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Risk Management of Subsea Pipeline Integrity and Failure Prevention

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Abstract**—** Subsea pipelines are critical offshore infrastructures used to transport oil, gas, and produced fluids. However, they are continuously exposed to corrosion, environmental loads, mechanical degradation, and third-party interference that may cause leakage, structural damage, or operational failure. This study aims to evaluate the risk of subsea pipeline damage and to develop an integrated failure-prevention framework by combining Fault Tree Analysis, Event Tree Analysis, and Bowtie Analysis. Fault Tree Analysis was used to identify the causes of subsea pipeline damage and to calculate the probability of the top event. Event Tree Analysis was used to evaluate possible consequence scenarios after pipeline damage occurs. Bowtie Analysis was then applied to integrate the causal factors, top event, safety barriers, and consequences into one structured risk-control model. The results show that the probability of subsea pipeline damage is 0.0297492. Pipeline structural integrity failure contributes 0.0179766, while third-party interference contributes 0.0119882. The most dominant basic events are failure to conduct periodic inspection, corrosion, gasket failure, emergency anchoring, and severe weather conditions. The Event Tree Analysis shows that minor damage with no significant fluid release has the highest probability, while catastrophic loss of containment has the lowest probability but the most severe consequence. The Bowtie model clarifies the role of preventive and mitigation barriers in reducing pipeline failure risk.

*Keywords***—** *Subsea Pipeline, Risk Management, Fault Tree Analysis, Event Tree Analysis, Bowtie Analysis*

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I. INTRODUCTION

Subsea pipelines are vital components of offshore production and structural systems, serving as the primary infrastructure for transporting production fluids, including crude oil, natural gas, and produced water, from offshore wells to onshore processing facilities or other offshore platforms. Unlike top-side facilities, subsea pipelines operate continuously in harsh, complex, and highly uncertain marine environments. These infrastructures are subjected to various internal operational loads, such as pressure fluctuations, temperature gradients, multiphase flow conditions, and corrosion mechanisms, as well as external environmental loads, including hydrostatic pressure, seabed instability, ocean currents, and wave-induced forces [1], [2], [3] . In addition to environmental and operational factors, subsea pipelines are vulnerable to anthropogenic hazards, such as anchor dragging, trawling activities, dropped objects, and impacts from subsea intervention equipment. The combination of these loads and hazards may lead to coating damage, local denting, deformation, buckling, leakage, or even complete structural failure.

Subsea pipeline failure can result in significant technical, economic, environmental, and social consequences. Pipeline leakage may cause production interruption, increased inspection and repair costs, marine pollution, and safety risks to offshore activities and nearby coastal communities. Therefore, maintaining pipeline integrity is not merely a technical requirement but also an essential aspect of risk governance, operational sustainability, and environmental protection in the offshore oil and gas sector [4]. Subsea pipelines are among the most vulnerable assets in offshore production systems because of their extensive installation length, continuous exposure to degradation mechanisms, and limited accessibility for direct inspection and maintenance. Consequently, undetected local damage may escalate into major failure events with broader consequences [5].

In the Indonesian context, several reported subsea pipeline leakage incidents, including cases around the Tuban Fuel Terminal, offshore East Lampung, and the Balongan-Indramayu waters, indicate that subsea pipeline failure remains a critical issue in the management of national oil and gas infrastructure. These cases should be carefully interpreted as empirical indications that subsea pipeline damage may generate substantial environmental and socio-economic impacts. However, such incidents must be supported by official or verifiable sources, such as government reports, company reports, regulatory documents, or credible news publications. Accordingly, subsea pipeline damage should not only be understood as a structural integrity issue but also as a risk management problem related to operational safety, environmental protection, and the sustainability of offshore industrial activities.

Risk analysis is required to systematically identify hazards, estimate the likelihood of occurrence, evaluate consequences, and formulate effective control measures. In subsea pipeline systems, risk assessment should consider two main aspects: risk control before failure occurs and risk control after failure has occurred. Pre-failure control is represented by preventive barriers,

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which are intended to reduce the likelihood of the top event. Post-failure control is represented by mitigative barriers, which aim to limit escalation and reduce the severity of consequences. Previous studies have identified maritime-related hazards, such as anchor drop, anchor drag, and ship sinking, as major threats to subsea pipeline integrity. This is also consistent with DNV RP-F107, which classifies maritime activities as important sources of risk to subsea pipelines [6]. Furthermore, subsea pipeline risk assessment is commonly performed by evaluating the frequency of hazardous events and the severity of their consequences to support decision-making in inspection, maintenance, and emergency response planning [7].

Although various risk assessment methods have been applied to subsea pipeline systems, many studies still tend to analyze failure causes and post-event consequences separately. Fault Tree Analysis is commonly used to identify causal pathways leading to a top event, whereas Event Tree Analysis is used to evaluate the possible development of consequence scenarios after the top event occurs. While these methods provide valuable insights into different aspects of risk, their separate application may not fully represent the relationship among threats, the top event, barrier effectiveness, and final consequences. This limitation may reduce clarity in risk communication, particularly when the results are intended to be used by stakeholders with different technical and managerial backgrounds.

To address this limitation, this study employs Bowtie Analysis as the main framework for evaluating the risk of subsea pipeline damage. Bowtie Analysis is a structured method that integrates the logic of FTA and ETA into a single visual risk model. The left side of the Bowtie diagram represents threats or causal factors that may lead to the top event, while the right side represents consequence pathways following the occurrence of the top event. Preventive barriers are positioned between threats and the top event, whereas mitigative barriers are positioned between the top event and final consequences. Through this structure, Bowtie Analysis enables a clearer representation of how a hazard may develop into pipeline damage, how the event may escalate, and how each barrier contributes to risk reduction [8], [9].

Unlike Bowtie Analysis that is used solely as a qualitative visualization tool, this study applies a semi-quantitative Bowtie Analysis approach by incorporating probability-based FTA and ETA results. The probability obtained from FTA is used to estimate the likelihood of the top event, namely subsea pipeline damage, whereas ETA is used to evaluate the probability of consequence development based on the success or failure of safety barriers after the top event occurs. This integration allows Bowtie Analysis to function not only as a risk communication tool but also as an analytical framework that links dominant causal factors, event probability, barrier performance, and final consequences.

The main problem addressed in this study is the lack of an integrated risk representation that simultaneously connects causes, the top event, safety barriers, and consequences of subsea pipeline damage within a single analytical framework. Therefore, this study aims to develop a semi-quantitative Bowtie Analysis model for subsea pipeline damage by integrating the results of FTA and ETA. Through this approach, failure causes can be systematically traced, consequence pathways can be structurally evaluated, and the roles of preventive and mitigative barriers can be more clearly classified. Table 1 summarizes the risk assessment methods applied in previous studies across various engineering and industrial sectors.

TABLE 1
RISK ASSESSMENT METHOD

Author	Objective	Method
[10]	This study aims to evaluate the segment-based risk profile of PT XYZ’s subsea gas pipeline using the Kent Muhlbauer semi-quantitative risk assessment model and Bowtie Analysis, in order to identify high-risk pipeline segments, dominant failure contributors, and appropriate preventive and mitigation barriers for pipeline safety management.	Bowtie Analysis
[11]	To construct a Bow-Tie risk model for natural gas pipeline leakage that integrates fault causes, critical leakage events, preventive and mitigation barriers, and accident consequences, supported by fuzzy Bayesian Network analysis for probability estimation and identification of weak links.	Bowtie Analysis
[12]	This study aims to quantify a Bow-Tie-based risk evaluation framework for natural gas pipelines by integrating fuzzy failure-probability estimation, consequence severity indexing, and risk matrix classification, enabling identification of risk factors, assessment of accident consequences, and determination of pipeline risk level.	Bowtie Analysis
[13]	This study applies Fault Tree Analysis as the core safety-analysis structure for modelling oil and gas leakage in subsea production systems, while extending conventional FTA through intuitionistic fuzzy α-cut interval importance measures to rank critical basic events under uncertain failure information	Fault Tree Analysis
[14]	To improve conventional FTA for subsea pipeline reliability design by proposing a Failure Expansion Tree that systematically identifies physical failure modes, reduces subjectivity, minimizes missed failure factors, and simplifies quantitative risk ranking.	Fault Tree Analysis
[15]	To perform fuzzy Fault Tree Analysis for oil and gas leakage in subsea production systems by constructing a generic fault tree, calculating minimal cut sets and top-event failure probability, and ranking critical basic events using importance measure	Fuzzy Fault Tree Analysis
[16]	This paper emphasizes the use of ETA within a Bow-Tie framework to describe and quantify the escalation pathways following gas pipeline leakage, particularly by assessing how safety-barrier performance influences the occurrence probabilities of different accident consequences.	Event Tree Analysis & Bowtie Analysis

CONTINUED TABLE 2
RISK ASSESSMENT METHOD

[17]	This study aims to analyze the consequence pathways of gas pipeline leakage using the Event Tree component of a Bow-Tie model, by tracing the escalation process from the top event of gas leakage through safety-barrier success or failure toward potential outcomes such as safe diffusion, jet fire, vapor cloud explosion, and personnel poisoning, supported by Dynamic Bayesian Network analysis for time-dependent consequence probability prediction.	Event Tree Analysis, Bowtie Analysis, & Bayesian Network
[18]	The objective of this paper is to develop and apply a fuzzy-based Event Tree Analysis method to evaluate the accident evolution pathways of the Xinda crude oil pipeline leakage, by identifying the initiating event, modelling subsequent conditional events, quantifying expert-based uncertainty using fuzzy set theory, and estimating the probability of each possible outcome event.	Fuzzy Event Tree Analysis
[19]	This study aims to analyze the risks associated with scaffolding work in offshore platform fabrication by identifying dominant hazards, evaluating their causes and consequences, and estimating the probability of accident outcomes using an integrated Bowtie Analysis, Fault Tree Analysis, and Event Tree Analysis approach.	FTA, ETA, Bowtie Analysis

As summarized in Table 1, previous pipeline-related risk studies have applied Bowtie Analysis, Fault Tree Analysis, and Event Tree Analysis to support failure identification, probability estimation, consequence evaluation, and barrier visualization. However, these studies generally emphasize one dominant analytical function, such as causal modelling, consequence-pathway analysis, or barrier representation. Therefore, this study extends existing literature by integrating failure causes, top-event probability, safety-barrier performance, and consequence pathways into a single semi-quantitative Bowtie-based framework for subsea pipeline integrity management

II. METHOD

A. Risk

Risk refers to the potential consequences arising from uncertainties that may affect the achievement of predetermined objectives. These uncertainties can stem from various sources, such as limited information, changes in environmental conditions, variability in resource availability, or dependencies on external parties [20]. Risks can be classified based on their severity, namely low, medium, or high. The greater the value of likelihood and consequence, the higher the level of danger of the risk [21]. This relationship is often visualized through a risk matrix, which serves as a practical tool for prioritizing risks and determining appropriate mitigation measures. By understanding the level of risk, decision-makers can allocate resources more effectively and implement preventive or corrective actions to reduce the probability and/or impact of potential failures.

The most common definition of risk is often expressed mathematically as follows [3]:

$$R\,(t) = Pf\,(t)\;x\;Cf(t) \tag{1}$$

Where:
$P\,f\,(t)$: Opportunity of failure
$C\,f\,(t)$: Consequences of failure

Likelihood refers to the level of possibility of a risk occurring, while consequence refers to the magnitude of the impact or consequences that arise if the risk occurs [22].

B. Risk Identification

Risk identification is a structured and iterative process for recognizing and documenting potential events or conditions that may affect project objectives. As the initial stage of risk management, it provides the basis for risk analysis, evaluation, and mitigation planning by mapping key sources of uncertainty, including technical failures, operational constraints, environmental factors, human error, resource limitations, and stakeholder-related influences.

Therefore, risk identification must be conducted comprehensively by integrating both qualitative and quantitative approaches to ensure that all relevant hazards and potential failure scenarios are properly captured. Qualitative approaches may be used to explore expert judgment, historical experience, and field observations, while quantitative approaches can support the estimation of probability, consequence, and risk priority. This combination is important to minimize the possibility of overlooking significant, hidden, or emerging risks that may develop during project implementation. According to [23], several commonly applied techniques in risk identification include:

- Brainstorming
  Collecting and categorizing ideas on possible risks, including potential problems and mitigation options.
- Interviewing
  Gathering insights from stakeholders through structured interviews.
- Questionnaires
  Distributing surveys to experts to gather their views and assessments of potential risks.

C. Risk Management

Risk management is an iterative process that includes identification, analysis, evaluation, treatment, and continuous monitoring of risks to support the achievement of organizational or project objectives. Risk is not only viewed as a potential source of loss, but also as a form of uncertainty that may create opportunities if properly managed. Therefore, risk management aims to reduce the likelihood and impact of adverse events while enhancing the potential benefits arising from uncertain conditions. Through effective risk management, decision-makers can establish priorities, allocate resources more efficiently, and improve project success and sustainability [24].

Furthermore, effective risk management requires an integrated approach that ensures traceability and consistency across all stages, from initial identification to post-treatment monitoring. According to [25], risk management can be grouped into three main components: risk analysis, risk evaluation, and risk control and reduction.

- Risk Analysis
  This stage aims to identify potential hazards and risk sources, trace the root causes of failure, and establish preventive measures to minimize the likelihood of risks.
- Risk Evaluation
  After analysis, the risks are evaluated to determine their acceptability, including assessment of financial and operational impacts, and identification of alternative solutions or approaches.
- Risk Control and Reduction
  This step involves implementing mitigation actions, communicating risks to relevant stakeholders, and conducting continuous monitoring to ensure effective control and apply corrective measures if needed.

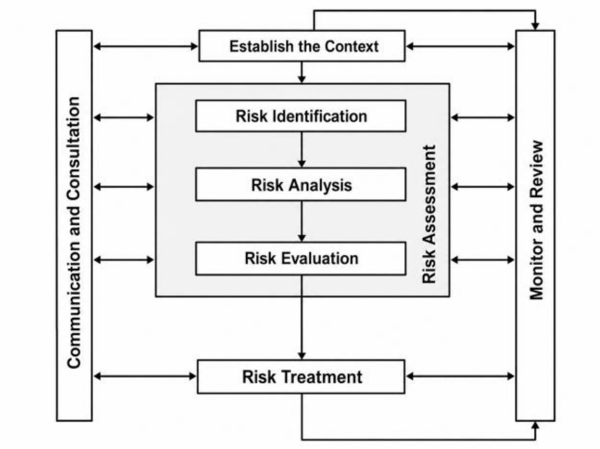

Figure 1 Risk Management Process
(Source: ISO Standards, 2018)

D. Fault Tree Analysis

Fault Tree Analysis is a deductive and structured method for identifying the potential causes of an undesired event, commonly referred to as the top event. The top event is decomposed into intermediate and basic events through logical relationships, allowing failure mechanisms to be examined systematically. [26].

FTA is commonly represented in the form of a tree diagram that illustrates the cause-and-effect relationships among events. These relationships are expressed through logical gates, particularly AND and OR gates. An OR gate indicates that the occurrence of any one contributing event is sufficient to trigger the higher-level event, whereas an AND gate indicates that all contributing events must occur simultaneously for the higher-level event to occur.

Through its graphical and logical structure, FTA enables the identification of root causes, failure pathways, and the minimum combinations of basic events that can lead to the occurrence of the top event, known as minimum cut sets. In addition to its qualitative function in understanding failure mechanisms, FTA can also be applied quantitatively to estimate the probability of the top event, provided that the probability data for each basic event are available. [27].

The probability calculation was performed by referring to the two main logic gates in Fault Tree Analysis, namely the AND and OR gates. The probability of each event combination was subsequently determined using the equations presented below [28].

AND GATE

$$P(t)=P(A) \times P(B) \times P(C) \times \ldots \times P(n) \quad (2)$$

OR GATE

$$P(t)= 1-[(1-P(A))\times(1-P(B))\times \ldots \times(1-P(n))] \quad (3)$$

E. Expert Assessment and Event Probability Estimation

In this study, expert-based assessment was employed to estimate the probability of each basic event used in the Fault Tree Analysis. This approach was adopted because quantitative historical failure data for subsea pipeline damage are often limited, incomplete, or unavailable for all identified basic events. Therefore, expert judgment was used as a structured method to transform qualitative engineering knowledge and operational experience into semi-quantitative probability values. The assessment process consisted of two main stages. First, each expert respondent was assigned a weighting score based on professional position, service time, educational level, and age. Second, the weighted expert responses were converted into a frequency index and subsequently transformed into basic event probability values. These probability values were then used as input parameters in the FTA calculation.

TABLE 3
EXPERT WEIGHTING CRITERIA

Group	Classification	Score
Professional Position	Senior Academic	5
	Junior Academic	4
	Engineer	3
	Technician	2
	Worker	1
Service Time	≥ 30 years	5
	20–29 years	4
	10-19 years	3
	6-9 years	2
	≤ 5 years	1
Education Level	PhD	5
	Master	4
	Bachelor	3
	Higher National Diploma	2
	School Level	1
Age	≥ 50 years	5
	40- 49 years	4
	30–39 years	3
	≤ 29 years	2

Table 2 presents the expert weighting criteria used to evaluate the relative competence of each respondent. The weighting system considers four main indicators: professional position, service time, education level, and age. Respondents with higher professional responsibility, longer service time experience, and higher educational qualifications were assigned higher scores. This weighting procedure ensures that the probability estimation does not treat all expert opinions equally without considering differences in expertise and practical experience. The total score obtained by each respondent was used to determine the expert weight. In general, the expert weight may be expressed as:

$$W_i = \frac{S_i}{\sum_{i=1}^{n} S_i} \quad (4)$$

Where $W_i$is the weight of the i-th expert, $S_i$is the total score of the i-th expert, and $n$is the total number of expert respondents. Through this weighting process, responses from experts with stronger professional and technical backgrounds have greater influence on the final frequency index. After determining the expert weights, the frequency index was calculated based on the weighted responses for each basic event. The frequency index represents the perceived likelihood of occurrence of a given basic event according to the expert assessment. The resulting frequency index was then converted into a quantitative probability value using the probability conversion scale shown in Table 3.

TABLE 4
PROBABILITY CONVERSION SCALE FOR BASIC EVENTS BASED ON FREQUENCY INDEX

Frequency Index	Probability	
	Quantitative	Qualitative
≤ 20 %	0.00001	Almost Never Occurs
> 20 % - 40 %	0.0001	Rarely Occurs
> 40 % - 60 %	0.001	Sometimes Occurs
> 60 % - 80 %	0.01	Often Occurs
> 80 % - 100 %	0.1	Almost Always Occurs

Table 3 shows the conversion scale used to transform the frequency index into quantitative probability values. The scale classifies the likelihood of occurrence into five levels, ranging from “Almost Never Occurs” to “Almost Always Occurs.” Each frequency index interval is associated with a corresponding probability value, from 0.00001\ to 0.1. This conversion enables qualitative expert judgment to be incorporated into the quantitative FTA model. The conversion process is important because FTA requires numerical probability values for each basic event. Therefore, the frequency index serves as an intermediate step between expert perception and quantitative risk modelling. A higher frequency index indicates a higher perceived likelihood of occurrence and is consequently assigned a larger probability value. Conversely, a lower frequency index represents a less frequent event and is assigned a smaller probability value.

Overall, this expert-based assessment provides a systematic basis for estimating basic event probabilities under conditions of limited empirical data. However, the resulting probability values should be interpreted as expert-informed estimates rather than purely statistical failure rates. Therefore, the reliability of the results depends on the relevance, experience, and consistency of the selected experts, as well as the appropriateness of the weighting and conversion procedures applied in the analysis.

F. Event Tree Analysis

Event Tree Analysis is a systematic analytical method used to evaluate the range of possible consequences that may result from an initiating event by considering the sequential success or failure of available protection, mitigation, or safety functions. ETA is commonly represented as a branching tree diagram that depicts the potential event pathways following the occurrence of an initial incident [29].

ETA adopts an inductive, bottom-up approach, beginning with a defined initiating event and progressing through a series of possible system responses to determine the resulting consequences. This method is particularly useful for describing accident sequences formed by combinations of the initiating event and the success or failure of systems intended to respond to it. The process generally involves identifying the initiating event and the relevant safety or response systems designed to prevent escalation or mitigate its impacts [30].

Through this structure, ETA enables the estimation of outcome probabilities, the evaluation of safety barrier effectiveness, and the identification of critical points where additional mitigation measures may be required. Besides assessing whether a risk event can be controlled, in which uncertainty can lead not only to adverse consequences but also to favorable or beneficial outcomes.

The probability of each ETA scenario is determined by multiplying the probability of the initiating event with the probabilities of success or failure of the safety barriers along the corresponding pathway. Thus, for a scenario consisting of one initiating event and several safety barriers, the probability of the final scenario (*i*) can be expressed as follows [31]:

$$P_{scenario,i} = P_{IE} \times \prod_{j=1}^{n} pj \; P_{scenario,i} = P_{IE} \times \prod_{j=1}^{n} pj \qquad (5)$$

Where:

$P_{scenario,\,I}$ = probability of the *i*-th final scenario

P_{IE} = probability of the initiating event

P_j = probability of success or failure of the *j*-th safety function

For each safety function, the probabilities of success and failure satisfy the following relationship:

$$P_{success,} = 1 - P_{failure,j} \qquad (6)$$

Where:

- $P_{success,j}$ is used when the safety function succeeds; and
- $P_{failure,j}$ is used when the safety function fails.

G. *Bowtie Analysis*

Bowtie analysis is an integrated risk assessment approach that combines the strengths of Fault Tree Analysis and Event Tree Analysis within a single graphical framework. This method is commonly used to identify a top event, along with its potential causes, consequences, and the barriers required to prevent the event from occurring or to mitigate its impacts. In the Bowtie structure, the left side represents the causal pathways or threats that may lead to the top event, which are typically analyzed using the logic of FTA. Meanwhile, the right side represents the possible consequence scenarios that may occur after the top event, which are commonly evaluated using the logic of ETA [32].

Through this structure, Bowtie analysis provides a clear visualization of the relationship between threats, preventive barriers, the top event, mitigation barriers, and consequences. Preventive barriers are positioned before the top event to reduce the likelihood of its occurrence, whereas mitigation barriers are positioned after the top event to reduce the severity of its impacts. Therefore, Bowtie analysis is useful for understanding how risks develop from initial causes to final consequences and for evaluating the adequacy of existing control measures.

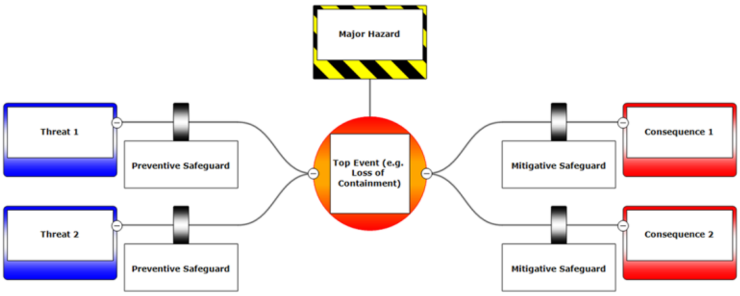

Figure 2 Diagram of Bowtie
(Source: Slatnick et al., 2022)

As illustrated in Figure 2, a Bowtie diagram typically represents a single Top Event that may be triggered by several potential threats and may subsequently result in a range of consequences. The left-hand side of the diagram depicts preventive barriers intended to reduce the likelihood of the Top Event, whereas the right-hand side represents mitigation barriers designed to limit or control the consequences after the Top Event has occurred. This structure enables a clear visualization of the causal pathways leading to the event and the consequence pathways that follow it, thereby supporting risk-informed decision-making [33].

III. RESULTS AND DISCUSSION

A. *Risk Identification for Subsea Pipeline Damage*

The initial stage of risk analysis is risk identification, which is conducted to systematically identify potential hazards in each subsea pipeline activity that may lead to pipeline damage or operational failure. In this study, the identified hazards were classified based on the failure mode, cause of failure, and potential effects on the subsea pipeline system. The results of this identification process are presented in Table 4.

TABLE 5
RISK IDENTIFICATION OF SUBSEA PIPELINE DAMAGE

Failure Mode	Cause of Failure	Potential Effects of Failure
Loss of Pipe Structural Integrity	Internal Corrosion	May cause pipe wall degradation, leakage, reduced flow performance, and increased risk of structural failure.
	Mechanical Connector Failure	May result in pipe disconnection, leakage, loss of integrity, and operational disruption.
	Environmental Loads	May cause pipe deformation, rupture, accelerated fatigue, and structural damage.
	External Corrosion	May reduce material strength, accelerate damage, and increase the risk of leakage or pipe failure.
Third-Party Interference	Anchor Drop and Mooring Impact	May damage the subsea pipeline or nearby systems, leading to leakage or system failure.
	Ship Sinking	May cause severe physical damage to subsea pipelines, increasing accident and pollution risks.
	Anchor Hooking	May pull or damage the pipeline, causing leakage, structural failure, or loss of system integrity.

B. Fault Tree Analysis of Subsea Pipeline Damage

Based on the risk identification results, the FTA model decomposed subsea pipeline damage into two main intermediate events: pipeline structural integrity failure and third-party interference. These intermediate events were further expanded into basic events representing degradation, operational deficiencies, environmental loading, corrosion mechanisms, mechanical failures, and external-interference mechanisms. The identified basic events, presented in Table 5, serve as the lowest-level causal factors in the fault tree structure and provide the basis for probability estimation, dominant contributor ranking, and targeted risk reduction strategies.

TABLE 6
BASIC EVENT OF SUBSEA PIPELINE DAMAGE

Code	Basic Event
C.1.1	Stress Corrosion Cracking
C.1.2	Hydrogen Assisted Corrosion
C.1.3	Mechanical Delayed Cracking
C.1.4	Pitting Corrosion
C.1.5	Improper Corrosion Inhibitor Dosage
C.1.6	Failure of Corrosion Inhibitor Injection System
C.1.7	Lack of Periodic Corrosion Monitoring
C.1.8	Coating Application Defect During Fabrication
C.1.9	Coating Damage Due to Pigging Activities
C.1.10	Extreme Temperature Conditions
C.2.1	Microbiological Activity
C.2.2	Cathodic Protection Failure
C.2.3	Anti-Corrosion Coating Failure
C.2.4	Failure to Conduct Periodic Inspection (ROV Survey, CP Survey, etc.)
C.2.5	Misinterpretation of Cathodic Protection Monitoring Results
C.2.6	Seawater Salinity Causing Anti-Corrosion Degradation
C.3.1	Sea Current Velocity Exceeding Design Limit
C.3.2	Extreme Wave Height (Storm Surge, Cyclone)
C.3.3	Vortex-Induced Vibration (VIV)
C.3.4	Submarine Landslide
C.3.5	Subsea Seismic Activity / Underwater Earthquake
C.3.6	Soft Soil Consolidation or Settlement
C.3.7	Seabed Scouring
C.4.1	NDT Error in Weld Connection Inspection
C.4.2	Mechanical Connector Design Error
C.4.3	Mechanical Connector Installation Error
C.4.4	Mechanical Connector Defect
C.4.5	Corrosion
C.4.6	Fluid Temperature Effects
C.4.7	Gasket Failure
C.4.8	Residual Stress and Tension
D.1.1	Human Error
D.1.2	Emergency Anchoring
D.1.3	Ineffective Pipeline Protection System
D.1.4	Vessel Route Deviation
D.1.5	Vessel Navigation System Failure
D.1.6	Absence of Collision Warning System (Pipeline Monitoring System)
D.1.7	Vessel Operating in Restricted Area
D.1.8	Mooring Line Crossing
D.2.1.1	Insufficient Pipeline Marker Buoys at Sea Surface
D.2.1.2	Navigation Error
D.2.1.3	Pipeline Route Data Not Updated in Electronic Navigation Charts
D.2.1.4	Loss of Position Accuracy Due to Sediment Shift or Subsea Earthquake
D.2.2.1	Anchor Dropped Too Close to Pipeline
D.2.2.2	Severe Weather Conditions
D.2.2.3	Lack of Crew Training Regarding Subsea Pipeline Protection Zones

CONTINUED TABLE 7
BASIC EVENT OF SUBSEA PIPELINE DAMAGE

D.2.2.4	Human Error During Navigation (Chart Misinterpretation, Negligence)
D.2.3.1	Subsea Detection System Failure
D.2.3.2	Absence of Early Warning System
D.2.3.3	AIS Vessel Tracking System Not Integrated with Pipeline Warning System
D.3.1	Operator Miscommunication
D.3.2	Hull Leakage
D.3.3	Loss of Vessel Stability

After the basic events were identified, the causal factor identification process using the Fault Tree Analysis approach was continued by developing a fault tree diagram with DPL 9 Fault Tree software. The developed fault tree diagram consists of two intermediate events: Loss of Pipe Structural Integrity, and Third-Party Interference, as shown in Figure 4.

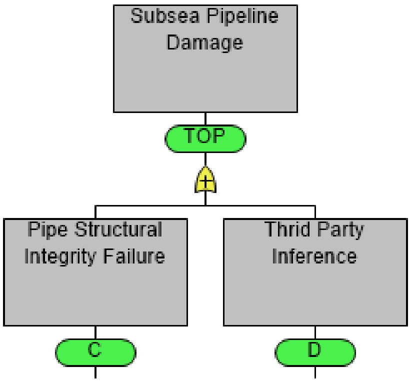

Figure 3 Subsea Pipe Damage Intermediate Event

Pipeline structural integrity failure refers to a condition in which a subsea pipeline is no longer able to maintain its mechanical strength, fluid containment function, and operational reliability under internal pressure, environmental loads, and degradation processes. In this study, the main contributing factors include internal corrosion, external corrosion, environmental loads, and mechanical connector failure. Internal and external corrosion can reduce pipe wall thickness, weaken material strength, and decrease the pressure-retaining capacity of the pipeline. Environmental loads, such as waves, currents, seabed instability, scour, and free-span formation, may increase stress, bending, vibration, and fatigue on the pipeline structure. Meanwhile, mechanical connector failure may occur at joints, flanges, or clamp sections due to installation defects, excessive loading, fatigue, or inadequate maintenance.

If these factors are not properly controlled through inspection, monitoring, corrosion protection, and maintenance programs, the pipeline may experience progressive damage. This damage can develop from wall thinning and local deformation into cracking, leakage, rupture, or total pipeline failure. Therefore, these factors are considered important causal pathways leading to subsea pipeline damage in the Fault Tree Analysis framework.

Third-party interference refers to external threats caused by vessel activities or accidental events occurring near the subsea pipeline route. In this study, the main contributing factors include anchor drop and mooring impact, anchor hooking, and ship sinking. Anchor drop and mooring impact may generate high impact or pulling loads on the pipeline, causing coating damage, denting, bending, or displacement. Anchor hooking can also lead to deformation, lateral movement, or local failure when the anchor becomes caught on the pipeline or its protective structure. Meanwhile, ship sinking may impose significant external loads due to direct contact between the vessel hull and the pipeline, as well as possible disturbance to seabed conditions.

If these factors are not properly controlled through pipeline route marking, restricted zones, vessel traffic monitoring, anchor management, and early warning systems, third-party interference may trigger serious pipeline damage. The potential consequences include deformation, leakage, rupture, or operational shutdown. Therefore, these factors are considered important external causal pathways leading to subsea pipeline damage in the Fault Tree Analysis framework.

B.1 Calculations of Basic Event Probability

Fault Tree Analysis was determined using a semi-quantitative approach based on expert judgment. This approach was applied because historical failure data specific to the analyzed system were not always available or sufficiently complete. Therefore, the probability of each basic event was obtained from expert questionnaire responses, which were subsequently converted into numerical probability values. The first stage involved determining the weight of each expert using the Expert Weighting Index. This index was used to assign different weights to experts based on their relevance, competence, experience, and technical involvement in the subject being analyzed. Through this weighting process, experts with higher levels of expertise or stronger relevance to the system contributed more significantly to the estimation of basic event probabilities. This approach aims to reduce subjectivity in risk assessment and improve the representativeness of aggregated expert judgments.

In this stage, each respondent was evaluated using several competency-based criteria, namely professional position, sea service experience, shore service experience, and educational level. These criteria were selected because they represent the respondent's technical familiarity, operational exposure, and decision-making relevance to subsea pipeline integrity and risk management. The score obtained from each criterion was summed up to produce the total respondent score. Subsequently, the total score of each respondent was divided by the cumulative score of all respondents to obtain the normalized respondent weight. Respondent weighting calculation was performed using Equation (4), based on the assessment criteria shown in table 2 and presented in table 6.

TABLE 8
RESPONDENT WEIGHTING CALCULATION BASED ON EXPERTISE CRITERIA

Calculation of Respondent Weights				
Service Time	Education Level	Age	Score	WJ
7	Bachelor	30	10	0.1020408
8	Bachelor	30	10	0.1020408
9	Bachelor	33	10	0.1020408
5	Bachelor	27	8	0.0816327
4	Bachelor	25	8	0.0816327
4	Bachelor	25	8	0.0816327
17	Bachelor	42	12	0.1224490
11	Bachelor	32	11	0.1122449
6	Bachelor	32	10	0.1020408
10	Bachelor	35	11	0.1122449
Total			98	1

After obtaining the expert assessment weights, each expert weight was multiplied by the corresponding frequency score assigned to each basic event based on the criteria shown in Figure 3. The weighted scores were then aggregated to determine the frequency index, which represents the relative likelihood of occurrence of each basic event. The frequency index was subsequently converted into a quantitative probability value using the predefined probability conversion criteria. The overall probability values of the identified basic events are presented in Table 7.

TABLE 9
PROBABILITY BASIC EVENT OF SUBSEA PIPELINE DAMAGE

Code	Basic Event	Probability
C.1.1	Stress Corrosion Cracking	0.0011498776
C.1.2	Hydrogen Assisted Corrosion	0.0000352551
C.1.3	Mechanical Delayed Cracking	0.0000276327
C.1.4	Pitting Corrosion	0.0001398571
C.1.5	Improper Corrosion Inhibitor Dosage	0.0001377449
C.1.6	Failure of Corrosion Inhibitor Injection System	0.0001372857
C.1.7	Lack of Periodic Corrosion Monitoring	0.0004620204
C.1.8	Coating Application Defect During Fabrication	0.0001177245
C.1.9	Coating Damage Due to Pigging Activities	0.0001147857
C.1.10	Extreme Temperature Conditions	0.0002406939
C.2.1	Microbiological Activity	0.0001281020
C.2.2	Cathodic Protection Failure	0.0000395714
C.2.3	Anti-Corrosion Coating Failure	0.0001580408
C.2.4	Failure to Conduct Periodic Inspection (ROV Survey, CP Survey, etc.)	0.0024805918
C.2.5	Misinterpretation of Cathodic Protection Monitoring Results	0.0001472041
C.2.6	Seawater Salinity Causing Anti-Corrosion Degradation	0.0001490408
C.3.1	Sea Current Velocity Exceeding Design Limit	0.0013403469
C.3.2	Extreme Wave Height (Storm Surge, Cyclone)	0.0001468367
C.3.3	Vortex-Induced Vibration (VIV)	0.0000458163
C.3.4	Submarine Landslide	0.0000261633
C.3.5	Subsea Seismic Activity / Underwater Earthquake	0.0000261633
C.3.6	Soft Soil Consolidation or Settlement	0.0002482245
C.3.7	Seabed Scouring	0.0015243878
C.4.1	NDT Error in Weld Connection Inspection	0.0001088163
C.4.2	Mechanical Connector Design Error	0.0012492449
C.4.3	Mechanical Connector Installation Error	0.0012492449
C.4.4	Mechanical Connector Defect	0.0012595306
C.4.5	Corrosion	0.0024642449
C.4.6	Fluid Temperature Effects	0.0001472041
C.4.7	Gasket Failure	0.0023815918
C.4.8	Residual Stress and Tension	0.0002425306
D.1.1	Human Error	0.0013519184
D.1.2	Emergency Anchoring	0.0023712143
D.1.3	Ineffective Pipeline Protection System	0.0002261837

TABLE 10
PROBABILITY BASIC EVENT OF SUBSEA PIPELINE DAMAGE

D.1.4	Vessel Route Deviation	0.0012674286
D.1.5	Vessel Navigation System Failure	0.0000268980
D.1.6	Absence of Collision Warning System (Pipeline Monitoring System)	0.0001379286
D.1.7	Vessel Operating in Restricted Area	0.0001473878
D.1.8	Mooring Line Crossing	0.0013609184
D.2.1.1	Insufficient Pipeline Marker Buoys at Sea Surface	0.0000645510
D.2.1.2	Navigation Error	0.0000472857
D.2.1.3	Pipeline Route Data Not Updated in Electronic Navigation Charts	0.0003584286
D.2.1.4	Loss of Position Accuracy Due to Sediment Shift or Subsea Earthquake	0.0000371837
D.2.2.1	Anchor Dropped Too Close to Pipeline	0.0014329184
D.2.2.2	Severe Weather Conditions	0.0021867143
D.2.2.3	Lack of Crew Training Regarding Subsea Pipeline Protection Zones	0.0000489388
D.2.2.4	Human Error During Navigation (Chart Misinterpretation, Negligence)	0.0001490408
D.2.3.1	Subsea Detection System Failure	0.0001481224
D.2.3.2	Absence of Early Warning System	0.0001389388
D.2.3.3	AIS Vessel Tracking System Not Integrated with Pipeline Warning System	0.0002392245
D.3.1	Operator Miscommunication	0.0002298571
D.3.2	Hull Leakage	0.0000461837
D.3.3	Loss of Vessel Stability	0.0000342449

Figure 4 presents the probability of distribution of the identified basic events contributing to subsea pipeline damage. The bar chart provides a comparative visualization of the probability values assigned to each basic event, allowing the most influential contributors to be distinguished from those with relatively lower likelihoods. Basic events with higher probability values represent more significant potential contributors to the occurrence of the top event and, therefore, require greater attention in risk control and mitigation planning.

Conversely, basic events with lower probability values indicate comparatively smaller contributions, although they remain relevant within the overall fault tree structure because their combined effects may still influence the total probability of subsea pipeline damage. Thus, this figure supports the identification and prioritization of critical failure sources in the FTA model.

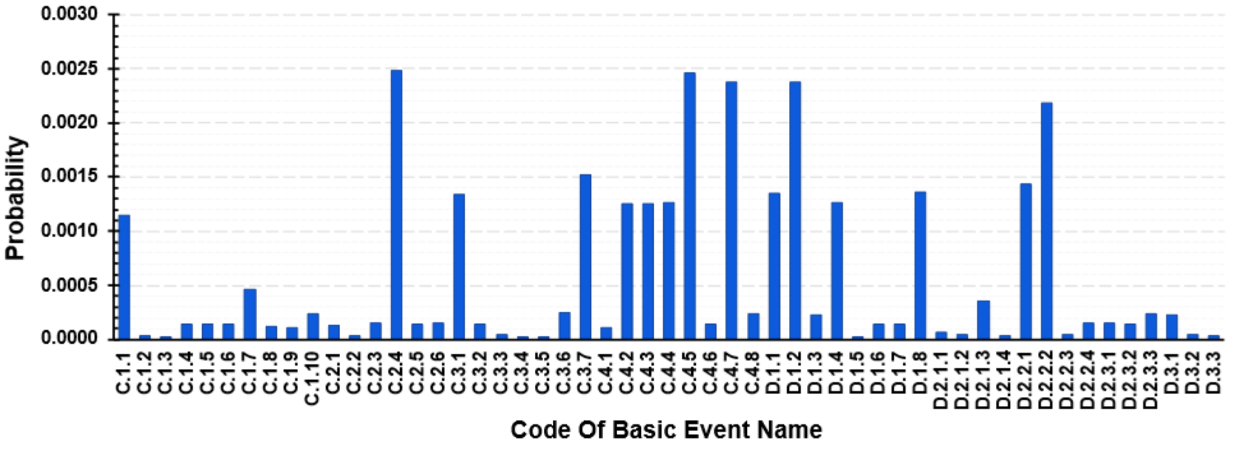

Figure 4 Probability Distribution of Basic Events Contributing to Subsea Pipeline Damage

Table 8 shows the five basic events with the highest probability values contributing to subsea pipeline damage. Based on Table 8, the basic event "lack of periodic inspection", including ROV survey, CP survey, and other inspection activities, has the highest probability compared with the other basic events. In this study, this basic event is classified under the external corrosion factor, because inadequate inspection may prevent early detection of coating degradation, cathodic protection failure, and corrosion activity on the external surface of the pipeline.

TABLE 11
HIGHEST PROBABILITY BASIC EVENT OF SUBSEA PIPELINE DAMAGE

Code	Basic Event	Probability	Rank
C.2.4	Failure to Conduct Periodic Inspection (ROV Survey, CP Survey, etc.)	0.002480592	1
C.4.5	Corrosion	0.002464245	2
C.4.7	Gasket Failure	0.002381592	3
D.1.2	Emergency Anchoring	0.002371214	4
D.2.2.2	Severe Weather Conditions	0.002186714	5

B.2 Minimal Cut-Set for Fault Tree Analysis

After the probability of each basic event was determined, the next stage of the analysis was to identify the minimum cut sets for each intermediate event in the Fault Tree Analysis model. The minimum cut set analysis was conducted to determine the smallest combinations of basic events that are sufficient to cause the occurrence of an intermediate event. In this stage, the logical relationship among basic events was evaluated based on the gate structure used in the FTA diagram, namely OR gates and AND gates. The OR gate indicates that the occurrence of any single basic event may trigger the intermediate event, whereas the AND gate indicates that several basic events must occur simultaneously for the intermediate event to occur. Accordingly, the probability of each intermediate event was calculated using the appropriate logical gate formulations, as expressed in Equations (2) and (3).

The minimum cut set for the intermediate event “Pipeline Structural Integrity Failure” is presented in Table 9, while the minimum cut set for the intermediate event “Third-Party Interference” is presented in table 10. These tables provide a structured representation of the basic event combinations that contribute to each intermediate event. By identifying the minimum cut sets, the analysis can determine which basic events, or event combinations have a critical role in the development of subsea pipeline damage. Therefore, the minimum cut set analysis not only supports the probability calculation within the FTA framework, but also provides a basis for prioritizing preventive measures, inspection strategies, and risk mitigation actions

TABLE 12
MINIMAL CUT SET PIPELINE STRUCTURAL INTEGRITY FAILURE

Code	Intermediate Event Name	Probability
C.1	Internal corrosion	0.0025604
C.2	External corrosion	0.0031009
C.3	Mechanical connector failure	0.0090693
C.4	Environmental load	0.0033544
	Total	0.0179766

After the minimum cut set for the intermediate event of subsea pipeline integrity loss was obtained, the next stage of the analysis was to determine the minimum cut set for the intermediate event of third-party interference. This analysis was conducted to identify the smallest combination of basic events that may trigger pipeline damage due to external activities.

TABLE 13
MINIMAL CUT SET OF THIRD-PARTY INTERFERENCE

Code	Intermediate Event Name	Probability
D.1	Anchor Drop and Mooring Impact	0.0068717
D.2	Anchor Hooking	0.0048431
D.3	Ship Sinking	0.0003103
	Total	0.0119882

The minimum cut sets of the two intermediate events, namely loss of subsea pipeline integrity and third-party interference, were integrated to determine the minimum cut set of the top event: subsea pipeline damage. This result identifies the critical failure paths and provides the basis for calculating the top event probability, as presented in Table 11.

TABLE 14
MINIMAL CUTSET FOR TOP EVENT SUBSEA PIPELINE DAMAGE

Code	Intermediate Event Name	Probability
C	Pipeline Structural Integrity Failure	0.0179766
D	Third-party interference	0.0119882
	Total	0.0297492

C. Event Tree Analysis

After identifying the causal factors of subsea pipeline damage through Fault Tree Analysis, the analysis was further extended using Event Tree Analysis. The FTA results provide a basis for understanding the root causes and dominant contributors to the top event, while ETA is used to evaluate the possible consequence pathways following the occurrence of the initiating event. In this study, subsea pipeline damage was considered as the initiating event, and several safety barriers were incorporated into the ETA model to represent the control and mitigation measures. The success or failure of each barrier generates different consequence scenarios, which are then used to estimate outcome probabilities and support risk-based decision-making.

The success probability of safety barriers is an important parameter in Event Tree Analysis, as it determines the likelihood that a safety barrier will function effectively after the occurrence of the initiating event. In this study, each safety barrier was evaluated based on its ability to prevent, control, or reduce the consequences of subsea pipeline damage. These success probability values were then used to develop ETA scenarios through combinations of successful and failed barrier conditions. The success probabilities of each safety barrier are presented in Table 12.

TABLE 15
PROBABILITY SUCCESS OF SAFETY BARRIER OF SUBSEA PIPELINE DAMAGE

No	Safety Barrier	Probability
1.	Detection and Alarm	0.8836247
2.	Alarm Verification and Decision Making	0.8469172
3.	Emergency Shutdown and Isolation	0.9235186
4.	Pressure and Inventory Control	0.8712639
5.	Area Control and Secondary Impact Prevention	0.8039475
6	Emergency Response, Inspection, and Repair	0.7816843

The success and failure probabilities assigned to each safety barrier in the Event Tree values were established using a literature-informed expert judgement approach, in which relevant literature on subsea pipeline integrity management, leak detection systems, emergency shutdown, pipeline isolation, pressure control, marine area control, emergency response, inspection, and repair was used as the basis for defining the safety function and criticality of each barrier. The literature was used to identify the role, complexity, and expected reliability of each barrier, while the numerical values were adjusted according to operational characteristics, human dependency, technical readiness, and uncertainties associated with offshore environmental conditions.

After the success probability of each safety barrier was determined, the next step was to calculate the failure probability of each barrier. The failure probability was obtained by subtracting the success probability from one, since each barrier in the Event Tree Analysis was modeled as two mutually exclusive states: success or failure. Therefore, the probability of failure of each safety barrier can be expressed as follows (5). Event Tree Analysis in Figure 5 presents the escalation pathway following subsea pipeline damage as the initiating event, with a probability of 2.97492×10^{-2}. The diagram evaluates how the event may develop through six sequential safety barriers: detection and alarm, alarm verification and decision-making, emergency shutdown and isolation, pressure and inventory control, area control and secondary impact prevention, and emergency response, inspection, and repair. Each barrier is assigned a probability of success and failure, thereby representing the ability of the safety system either to interrupt accident progression or to permit escalation toward more serious consequences.

The results indicate that the least severe outcome occurs when the protection system functions effectively, leading to minor damage with no significant fluid release, with a probability of $P(O1) = 1.126 \times 10^{-2}$. If subsequent barriers fail partially, the event may progress to local damage with delayed repair or controlled release with moderate consequences, with probabilities of $P(O2) = 3.144 \times 10^{-3}$ and $P(O3) = 1.663 \times 10^{-3}$, respectively. Further degradation of barrier performance may result in major release requiring shutdown, with a probability of $P(O4) = 1.378 \times 10^{-4}$. More severe escalation may generate severe release with delayed mitigation, with $P(O5) = 6.954 \times 10^{-6}$, whereas catastrophic loss of containment represents the most critical scenario, with $P(O6) = 2.233 \times 10^{-7}$.

Although the probability of catastrophic loss of containment is relatively low, its potential impact remains substantial because it may affect operational safety, environmental protection, production continuity, regulatory compliance, and recovery cost. Therefore, the ETA should not be interpreted only from the magnitude of probability, but also from the severity of consequence and the reliability of each protective layer. From a risk management perspective, emergency shutdown and isolation shows the highest success probability, indicating its key role in limiting escalation after pipeline damage. Conversely, area control and secondary impact prevention, together with emergency response, inspection, and repair, show relatively lower success probabilities than the other barriers. These barriers should therefore be prioritized for improvement through stronger emergency procedures, faster inspection mobilization, improved repair readiness, clearer exclusion-zone control, and better coordination among operators, emergency teams, and maintenance units.

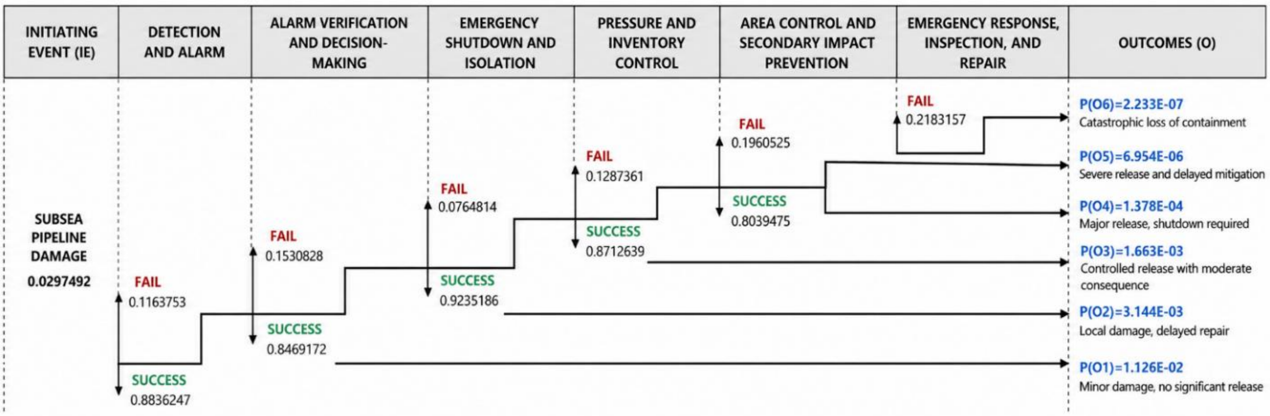

Figure 5 Event Tree Analysis of Consequence Pathways Following Subsea Pipeline Damage

D. *Mitigation Factor of Subsea Pipeline Failure Using Bowtie Analysis*

The FTA and ETA results were integrated into a Bowtie framework, with subsea pipeline damage defined as the top event. FTA-derived causes form the left side, while ETA-derived consequences form the right side. Preventive and mitigation barriers were assigned accordingly, as shown in Figures 6 and 7.

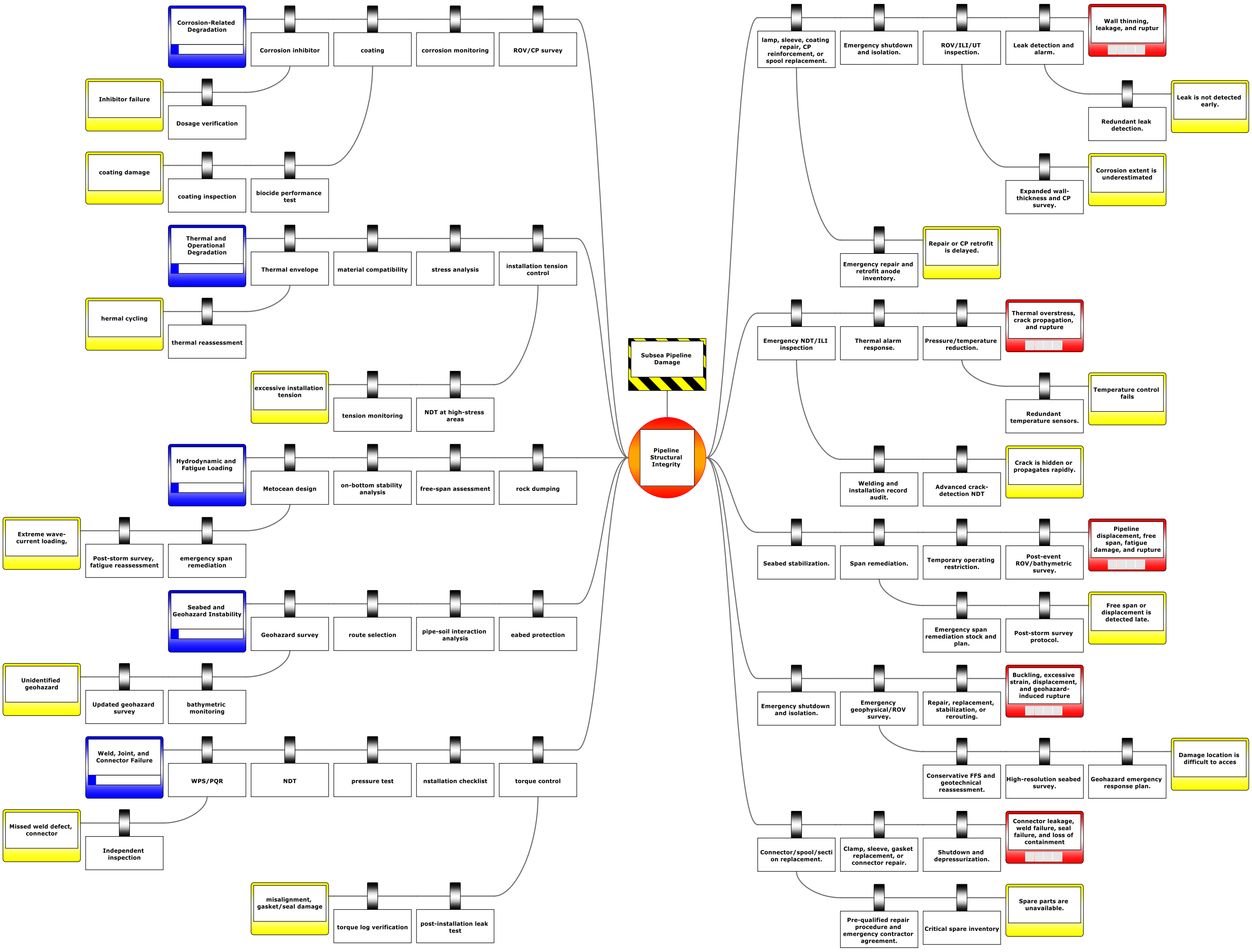

Figure 6 Bowtie Diagram of Pipeline Structure Failure

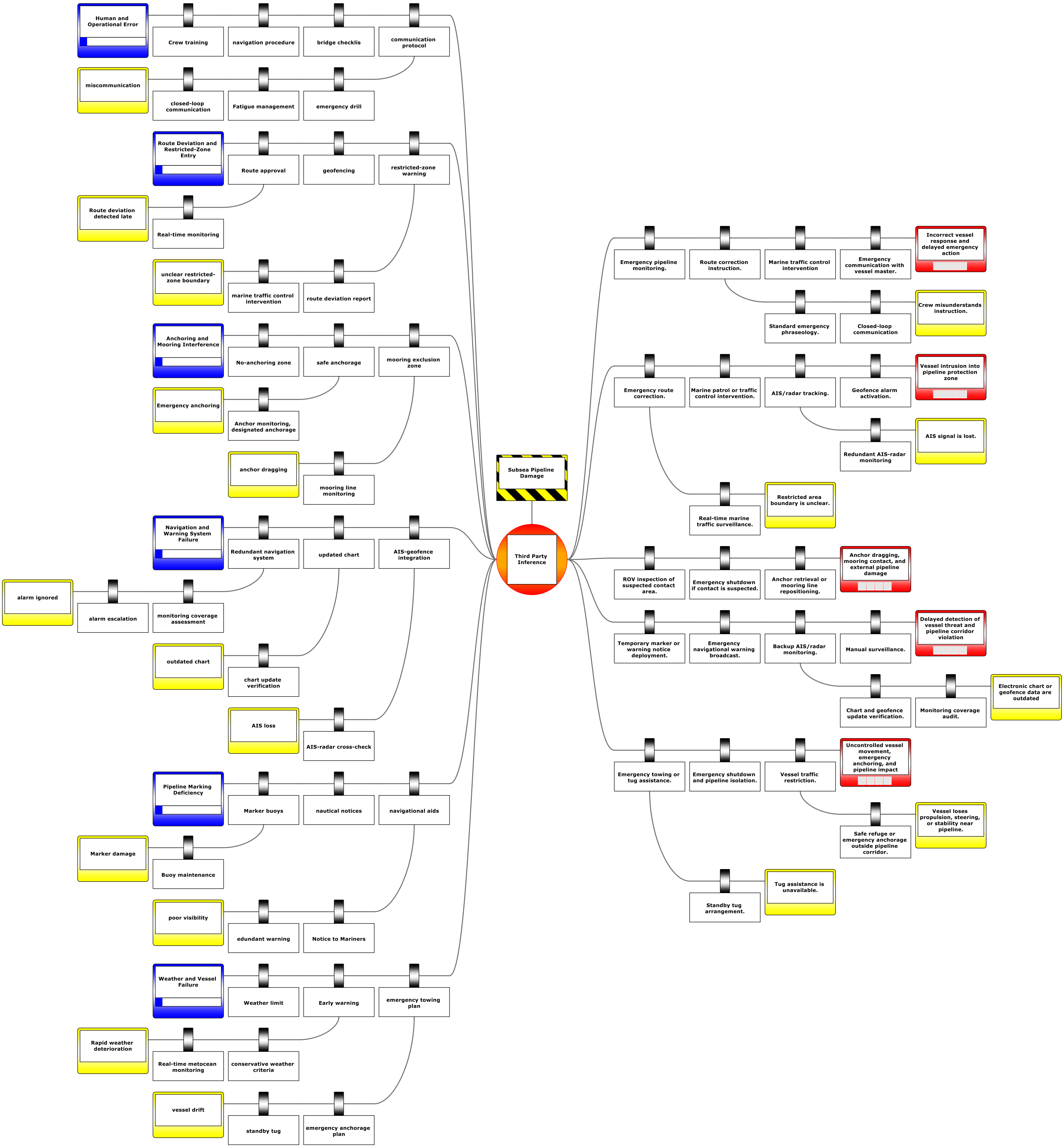

Figure 6 Diagram Bowtie of Third-Party Interference

E. Discussion

The results of this study show that subsea pipeline damage is governed by the interaction between integrity degradation, external interference, and the performance of safety barriers. The FTA results indicate that pipeline structural integrity failure contributes more strongly to the top event probability than third-party interference. This suggests that the dominant risk mechanism is associated with progressive deterioration of pipeline integrity rather than sudden external impact alone. Therefore, integrity management should prioritize continuous inspection, corrosion monitoring, connector reliability assessment, and environmental load surveillance.

The highest-probability basic event is failure to conduct periodic inspection. This finding is important because inspection failure is not a direct physical damage mechanism, but a management-related deficiency that allows corrosion, connector degradation, coating failure, or other defects to remain undetected. In this context, inadequate inspection acts as an enabling condition that allows technical degradation to progress into pipeline failure. This supports the need for a risk-based inspection strategy rather than relying only on fixed-interval inspection.

The ranking of dominant basic events also indicates that subsea pipeline risk is multidomain in nature. Corrosion and gasket failure represent integrity-related threats associated with material degradation and loss of containment, whereas emergency anchoring and severe weather conditions represent external and environmental threats that may impose sudden loads on the pipeline. Consequently, risk reduction should be integrated across inspection planning, corrosion protection, connector assessment, marine traffic control, anchoring regulation, and weather-based operational restrictions.

The ETA results show that consequence severity depends strongly on the sequential performance of safety barriers after the initiating event occurs. Minor damage with no significant fluid release has the highest probability, while catastrophic loss of containment has the lowest probability but the most severe consequence. Therefore, low-probability outcomes should not be neglected, particularly when they may lead to environmental pollution, production shutdown, regulatory consequences, reputational damage, and high recovery costs. Risk prioritization should therefore consider both likelihood and consequence severity.

Barrier performance analysis further indicates that emergency shutdown and isolation have a relatively high success probability, confirming their important role in limiting escalation after pipeline damage occurs. However, area control, secondary impact prevention, emergency response, inspection, and repair show lower success probabilities. This suggests that the weakest part of the post-event safety system may be associated with coordination-intensive barriers, which depend on human response, offshore mobilization, inter-agency communication, and real-time decision-making. Improving post-event resilience therefore requires not only reliable equipment, but also stronger emergency procedures, faster inspection mobilization, clearer exclusion-zone enforcement, and better coordination among pipeline operators, marine traffic authorities, and emergency response teams.

The novelty of this study lies in the integration of FTA, ETA, and Bowtie Analysis into a semi-quantitative risk framework for subsea pipeline damage. In conventional applications, FTA is often used to identify failure causes, ETA is used separately to evaluate consequence pathways, and Bowtie Analysis is commonly treated as a qualitative visualization tool. In contrast, this study links probability-based FTA results with ETA consequence pathways and integrates both into a Bowtie structure. As a result, the Bowtie model functions not only as a communication diagram, but also as an analytical framework that connects threats, top event probability, preventive barriers, mitigation barriers, and final consequences.

From a practical perspective, the proposed framework supports pipeline integrity management by distinguishing preventive and mitigation barriers. Preventive actions should prioritize periodic ROV and CP surveys, corrosion protection, coating management, connector inspection, environmental load monitoring, route marking, AIS-based vessel monitoring, and navigation chart updating. Mitigation actions should strengthen leak detection, emergency shutdown and isolation, pressure and inventory control, spill containment, subsea inspection and repair, and environmental monitoring.

Nevertheless, the results should be interpreted with methodological caution. The probability values used in this study were derived from semi-quantitative expert judgment rather than long-term empirical failure databases. Therefore, the calculated probabilities should be understood as expert-informed estimates, not absolute statistical failure rates. In addition, the FTA and ETA calculations assume logical independence among several events and safety barriers, whereas real offshore systems may involve dependency, common-cause failure, and correlation among human, technical, and environmental factors. Future studies should incorporate sensitivity analysis, uncertainty propagation, Bayesian updating, or dynamic risk modelling to improve the robustness of the probability estimates.

Overall, the findings confirm that subsea pipeline damage prevention requires an integrated barrier-management perspective. By linking dominant causal factors, escalation pathways, and preventive and mitigation controls, the proposed FTA–ETA–Bowtie framework provides a more transparent basis for inspection planning, emergency preparedness, and risk-informed decision-making in subsea pipeline integrity management.

IV. CONCLUSION

This study evaluated the risk of subsea pipeline damage and developed an integrated failure-prevention framework by combining Fault Tree Analysis, Event Tree Analysis, and Bowtie Analysis. The results show that the probability of subsea pipeline damage as the top event is 0.0297492. This probability is mainly contributed by pipeline structural integrity failure, with a value of 0.0179766, followed by third-party interference, with a value of 0.0119882. These findings indicate that subsea pipeline damage is more strongly influenced by integrity degradation mechanisms than by external interference, although both hazard groups remain important in the overall risk structure.

The Fault Tree Analysis identified the dominant basic events contributing to subsea pipeline damage. Failure to conduct periodic inspection, corrosion, gasket failure, emergency anchoring, and severe weather conditions were found to have the highest probability values. This result emphasizes that subsea pipeline failure is not only caused by direct technical degradation, but also by weaknesses in inspection, monitoring, and operational control. Therefore, periodic ROV surveys, cathodic protection surveys, corrosion monitoring, connector reliability assessment, and environmental-load monitoring should be prioritized in pipeline integrity management.

The Event Tree Analysis showed that the consequence of subsea pipeline damage depends strongly on the sequential performance of safety barriers after the initiating event occurs. The scenario with minor damage and no significant fluid release had the highest probability, while catastrophic loss of containment had the lowest probability but the most severe consequence. This finding indicates that low-probability scenarios should not be neglected, because catastrophic pipeline failure may result in environmental pollution, production shutdown, regulatory consequences, and high recovery costs.

The Bowtie Analysis successfully integrated the causal pathways from FTA and the consequence pathways from ETA into a single structured risk-control framework. This framework clarifies the role of preventive barriers, such as corrosion protection, periodic inspection, mechanical connector quality assurance, pipeline route marking, exclusion zones, and AIS-based vessel monitoring. It also clarifies the role of mitigation barriers, such as leak detection, emergency shutdown and isolation, pressure and inventory control, emergency response, subsea inspection and repair, spill containment, and environmental monitoring. Thus, the proposed Bowtie framework can support risk-informed decision-making by linking dominant causes, top event probability, safety barriers, and final consequences in one integrated model.

The main contribution of this study is the development of a semi-quantitative Bowtie-based risk assessment framework for subsea pipeline damage. Unlike a purely qualitative Bowtie diagram, the proposed framework incorporates FTA-based probability estimation and ETA-based consequence evaluation. This makes the framework more useful for prioritizing inspection, strengthening barrier management, and improving emergency preparedness. However, the probability values used in this study were derived from expert judgment because detailed historical failure data were limited.

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APPENDIX A

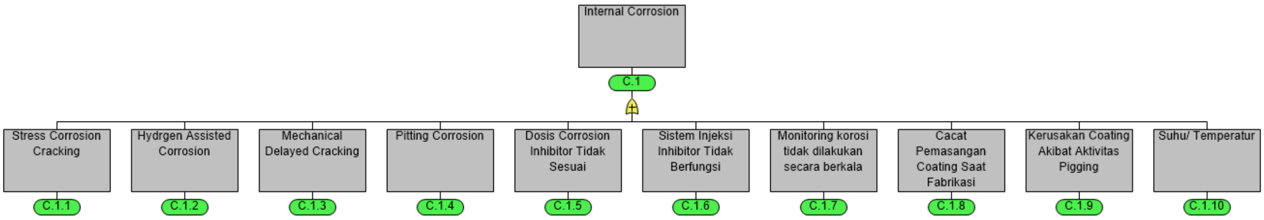

Figure 7 Fault Tree Diagram for Internal Corrosion

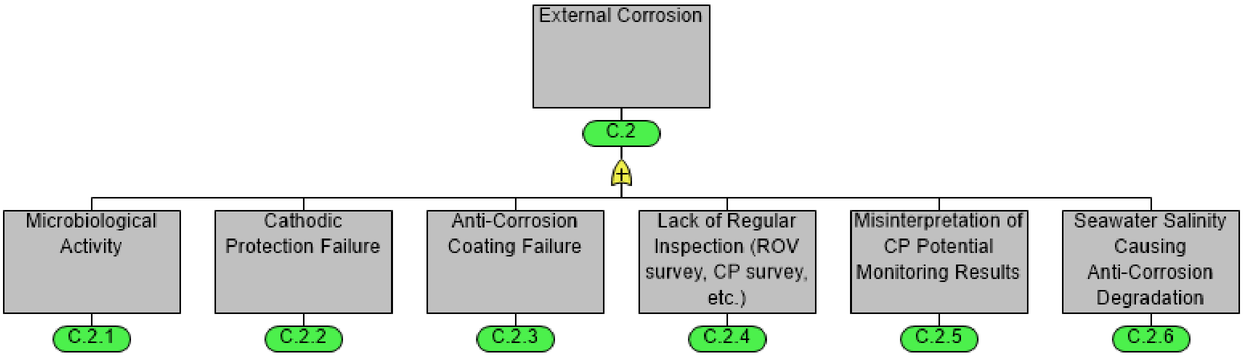

Figure 8 Fault Tree Diagram for External Corrosion

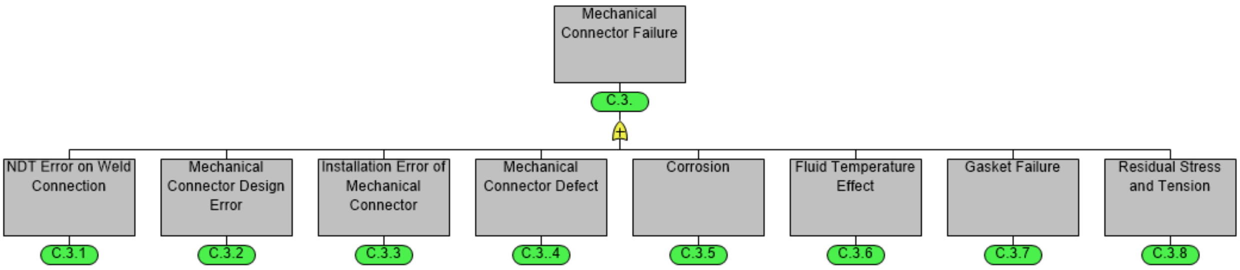

Figure 9 Fault Tree Diagram for Mechanical Conector Failure

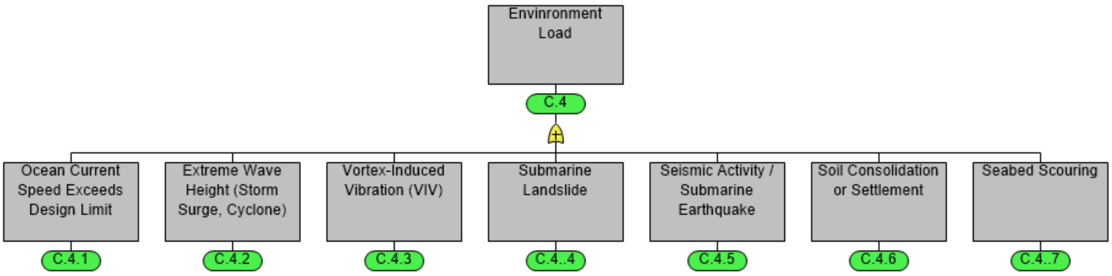

Figure 10 Fault Tree Diagram for Evinronment Load

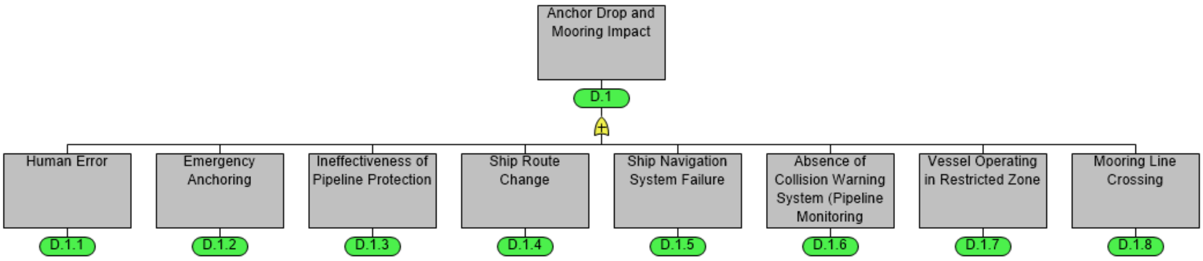

Figure 11 Fault Tree Diagram for Anchor Drop and Mooring Impact

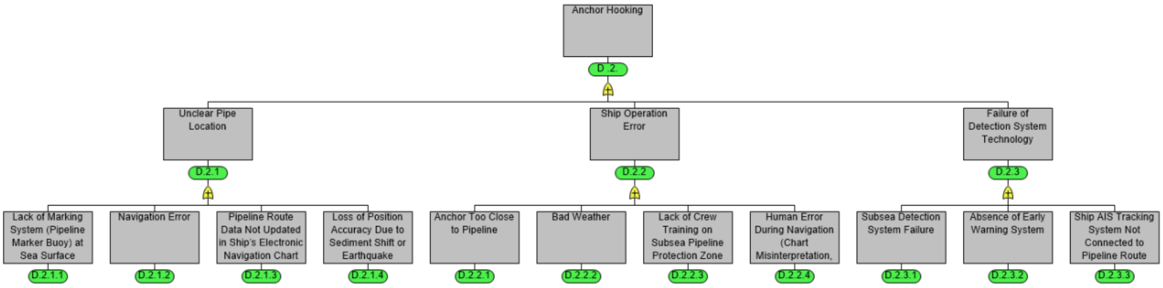

Figure 12 Fault Tree Diagram for Anchor Hooking

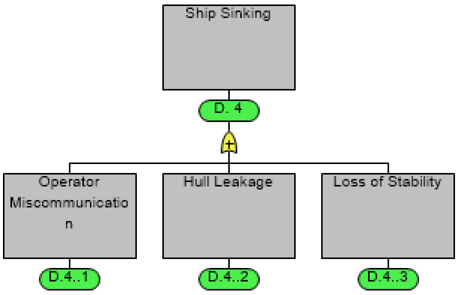

Figure 13 Fault Tree Diagram for Ship Sinking