predicted	Mass psychology when hearing rumors of fuel shortages	Visible from the surge in queues at gas stations
Price Stability	Failure Effect	Possible Mode	Control measures implemented
Fuel distributed is sold at unreasonable prices due to supply disruptions	Social instability and public complaints	Illegal retailers take advantage of the flood situation	Difficult to monitor because it occurs in the black market/non-gas stations

Table 6 shows the risk sub-indicators found in the Consumer Response and Price Stability variables. The consumer response indicator consists of 1 sub-indicator, as does the price stability indicator, which has 1 sub-indicator.

The next stage involves assessing the Severity, Occurrence, and Detection (SOD) levels for each indicator in order to obtain a Risk Priority Number (RPN) and determine critical risks. The SOD assessment scale is set at levels 1 to 10. This assessment involves five expert respondents, consisting of three representatives from the Regional Disaster Management Agency (BPBD) and two representatives from PT Elnusa Petrofin. The number of respondents is limited to five experts because FMEA based on expert judgment emphasizes depth of experience. The involvement of these five respondents was based on their competence and experience in planning and implementing emergency fuel distribution strategies after floods in the Sumatra region.

Table 7. List of Respondents

No	Name	Agency	Position
1	Respondent (1)	Regional Disaster Management Agency	Head of Emergency and Logistics Division
2	Respondent (2)	Regional Disaster Management Agency	Field Coordination
3	Respondent (3)	Regional Disaster Management Agency	TRC Member
4	Respondent (4)	PT ELNUSA PETROFIN	Manager
5	Respondent (5)	PT ELNUSA PETROFIN	Staff

Severity Value

Severity is the first step in analyzing risk, which is to calculate how severe the impact of failure will be on the continuity of fuel supply to the community. The impact is rated on a scale of 1 to 10, where 10 is the worst impact. The ratings are determined based on the table below:

Table 8. Severity Rating Scale

Rank	Severity	Description
10	Extremely Severe	System failure that causes extreme impact and is highly dangerous
9	Severe	System failure that causes serious risk of danger
8	Very High	System cannot function at all
7	High	The system is still running, but cannot be used optimally
6	Moderate	The system is operating but experiencing a decline in performance that impacts results/output.
5	Low	A gradual decline in system performance occurred
4	Very Low	Minimal impact on system performance
3	Minor	Slight disruption to system performance
2	Very minor	Impact on the system is minimal and can be ignored
1	No effect	Does not cause any impact

Occurrence Value

Once the severity rating has been determined, the next step is to determining the for occurrence. Occurrence is the likelihood of how often such failures occur in the Sumatra region. Occurrence is a rating value adjusted to the estimated frequency and/or cumulative number of failures that may occur. The determination of the degree and rating of occurrence can be seen in the table below.

Table 9. Occurrence Rating Scale

Rank	Occurrence	Description
10	Very high	Frequently fails
9		
8		
7	High	Repeated failures
6		
5	Moderate	Rare failures
4		
3	Low	Very low failure rate
2		
1	No effect	Almost no failure

Detection value

After obtaining the occurrence value, the next step is to determine the detection value. The determination of the detection value can be seen in the table below.

Table 10. Detection Value Scale

Ranking	Detection	Description
10	Almost Impossible	The inspection process is almost incapable of identifying potential causes, failure mechanisms, or failure modes
9	Very Difficult	Inspectors have a very small chance of detecting potential causes, failure mechanisms, and failure modes.
8	Difficult	The likelihood of the inspection identifying potential causes or failure mechanisms and modes is low.
7	Very low	The examination has a very low chance of finding potential causes, failure mechanisms, or failure modes.
6	Low	The ability of inspections to detect potential causes, failure mechanisms, and failure modes is still limited
5	Moderate	The inspection has a moderate level of probability in identifying potential causes, failure mechanisms, and failure modes
4	Above average	The inspection has a fairly good chance of detecting potential causes, failure mechanisms, and failure modes.
3	High	The examiner has a high probability of identifying potential causes, failure mechanisms, and failure modes.
2	Very High	The examiner is almost always able to detect potential causes, failure mechanisms, and failure modes.

1	Almost certain	The inspection process always successfully identifies potential causes, failure mechanisms, and failure modes.
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The severity, occurrence, and detection values are obtained from the average values given by respondents. The average value for each indicator is obtained by dividing the total number of values by the number of indicators assessed.

Table 11. Calculation of Risk Priority Number for Land Transportation Access Failure

Land Transportation Access Failure	S	O	D
Main Route Vulnerability			
Critical road closures due to flooding	8,2	7	4
Gas stations that can only be accessed via a single distribution route	8,4	6,8	4,2
Vulnerable points / access disruption	8	6,6	4
Average (SOD Indicator Weight)	8,2	6,8	4,06
Real-time data availability	S	O	D
Accuracy of real-time GIS mapping with field conditions during disasters	7,8	6,8	3,6
Average (SOD Indicator Weight)	7,8	6,8	3,6

Table 12. Calculation of Risk Priority Number for Alternative Resource Access Failure

Alternative Resource Failure	S	O	D
Alternative Fleet Readiness			
There are no standby contracts for modes of transport that requires a long time to load fuel at the alternative port	7,8	6,6	3,8
Safety concerns / condition of the new alternative road	7,6	6,6	3,6
Average (SOD Indicator Weight)	7,7	6,6	3,7
Sufficiency of Reserve Stocks	S	O	D
Buffer stock at TBBM is insufficient to meet surge in demand / long road closure duration	7,6	6,6	3,6
Delay in Activating Emergency Fuel Stock Management	7,6	6,6	3,6
Failure to Load Fuel at Depot	7,6	6,8	3,6
Average (SOD Indicator Weight)	7,6	6,67	3,6

Table 13. Calculation of Risk Priority Number for Last-Mile Logistics Failures

Last-Mile Logistics Failures	S	O	D
Access to fuel distribution points			
Number of partially isolated gas stations	7,6	6,4	3,6
Average (SOD Indicator Weight)	7,6	6,4	3,6
Fuel Distribution Infrastructure	S	O	D
Gas stations in vulnerable areas that do not have loading and unloading facilities for <i>drumming</i> units or 4x4 tanks	7,6	6,4	5,2
Average (SOD Indicator Weight)	7,6	6,4	5,2

Table 14. Calculation of Risk Priority Number for Coordination and Regulation Failures

Failure of Coordination and Regulation	S	O	D
Rapid Decision Making			

Time required for regional management to decide on emergency routes	7,8	6,6	3,8
Average (SOD Indicator Weight)	7,8	6,6	3,8
Permits and Bureaucracy	S	O	D
Time required to obtain permission from BPBD/TNI/POLRI for tank trucks to pass through disaster zones	7,8	6,2	4,4
Average (SOD Indicator Weight)	7,8	6,2	4,4
SOP and Communication	S	O	D
Number of vital communication disruptions (radio/satellite) between the fleet in the field and the emergency control center during operations	7,8	6,4	4,8
Number of revisions required to the emergency distribution SOP	7,6	6,2	3,4
Average (SOD Indicator Weight)	7,7	6,3	4,1

Table 15. Calculation of Risk Priority Number for Non-Physical External Factor Failures

Non-Physical External Factor Failure	S	O	D
Consumer Response			
Surge in <i>demand/panic buying</i> due to supply uncertainty	7,8	6,2	2,2
Average (SOD Indicator Weight)	7,8	6,2	2,2
Price Stability	S	O	D
Fuel distributed is sold at unreasonable prices due to supply disruptions	8,2	7	2,2
Average (SOD Indicator Weight)	8,2	7	2,2

Table 16. Recapitulation of Risk Priority Number Calculations

Risk Indicator	RPN
Main Route Vulnerability	226,3
Real-time Data Availability	190,94
Alternative Fleet Readiness	188,03
Sufficiency of Reserve Stock	182,49
Access to fuel distribution points	175,10
Fuel distribution infrastructure	252,93
Rapid decision-making	195,62
Permits and bureaucracy	212,78
SOP and Communication	198,89
Customer Response	106,39
Market Stability	126,28
Total RPN	2055,83
Critical Value	186,89

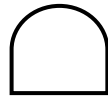
From the analysis results, seven critical risk indicators were obtained, namely main route vulnerability, real-time data availability, alternative fleet readiness, fuel distribution infrastructure for fuel distribution, rapid decision-making, licensing and bureaucracy, and SOPs and communication. Table 16 presents a summary of the Risk Priority Number (RPN) values for all risk indicators, where the critical value is calculated by dividing the total RPN by the number of indicators assessed.

3.3 Critical Risk Analysis with Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is used to describe the relationship between failures in a system and the causes that lead to those failures. Each fault tree is constructed based on a top event, which then forms branches containing events that contribute to the occurrence of the top event. These branches will stop when all relevant causal events have been identified.

In a fault tree, certain symbols are used to show the relationships between events that are necessary for

the top event to occur. These symbols describe the types of relationships and interactions between each event in the fault tree, namely:



The AND gate indicates a condition in which all events below the gate (input events) must occur for the event above the gate (output event) to occur. In other words, the output event will only occur if all input events occur simultaneously.

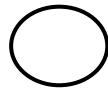


An OR gate describes a condition in which one or more events below the gate (input events) can cause an event above the gate (output event) to occur. In other words, the output event will occur if at least one of the input events occurs.

The following symbols are used to represent an event or occurrence in a fault tree:



A rectangle is the main block in a fault tree used to represent a negative event. This symbol is usually located at the top of the tree (top event), but can also be placed along the tree to indicate other events that can be further developed. This rectangle is a symbol that has a logic gate and input events below it.



Circles are used to represent basic events in a fault tree. This symbol is located at the bottom of the tree and does not require further development or details. Circles do not have gates or input events underneath them.



Diamonds are used to identify undeveloped events. These events cannot be further elaborated due to limited available information.

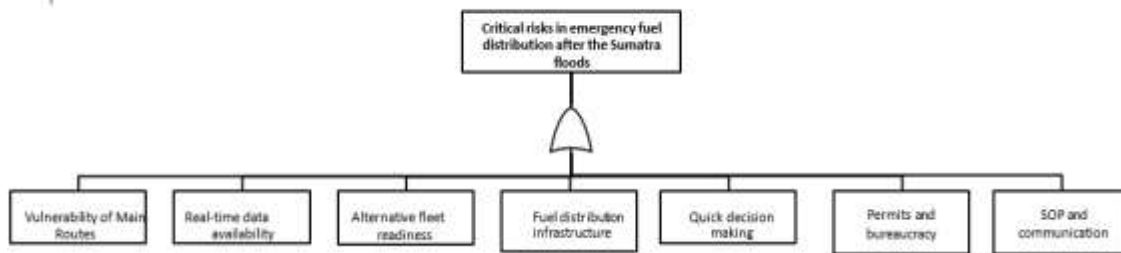


Figure 2. Top Critical Risk Events in Emergency Fuel Distribution after the Sumatra Flood Disaster

The analysis results show the top risk events in the emergency distribution of fuel after the flood disaster. From the FMEA process, seven critical risks were identified, which will be further analyzed to identify the basic events of each of these top events.

FTA Main Route Vulnerability Indicators

Table 17. Main Route Vulnerability Indicators

Main Route Vulnerability	
1	Closure of critical roads due to flooding
2	Gas stations that can only be accessed by a single distribution route
3	Vulnerable points / access disruption

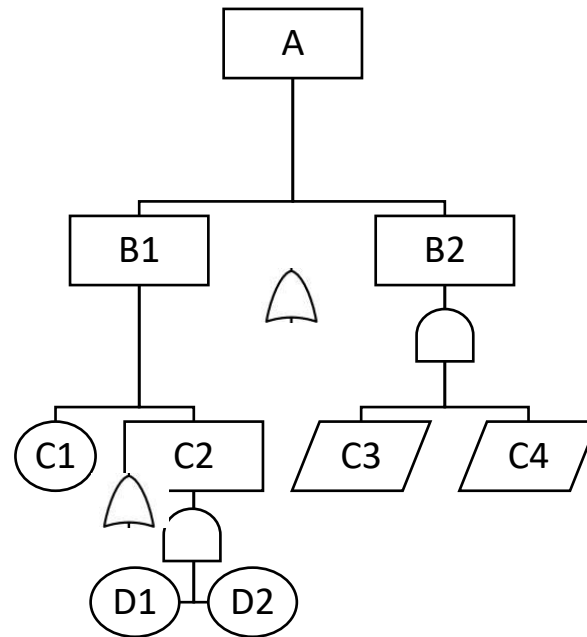


Figure 3. FTA Main Route Vulnerability Indicator

Table 18. Description of the Main Route Vulnerability FTA indicator

EVENT	TYPE	DESCRIPTION	EVENT	TYPE	DESCRIPTION
A	OR	Failure of land transportation access on the main distribution route	B2	AND	Infrastructure design factors
B1	OR	Weather and environmental factors	C3	BASIC	Absence of backup routes
C1	BASIC	High seasonal rainfall factor	C4	BASIC	Limited road access
C2	AND	Geological characteristics of Sumatra			
D1	BASIC	Uncertainty of damage time			
D2	BASIC	Area isolation			

$$A = B1 + B2$$

$$B1 = C1 + C2$$

$$B2 = C3 \cdot C4$$

$$C2 = D1 \cdot D2$$

The equation for the peak event can be obtained through a substitution process, ultimately forming an equation that represents the top event.

$$A = (C1 + C2) + (C3.C4)$$

$$A = (C1 + (D1.D2)) + (C3.C4)$$

$$A = C1 + D1.D2 + C3.C4$$

This results in a minimum cut set, namely:

MCS 1 = {C1} High seasonal rainfall factor (a single failure directly causes land transportation access on the main distribution route to fail)

MCS 2 = {D1D2} Uncertainty of damage timing **AND** regional isolation (both cause land transportation failure on the main distribution route through the geological characteristics of Sumatra)

MCS 3 = {C3C4} Absence of backup routes **AND** limited road access (both causing land transportation failure on the main distribution route through infrastructure design factors)

FTA indicator Real-time data availability

Table 19. Real-time data availability indicators

Real-time data availability	
1	Accuracy of real-time GIS mapping with field conditions during disasters

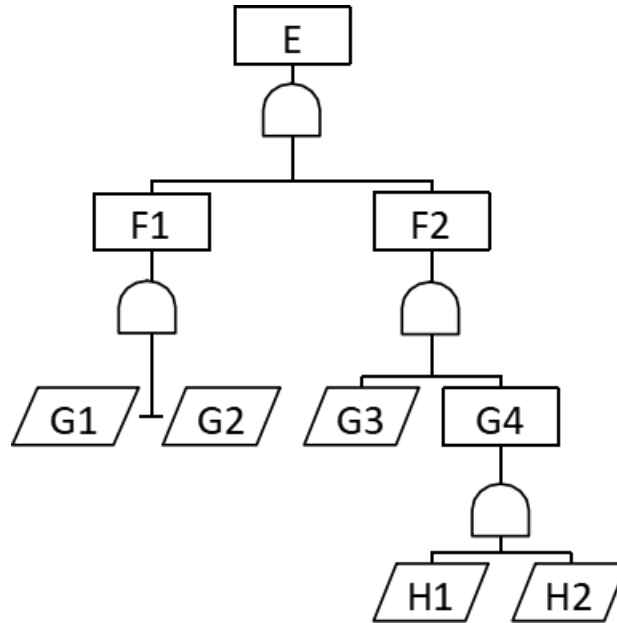


Figure 4. FTA indicator for real-time data availability

Table 20. Description of the FTA indicator for real-time data availability

EVENT	TYPE	DESCRIPTION	EVENT	TYPE	DESCRIPTION
E	AND	Real-time data availability failure	F2	AND	Input inaccuracies and field data updates
F1	AND	Dependence on communication infrastructure in blank spot areas	G3	BASIC	Data that is not relevant to real conditions
G1	BASIC	Absence of satellite/GSM signal	G4	AND	Emergency route interpretation error
G2	BASIC	Failure of automatic data transmission	H1	BASIC	System inability to synchronize data
			H2	BASIC	Limitations of physical sensors at the disaster site

$$E = F1 \cdot F2$$

$$F1 = G1 \cdot G2$$

$$F2 = G3 \cdot G4$$

$$G4 = H1 \cdot H2$$

The equation for the peak event can be obtained through a substitution process, ultimately forming an equation that represents the top event.

$$E = (G1 \cdot G2) \cdot (G3 \cdot G4)$$

$$E = (G1 \cdot G2) \cdot (G3 (H1 \cdot H2))$$

$$E = G1 \cdot G2 \cdot G3 \cdot H1 \cdot H2$$

Thus, the minimum cut set is obtained, namely:

{G1.G2.G3.H1.H2} Failure of real-time data availability only occurs if **ALL FIVE** factors (absence of signal, transmission failure, irrelevant data, inability to synchronize, and sensor limitations) occur simultaneously.

FTA indicator of Alternative Fleet Readiness

Table 21. Alternative Fleet Readiness Indicators

Alternative Fleet Readiness	
1	No standby contracts for modes that require a long time to load fuel at alternative ports
2	Security concerns / condition of new alternative roads

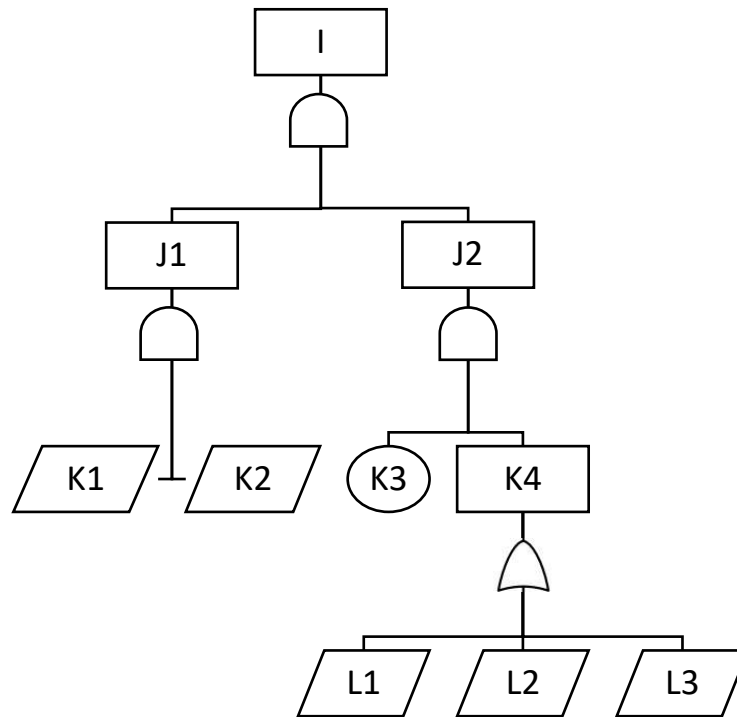


Figure 5. FTA Alternative Fleet Readiness Indicators

Table 22. Description of FTA Alternative Fleet Readiness Indicators

EVENT	TYPE	DESCRIPTION	EVENT	TYPE	DESCRIPTION
I	AND	Failure of alternative fleet readiness	J2	AND	Inadequate infrastructure facilities
J1	AND	Contract and administrative issues	K3	BASIC	Fleet specifications do not match the gas station
K1	BASIC	Absence of a standby contract	K4	OR	Work safety issues
K2	BASIC	Delays in administrative processes	L1	BASIC	Damage to fleet due to extreme terrain
			L2	BASIC	Lack of trained drivers
			L3	BASIC	Limited access to decent roads

$$I = J1 \cdot J2$$

$$J1 = K1 \cdot K2$$

$$J2 = K3 \cdot K4$$

$$K4 = L1 + L2 + L3$$

The equation for the peak event can be obtained through a substitution process, ultimately forming an equation that represents the top event.

$$I = (K1 \cdot K2) \cdot (K3 \cdot K4)$$

$$I = (K1 \cdot K2) \cdot (K3(L1 + L2 + L3))$$

$$I = (K1 \cdot K2 \cdot K3 \cdot L1) + (K1 \cdot K2 \cdot K3 \cdot L2) + (K1 \cdot K2 \cdot K3 \cdot L3)$$

Thus, the minimum cut set is obtained, namely:

$$MCS 1 = \{K1 \cdot K2 \cdot K3 \cdot L1\}$$

$$MCS 2 = \{K1 \cdot K2 \cdot K3 \cdot L2\}$$

$$MCS 3 = \{K1 \cdot K2 \cdot K3 \cdot L3\}$$

This system is highly dependent on standby contracts, administrative processes, and fleet specifications. If one of these three components functions properly, then failure of the alternative fleet readiness will never occur, even though one of the critical points is fleet damage due to extreme terrain, lack of trained drivers, and limited access to passable roads.

FTA Fuel Distribution Infrastructure Indicators

Table 23. Fuel Distribution Infrastructure Indicators

Fuel Distribution Infrastructure	
1	Gas stations in vulnerable areas that do not have loading and unloading facilities for <i>drumming</i> units or 4x4 tanks

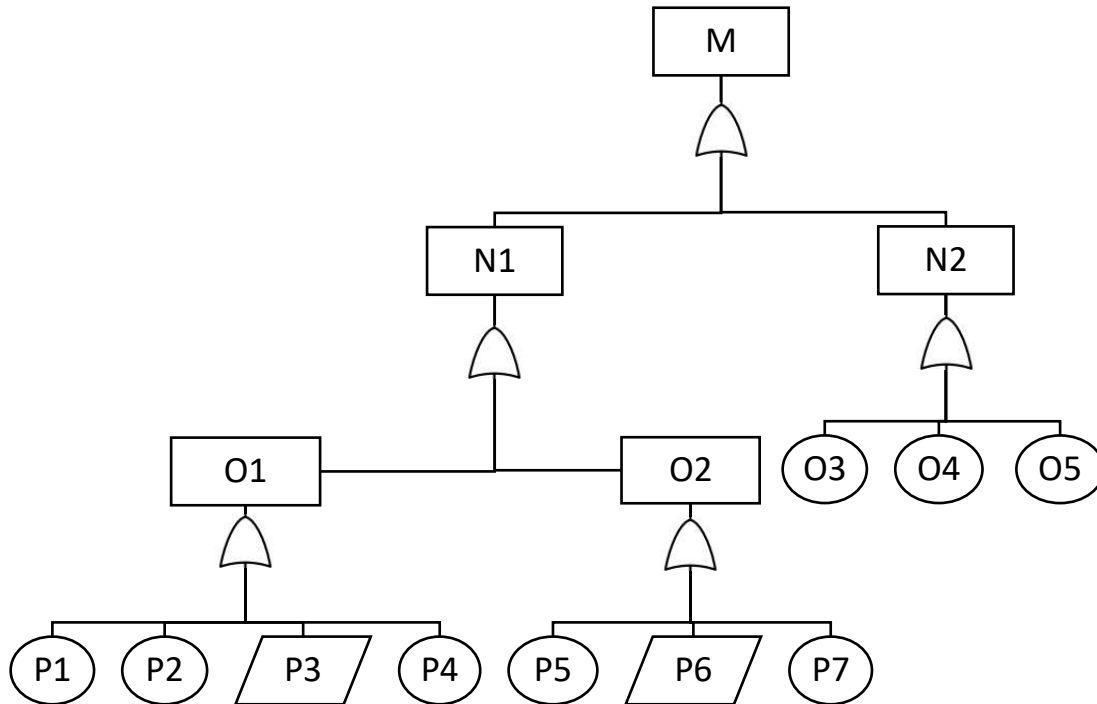


Figure 6. FTA Fuel Distribution Infrastructure Indicator

Table 24. Description of FTA indicators for Fuel Distribution Infrastructure

EVENT	TYPE	DESCRIPTION	EVENT	TYPE	DESCRIPTION
M	OR	Failure of fuel distribution infrastructure	N2	OR	Disconnected access
N1	OR	Facility failure at the fuel terminal	O3	BASIC	Bridge Collapse
O1	OR	Failure of lines and connections Distribution	O4	BASIC	Road flooded
P1	BASIC	Damage to the loading pump	O5	BASIC	Landslide
P2	BASIC	Damage to docks/pipelines			
P3	BASIC	Water contamination in storage tanks			
P4	BASIC	Failure of the backup electrical system (generator)			
O2	OR	Failure of facilities at gas stations			
P5	BASIC	Damage to dispenser and nozzle			
P6	BASIC	Leakage from underground tank			
P7	BASIC	Unloading capacity is incompatible			

$$M = N1 + N2$$

$$N1 = O1 + O2$$

$$N2 = O3 + O4 + O5$$

$$O1 = P1 + P2 + P3 + P4$$

$$O2 = P5 + P6 + P7$$

The equation for the peak event can be obtained through a substitution process, ultimately forming an equation that represents the top event.

$$M = (O1 + O2) + (O3 + O4 + O5)$$

$$M = ((P1 + P2 + P3 + P4) + (P5 + P6 + P7) + ((O3 + O4 + O5)$$

$$M = P1+P2+P3+P4+P5+P6+P7+O3+O4+O5$$

Thus, the minimum cut set is obtained, namely:

$$MCS = \{ P1+P2+P3+P4+P5+P6+P7+O3+O4+O5 \}$$

The fault tree structure, which is entirely based on **OR** gates, indicates the absence of a system redundancy mechanism, so that each basic event has the potential to become a single point of failure. Because there are 10 possible single causes (loading pump failure, dock/pipeline failure, water contamination in storage tanks, backup power system failure, dispenser and nozzle failure, underground tank leakage, incompatible unloading capacity, bridge collapse, flooded roads, and landslides), a minor failure at the lower level can have fatal consequences at the peak event, namely the failure of the fuel distribution infrastructure.

FTA Rapid Decision-Making Indicators

Table 25. FTA Rapid Decision Making Indicators

Rapid Decision Making	
1	Time required for regional management to decide on an emergency route

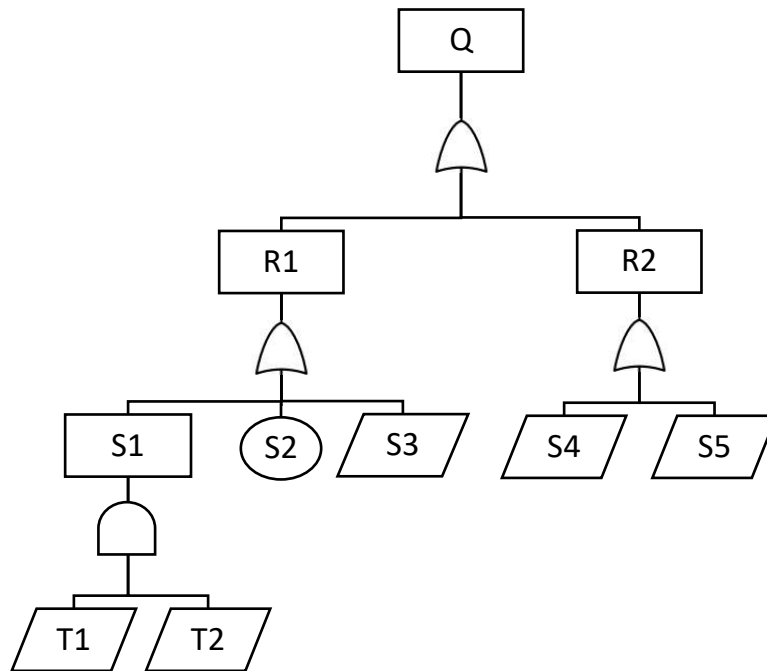


Figure 7. Rapid Decision-Making Indicators

Table 26. Explanation of FTA indicators for Rapid Decision Making

EVENT	TYPE	DESCRIPTION	EVENT	TYPE	DESCRIPTION
Q	OR	Failure to Make Quick Decisions	R2	OR	External coordination constraints
R1	OR	Bureaucratic and organizational barriers	S4	BASIC	Delays in obtaining permits from relevant agencies
S1	AND	Instability of Emergency	S5	BASIC	Uncertainty of road

		Distribution SOP	handling time
T1	BASIC	Normalcy Bias	
T2	BASIC	Lack of crisis simulation	
S2	BASIC	Layered approval structure	
S3	BASIC	Unclear field authority	

$$Q = R1 + R2$$

$$R1 = S1 + S2 + S3$$

$$R2 = S4 + S5$$

$$S1 = T1 \cdot T2$$

The equation for the peak event can be obtained through a substitution process, ultimately forming an equation that represents the top event.

$$Q = (S1 + S2 + S3) + (S4 + S5)$$

$$Q = ((T1 \cdot T2) + S2 + S3) + (S4 + S5)$$

$$Q = T1 \cdot T2 + S2 + S3 + S4 + S5$$

Thus, the minimum cut set is obtained, namely:

$$MCS 1 = \{T1 \cdot T2\}$$

$$MCS 2 = \{S2 + S3 + S4 + S5\}$$

This system has **4 single points** of failure and **1 redundancy point** that triggers bureaucratic and organizational obstacles.

FTA Permit and Bureaucracy Indicators

Table 27. Permit and bureaucracy indicators

Permits and bureaucracy	
1	Time required to obtain permits from BPBD/TNI/POLRI for tank trucks to pass through disaster zones

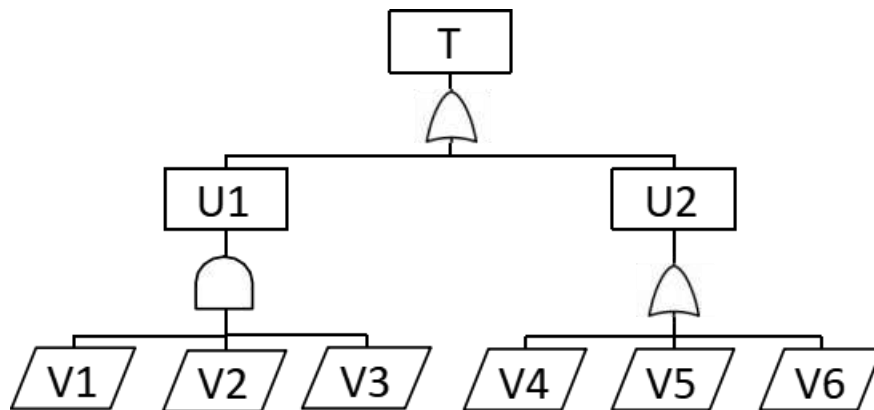


Figure 8. FTA Permit and bureaucracy indicators

Table 28. Description of FTA indicators on licensing and bureaucracy

EVENT	TYPE	DESCRIPTION	EVENT	TYPE	DESCRIPTION
T	OR	Failure of permits and bureaucracy	U2	OR	Communication and data transparency
U1	AND	Barriers to coordination between agencies	V4	BASIC	Delays in issuing emergency crossing permits
V1	BASIC	Lack of liaison officers	V5	BASIC	Delays in verifying partner documents
V2	BASIC	Cross-regional regulatory inconsistencies	V6	BASIC	Inaccurate supporting data for permits
V3	BASIC	Absence of priority protocol (golden path)			

$$T = U1 + U2$$

$$U1 = V1.V2.V3$$

$$U2 = V4 + V5 + V6$$

The equation for the top event can be obtained through a substitution process, ultimately forming an equation that represents the top event.

$$T = U1 + U2$$

$$T = (V1.V2.V3) + (V4 + V5 + V6)$$

$$T = V1.V2.V3+V4+V5+V6$$

Thus, the minimum cut sets are obtained, namely:

$$MCS 1 = \{V1\}$$

$$MCS 2 = \{V2\}$$

$$MCS 3 = \{V3\}$$

$$MCS 4 = \{V4+V5+V6\}$$

Achieving successful coordination between agencies requires the support of liaison officers, cross-regional regulatory synchronization, and the existence of a priority protocol (golden path) simultaneously. In the event of delays in issuing emergency crossing permits, delays in verifying partner documents, and inaccuracies in supporting permit data are the most critical points in this system. Failure in any of these three areas will immediately trigger permit failure and bureaucracy.

FTA SOP and Communication Indicators

Table 29. SOP and Communication Indicators

SOP and Communication	
1	Number of vital communication disruptions (radio/satellite) between the fleet in the field and the emergency control center during operations
2	Number of revisions required to the emergency distribution SOP

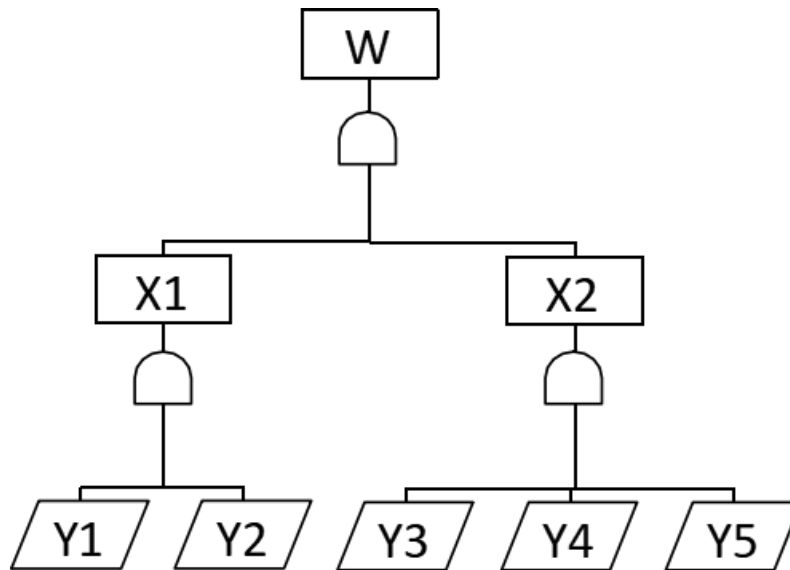


Figure 9. FTA SOP and Communication Indicators

Table 30. Explanation of FTA indicators for SOP and Communication

EVENT	TYPE	DESCRIPTION	EVENT	TYPE	DESCRIPTION
W	AND	Failure of SOP and communication	X2	AND	Weaknesses in SOP design and adaptation
X1	AND	Human factors and competencies (human resources)	Y3	BASIC	SOPs are too rigid for emergency conditions
Y1	BASIC	Non-compliance with protocols	Y4	BASIC	SOP instability
Y2	BASIC	Unclear roles in critical protocols			

$$W = X1 \cdot X2$$

$$X1 = Y1 \cdot Y2$$

$$X2 = Y3 \cdot Y4 \cdot Y5$$

The equation for the top event can be obtained through a substitution process, ultimately forming an equation that represents *the top event*.

$$W = (Y1 \cdot Y2) \cdot (Y3 \cdot Y4 \cdot Y5)$$

$$W = Y1 \cdot Y2 \cdot Y3 \cdot Y4 \cdot Y5$$

Thus, *the minimum cut set* is obtained, namely:

$$MCS = \{Y1 \cdot Y2 \cdot Y3 \cdot Y4 \cdot Y5\}$$

The peak event of SOP and communication failure will occur if **all five basic events occur simultaneously**. If one of the five factors is successfully prevented, the entire system will remain safe.

From *the Fault Tree Analysis* that has been conducted, several *basic events* are obtained for each *top event*. Furthermore, based on the identification of these *basic events*, appropriate solution or handling steps will be formulated.

Risk Response Planning

Based on the results of the Fault Tree Analysis (FTA) and the risk table with a critical value of 186,89, the Risk Response Planning designed for the emergency fuel distribution route in Sumatra is recommended as follows:

Main Route Vulnerability, focusing on mitigating physical barriers that disrupt land transportation access (**RPN 226,38**)

Preventive action: Conduct field surveys during clear weather to map escape routes and physically validated safety zones.

Mitigation: Periodically map landslide and flood-prone areas and keep heavy equipment on standby at strategic locations along the Sumatra route.

Corrective action: Activate and dispatch the alternative fleet immediately after the main route is declared impassable due to flooding or landslides.

Real-Time Data Availability, focusing on providing accurate information to reduce administrative activity risks (**RPN 190,94**)

Preventive action: Develop an automatic synchronization system between fuel station stock data and the control center (Digital Ground Checking) to minimize data inaccuracies.

Mitigation: Prepare a backup satellite connection so that if the main data route is cut off during flooding, data can still be sent (reducing the adverse effects of connection loss).

Corrective action: Conduct manual reporting/physical verification immediately after the digital system is detected to have experienced a total disruption due to a disaster.

Alternative fleet readiness, This strategy aims to ensure the availability of non-regular modes of transportation when the main route is cut off (**RPN 188,03**).

Preventive action: Establish standby contracts/agreements with third parties for the provision of special fleets such as 4x4 tank trucks, small trucks, or barges that can be activated immediately during flood emergencies.

Mitigation: Conducting special simulation training for alternative fleet drivers on safety procedures in flood conditions and emergency navigation techniques.

Corrective action: Activate and dispatch the contracted 4x4 fleet or barges (standby contract) immediately after the main land route is declared completely impassable.

Fuel Distribution Infrastructure, focusing on monitoring key assets to maintain inventory management (**RPN 252,93**)

Preventive action: Build flood barriers around storage tank areas to prevent water from entering and damaging the system.

Mitigation: Insure critical distribution assets to ensure the availability of recovery funds and minimize economic losses to the company.

Corrective action: Renovate or replace damaged gas station pumps and dispensers immediately after floodwaters recede.

Rapid Decision Making, this strategy focuses on the speed of management response with the support of accurate data (**RPN 195,62**)

Preventive action: Develop emergency authority protocols that allow regional managers to make discretionary decisions (such as route diversions or use of emergency funds) without waiting for multiple layers of approval from headquarters.

Mitigation: Establish technical indicators (e.g., if the flood height at point X > 50 cm, then automatically

divert the route to route B) to reduce thinking time during a crisis.

Corrective action: Regional managers immediately take operational control using emergency funds to rent temporary warehouses or local transportation modes without waiting for approval from headquarters.

Permits and bureaucracy, This strategy is designed to cut through administrative barriers that slow down distribution (**RPN 212,78**).

Preventive action: Sign a pre-disaster Memorandum of Understanding (MoU) with BPBD, TNI, and Polri to implement a "green lane" for fuel fleets to receive escort and priority passage.

Mitigation: Simplifying internal administrative SOPs specifically for emergency conditions

Corrective action: Assign special personnel at the regional aid coordination post to handle permits face-to-face and speed up the bureaucratic process in the field

SOP and Communication, Focus on systemic improvements to reduce human resource management risks (**RPN 198,89**).

Preventive action: Conducting routine emergency response simulations for all distribution personnel so they understand their roles in the SOP without having to wait for multiple layers of instructions

Mitigation: Establish a temporary command center that serves as the sole source of instruction (Single Point of Command) to avoid overlapping orders that confuse human resources in the field.

Corrective action: Send special staff to locations that have lost contact to coordinate face-to-face and take over operational control at isolated points.

4. Conclusion

Based on a series of analyses that have been carried out, starting from FMEA identification, determining critical RPN values, to mapping root causes through Fault Tree Analysis (FTA), the following are the main conclusions:

a. Identification of the Most Critical Risks

Quantitative analysis results show that Fuel Distribution Infrastructure (RPN 252,93) is the most critical risk indicator. This indicates that physical damage to facilities poses the greatest threat to the smooth distribution of fuel. Other high risks arise in the areas of main route vulnerability and bureaucratic permits, which are the next critical factors that require immediate attention due to their significant impact on response speed.

b. Causality Relationships in Fault Tree Analysis

Through the FTA approach, it was found that distribution failure is not a single event, but rather an accumulation of various interrelated factors: *Natural & environmental factors:* Sumatra's unstable geological characteristics and high seasonal rainfall are the main triggers for road subsidence and flooding at critical points. *Systemic & technological weaknesses:* real-time data failure was triggered by inaccurate GIS mapping and dependence on satellite connections in blank spot areas, resulting in ineffective/misguided decision-making. *Design limitations:* Distribution is often completely halted due to reliance on a single distribution route and limited access to suitable roads for tanker fleets.

c. Contribution to Energy Security: The implementation of this emergency distribution strategy provides a concrete solution to overcome fuel shortages after flooding, thereby minimizing the potential for wider economic losses. This study fills a gap in the literature on energy distribution in disaster areas, providing a framework for stakeholders to maintain energy supply stability even when land transportation infrastructure is completely disrupted.

The integrated FMEA–FTA approach has proven effective not only in prioritizing risks but also in revealing the systemic failure structure of post-disaster fuel distribution.

Bibliography

A, S., & N, Z. S. (2004). Joint Technical Committee Risk Management. *Standart Risk Management*, 4360.

Abrar Husen, M. (2009,2011). *Manajemen Proyek*. Jakarta.

Amalia, R. (Sept 2012). Analisa keterlambatan proyek pembangunan sidoarjo Town Square menggunakan metode Fault Tree Analysis (FTA). In *Jurnal Teknik ITS Vol 1 No 1* (pp. ISSN : 2301-9271). Surabaya: Institut Teknologi Surabaya.

Andinda, F. M. (2014). Analisa keterlambata proyek menggunakan metode fault tree analysis (FTA).

Aningrum, A. S., Rudianto, H., Mahmudi, A., & Prasetyo, E. (2024). Analisis Faktor Penyebab Keterlambatan menggunakan metode fault tree analysis (Studi Kasus pembangunan Office Headquarter Surabaya). *Jurnal Inter Tech*.

Clemens, P. L. (2002). Fault Tree Nalysis, Fourt edition. In J. Sverdrup. George Washington University.

- Fafedi Eting, F. (1945, Agustus 17). Menghitung Biaya dan Waktu dengan metode Critical Path Method pada proyek pembangunan double decker mapolda Jawa Tengah. *Jurnal Teknik UNTAG VOL.1 No 35 (2018) ISSN : 1701-8101*.
- Fitria, M., & Faisal. (2009, Desember). Penggunaan Aljabar Boolean dalam menganalisis kegagalan pada Fault Tree Analysis. *Jurnal Matematika Murni dan Terapan Vol 3 No 2, 27-38*.
- Frame, J. D. (2003). *Managing Risk in Organizations, a guide for managers*. San Fransisco, USA: Jossey Bass.
- Gasperz, V. (2001). *Total Quality Management*. Jakarta: PT Gramedia Pustaka Utama.
- Hanafi, M. M. (2006). *Manajemen Risiko*. Yogyakarta: Unit Penerbitan Percetakan Sekolah Tinggi Ilmu Manajemen YKPN.
- Jervis, B. M., & Levinn, P. (1988). *Construction Law*. McGraw-Hill: Inc.
- Johsonbaugh, R. (2001). *Discrete Mathematics Fifth Edition*. Pretince Hall: New Jersey.
- Lipschutz, S., & Marc Lars Lipson. (2001). *Seri Penyelesaian Soal Schaum Jilid 1 Matematika Diskrit*. Jakarta: Salemba Teknika.
- McDermott, R. E., Mikulak, J. E., & Beauregard, M. R. (1996). *The Basics of FMEA*. New York: Productivity Press.
- Rosih, R. A., Choiri, M., & Yuniarti, R. (n.d.). Analisis Risiko Operasional pada Departemen Logistik dengan menggunakan metode FMEA. *Jurnal rekayasa dan manajemen sistem industri Vol 3 No 3 Teknik Industri Universitas Brawijaya*.
- Servanio, D. (2019). Analisis Penyebab keterlambatan pada proyek pembangunan gedung kandang hewan Fakultas Kedokteran Unair C Surabaya menggunakan metode Fault Tree Analysis (FTA). *Jurnal Teknik Untag Vol 1 No 22, ISSN : 1701-9601*.
- Tchankova, L. (2002). Risk identification - basic stage in risk management. *Enviromental Management and Health, Vol.13, pp.290-297*.
- Vaughan, C. A. (1976). *Risk Management and Isurance*. New York: Mc Graw-Hill.