International Research Journal of Engineering, IT & Scientific Research
Available online at https://sloap.org/journals/index.php/irjeis/
Vol. 11 No. 4, July 2025, pages: 71-87
ISSN: 2454-2261
https://doi.org/10.21744/irjeis.v11n4.2518

Fuzzy risk analysis for field condition, external, and technical risk factors in Subsea Pipeline Construction Projects to improve contingency cost accuracy

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Article history:

Submitted: 09 March 2025
Revised: 18 April 2025
Accepted: 27 May 2025

Keywords:

construction project;
Contingency cost accuracy;
external;
field condition;
fuzzy risk analysis;
subsea pipeline;
technical;

Abstract

This study focuses on identifying the relationship between risk factors related to environmental conditions, external factors, and technical aspects that affect the cost performance of underwater pipeline construction projects. The main objectives of this study are to understand the qualitative risk assessment that affects the contingency cost performance of underwater pipeline construction projects and to identify the relationship between various risk factors. The methodology in this study involves a case study approach on a submarine pipeline project in the Java Sea, utilizing historical analysis and expert information to identify potential risks and their impacts on project costs using fuzzy-based qualitative and quantitative analysis. The study found two field condition risk factors, one external risk, and thirteen technical risk factors in a submarine pipeline construction project using the S-Lay method. In an academic context, this study conducts an in-depth and detailed analysis of the identification stage, analysis, classification of risk levels (field conditions, external, and technical), relationships between risk variables, corrective actions, corrective action costs, and contingency cost analysis. The results of the analysis help in estimating project costs in more detail.

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1 Introduction

Indonesia has natural gas reserves of 62.9 TCF, making it one of the largest in Southeast Asia (ESDM, 2021). Utilizing gas as a transitional energy source can reduce dependence on more polluting fossil fuels, such as coal. Natural gas has the advantage of lower emissions, with CO2 emissions around 40% less than coal (IEA, 2017). Indonesia's commitment to reduce methane emissions and increase gas use by 24% by 2050 shows a cleaner direction towards renewable energy (IESR, 2023).

However, natural gas management requires adequate infrastructure, especially undersea pipelines. The development of this infrastructure faces significant obstacles such as cost overruns anddelayschedule. Research shows that gas pipeline projects in Indonesia, such as South Sumatra-West Java, experienced cost overruns of up to 15%, which had a negative impact on operational smoothness and loss of project activity productivity (Aulia, 2014).

This study aims to identify risk factors that affect the cost of a subsea gas pipeline project and implement risk management to minimize cost overruns and delays. By analyzing environmental, external, and technical factors, it is expected that effective preventive measures can be produced (Yusuf et al., 2025). These findings are important to improve the effectiveness of energy infrastructure project management in Indonesia.

The objectives of this research are as follows:1) Identifying field conditions, external, technical risk factors that affect the cost performance of subsea pipeline construction projects; 2) Conducting a fuzzy-based qualitative risk assessment affecting the performance of a subsea pipeline construction project to understand the level of risk faced; 3)Analyze the relationship between field condition, external, and technical risk factors in submarine pipeline construction projects to improve project cost estimates (Fallahnejad, 2013; Wen et al., 2024).

Literature Review
Subsea Pipeline Construction Project

A subsea pipeline is a network of pipes installed on the seabed to transport oil, gas, and liquids from offshore production facilities to onshore processing plants. Its main function is to facilitate long-distance hydrocarbon transportation and connect offshore platforms with onshore. The advantages of subsea pipelines include reduced environmental impact, efficiency in transporting bulky materials, and the ability to operate in challenging environments (Nursanti et al., 2018). The subsea pipeline construction process includes several stages, namely the Construction Implementation Method, Front-End Engineering Design (FEED), engineering phase, procurement phase, and construction/installation phase.

Management Cost Project Contingency

Project cost management is the process of planning and controlling costs required to ensure a project is within the agreed budget. The total cost of a project reflects the professionalism and technical ability in managing resources and generating profits (Siregar, 2011). Management includes cost estimation, determination, and cost control. Contingency cost management is an important component that aims to reduce risks and gaps during project implementation, with funds set aside for unforeseen costs (Project Management Institute, 2017). The application of appropriate risk analysis methods can help determine the amount of contingency costs required, thereby increasing the likelihood of project success with a well-planned contingency budget (Khamooshi & Khosravi, 2020).

Field Condition Variables

Project field conditions include elements of air depth, seabed features, geographic location, geotechnical properties, and adverse weather, which have a significant impact on risk management (Wiguna et al., 2017). Analysis of field condition variables is important to assess the actual conditions surrounding the project, which can affect safety and operations. With this understanding, project managers can implement effective risk strategies to mitigate negative impacts, ensuring the project remains on budget and on schedule despite external challenges (Siregar, 2011).

External Variables

External project factors include elements such as delays in permit approvals, changes in tax regulations, and community improvement actions that significantly affect project management and performance risks (Nwosu & Enyiche, 2011). Analysis of external variables is important for assessing risks that may affect the success of project implementation, allowing project managers to develop strategies to mitigate negative impacts and enhance success (Al-Gahtani et al., 2023). Understanding these variables is critical to accurate project planning and execution, so that projects remain on budget and schedule despite external challenges (Siregar, 2011).

Technical Variables

Technical factors of a project include elements such as the technology used, hardware and software specifications, operational parameters, and technical standards and implementation methods, which are critical to ensuring successful project implementation according to specifications (Hatmoko & Khasani, 2019). In project management, analysis of technical variables helps in cost estimation and control, as well as budget determination throughout the project cycle (Siregar, 2011). Understanding technical variables also allows for accurate risk identification and assessment, so that potential problems can be identified early (Nwosu & Enyiche, 2011).

2 Materials and Methods

The following are the research stages arranged by the author in conducting this research. These stages describe the workflow applied to answer the research objectives that have been explained previously.

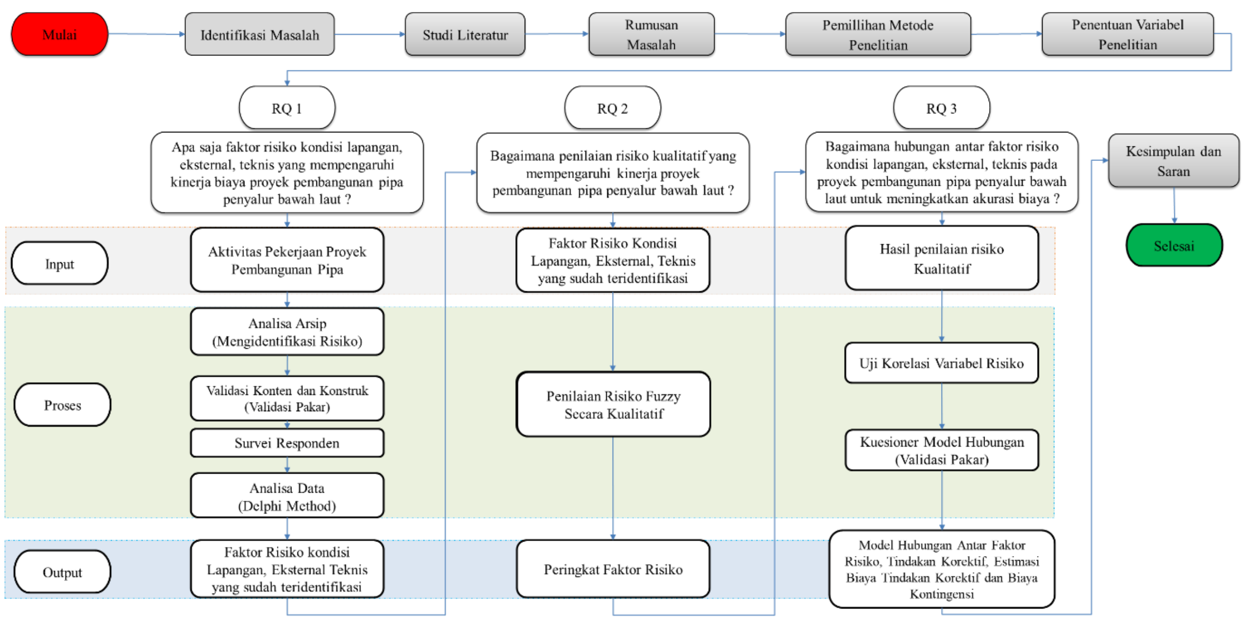

Figure 1. Research Flowchart

3 Results and Discussions

The following in Figure 2 is a structured process used to identify risks, analyze risks, and model risk factors in submarine pipeline construction projects.

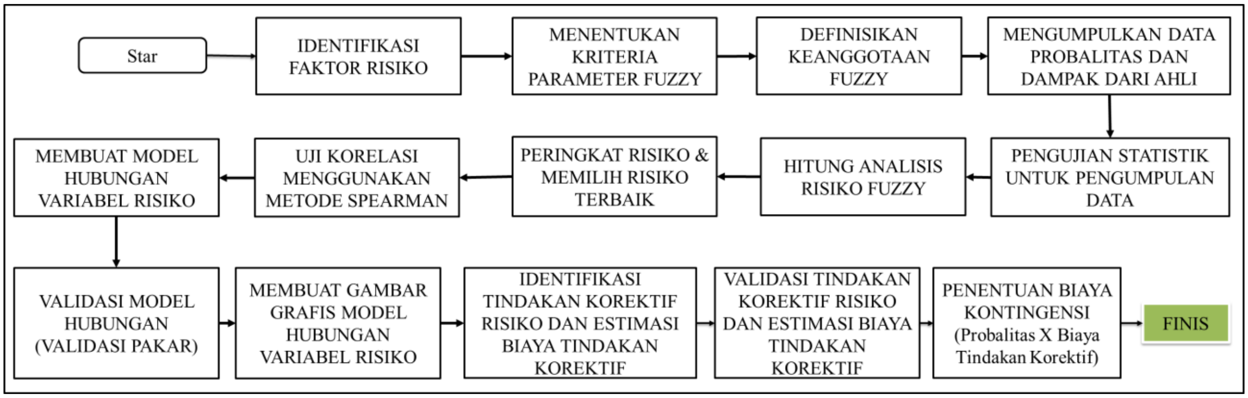

Figure 2. Flowchart for Fuzzy Analysis Application

3.1 Determination of Risk Factors

The first stage in project risk management is the determination of risk factors, where there are 38 identified risks that can affect the success of the project. These risks include field conditions, external factors, and technical factors, each of which has the potential to have a significant impact on the project schedule and budget. The risk identification process was carried out comprehensively through literature reviews, project document analysis, and consultation with experts, ensuring that all relevant aspects were taken into account. The results of this phase, summarized in Table 1, provide a clear Figure of the risks that need to be monitored and managed during project implementation.

Table 1
Risk Factors Identified in Subsea Pipeline Construction

Code	Variables	Sub-Code	Risk Factor Description	Source
X1	Field Conditions	X1.1	Extreme weather conditions that result in transportation and installation being stopped/disrupted	(Aulia, 2014); (Latief, & Aulia, 2024)
		X1.2	The occurrence of free span in pipes is due to the pipe being on an uneven seabed contour.	(Aulia, 2014); (Latief, & Aulia, 2024)
		X1.3	The pipes installed/laid out are unstable on the seabed	(Latief, & Aulia, 2024)
X2	External	X2.1	Delays in licensing approval from government agencies	(Nursanti et al., 2018), (Fallahnejad, 2013), (Hatmoko & Khasani, 2019), (Latief, & Aulia, 2024)
		X2.2	Changes in Tax Regulations/ Increases in tax rates resulting in increased costs of purchasing materials	(Nursanti et al., 2018), (Abd El Khalek et al., 2016), (Al-Gahtani et al., 2023), (Dimitroff, 2014)
		X2.3	Demonstrations by residents (including fishermen) resulted in the installation activities being halted.	(Kraidi et al., 2020), (Dimitroff, 2014)
X3	Technical	X3.1	There was damage to the bevel and external concrete coating of the pipe during transportation to the field.	(Kraidi et al., 2020)
		X3.2	Damage to the bevel and external concrete coating of the pipe due to being hit/struck during lifting/staking	(Nursanti et al., 2018)
		X3.3	Delay in completion of material fabrication (pipe/riser clamp/crossing support) in the workshop	(Abd El Khalek et al., 2016)
		X3.4	Delays in the arrival of ships and materials/equipment for construction activities	(Hatmoko & Khasani, 2019), (Melvill, 2024)
		X3.5	Unavailability of spare parts for equipment in the field during construction/installation	(wosu & Enyiche, 2011), (Hatmoko & Khasani, 2019)
		X3.6	Damage/failure of lifting operations using a crane during construction	(Melvill, 2024)
X3	Technical	X3.7	Equipment damage/mechanical breakdown occurs during construction	(Melvill, 2024)
		X3.8	Damage to Steel Cable (Wire Sling) Occurs	(Melvill, 2024)
		X3.9	Damage to the AHT/towing tug engine	(Nursanti et al., 2018)
		X3.10	Fatal accident conditions for technicians working at heights	(Nursanti et al., 2018), (Melvill, 2024)

Code	Variables	Sub-Code	Risk Factor Description	Source
		X3.11	Fire in the firing line work area of the installation ship (pipelay barge) during welding	(Nursanti et al., 2018)
		X3.12	Damage to existing underwater facilities (pipes, cables) due to being pulled by anchors	(Nursanti et al., 2018), (Melvill, 2024)
		X3.13	Damage to the pipeline being installed due to being hit by a sinking ship/barge	(Nursanti et al., 2018)
		X3.14	High rate of rejection/rework of documents for fabrication and installation, due to poor quality of consultant/contractor documents/drawings	(Hatmoko & Khasani, 2019), (Melvill, 2024)
		X3.15	Delay in the document/drawing approval process from the owner team	(Hatmoko & Khasani, 2019), (Latief, & Aulia, 2024)
		X3.16	The condition of inaccuracy in the engineering design calculation and analysis process	(Kraidi et al., 2018), (Hatmoko & Khasani, 2019)
		X3.17	Significant increase in material take off (MTO) or bill of quantity (BOQ) from detailed engineering study results	(Melvill, 2024)
		X3.18	The quality of the materials sent to the field does not meet the requirements	(Melvill, 2024)
		X3.19	High rejection/rework rates from failed welds/non-destructive testing (NDT)"	(Kraidi et al., 2020)
		X3.20	A delay in the approval process from the inspection company/certification authority during pipe testing	(Nursanti et al., 2018)
		X3.21	Status of expired equipment/material certificates in the field	(Kraidi et al., 2018), (Latief, & Aulia, 2024)
X3	Technical	X3.22	The riser clamp cannot be installed	(Al-Gahtani et al., 2023), (Kraidi et al., 2018)
		X3.23	Buckle damage to pipes (buckle/overstress) during pipe laying	(Melvill, 2024)
		X3.24	Flanges, gaskets, and bolting installation errors	(Kraidi et al., 2018)
		X3.25	Risk of the pig getting stuck during pre-commissioning	(Hatmoko & Khasani, 2019)
		X3.26	Pipe Indicated to Leak During Precommissioning Testing	(Melvill, 2024)
		X3.27	There is still water content in the pipe during pre-commissioning/ dewatering	(Kraidi et al., 2018)
		X3.28	Simultaneous operation (SIMOP) constraints with operation/drilling or other projects	(Nursanti et al., 2018), (Kraidi et al., 2018)
		X3.29	Error in placing the target box coordinates during pipe deployment	(Nursanti et al., 2018), (Kraidi et al., 2018)
		X3.30	The pipeline route that was laid deviated from the corridor of the planned route of the deployment.	(Kraidi et al., 2020)
		X3.31	Repetition of construction/installation work (rework) due to design, fabrication or construction method errors	(Nursanti et al., 2018), (Kraidi et al., 2020), (Melvill, 2024)
		X3.32	Delay in completion of construction/installation	(Kraidi et al., 2020), (Melvill, 2024)

3.2 Determination of Fuzzy Parameter Criteria Function

At this stage, the Fuzzy approach is used to determine the criteria parameters in assessing the probability and impact of risk with a 5-point scale. These criteria are determined based on consultation with experts in related fields and supported by references from literature and case studies, including data from company "Z". This process provides a clearer and more measurable definition of the level of probability and impact, which is then used as input in risk calculations. The measurement scale for assessing the probability and impact of risk can be seen in Tables 2 and 3.

Table 2
Risk Probability Assessment Criteria [15]

Scale	Probability Assessment	Probability Value (P)	Comment	
1	Rare/Almost Impossible	$0\% < P \leq 20\%$	Unheard of in the Oil and Gas Industry	<10-6 times per year
2	Rarely happening	$20\% < P \leq 40\%$	Previously heard in the Oil and Gas Industry	10-6 to 10-4 times per year

Scale	Probability Assessment	Probability Value (P)	Comment	
3	It Could Happen	40% < P ≤ 60%	It has occurred in the work operation area up to 1 time in the last 100 years	10-4 to 10-2 times per year
4	Very Likely to Happen	60% < P ≤ 80%	It has occurred in the work operation area up to 1 time since last year	10-2 to 1 time per year
5	Almost certain to happen	80% < P < 100%	It has happened in the work area several times since last year.	>1 time per year

Table 3
Risk Impact Assessment Criteria [15]

Scale	Consequence Assessment	Impact of Schedule	Financial Costs/Impacts	Impact of Coverage/Quality
1	Very small	Schedule Increase < 1%, or (< 1 day)	Cost Impact < 1% of Project Cost	Quality degradation is almost non-existent
2	Small	1% ≤ Schedule Increase < 5%, or (1 day to 1 week)	1% ≤ Cost Impact < 2% Project Cost	Some parts of the coverage area are affected
3	Currently	5% ≤ Schedule Increase < 10%, or (1 - 2 weeks)	2% ≤ Cost Impact < 3% Project Cost	Most of the coverage area is affected
4	Big	Schedule increase ≤ 10% < 20%, or (2 weeks - 1 month)	3% ≤ Cost Impact < 4% Project Cost	Quality degradation is unacceptable to the Project Sponsor.
5	Very large	Increase Schedule ≥ 20%, or ≥ 1 month	Cost Impact ≥ 4% of Project Cost	Project results are useless

A rule-based fuzzy system consists of four main components: rules, fuzzifiers, inference, and processors. In the context of probability and impact assessment in this study, fuzzy functions are modeled usingfunctiontrapezoid to describe overlapping and imprecise boundaries between categories, providing hope in the assessment. Figures 3 and 4 and Table 4 show the application of the trapezoid function in a fuzzy system, as well as the visualization of the interactions between categories that influence each other.

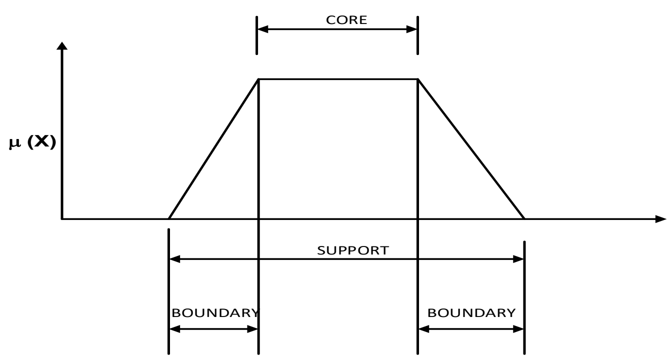

Figure 3. Fuzzy Membership Trapezoidal Function [15]

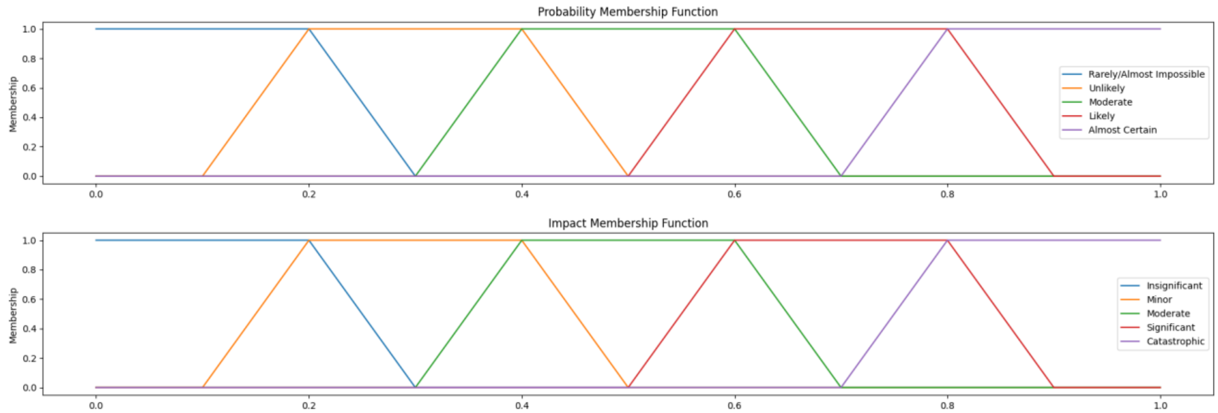

Figure 4. Fuzzy Membership for Probability and Impact [15]

Table 4
Linguistic Variables & Corresponding Trapezoidal Membership Functions [15]

Scale	Probabilistic Linguistics	Impact Linguistics	Fuzzy Membership Function	Meaning
1	Rare/Almost Impossible	Very small	0; 0; 0.2; 0.3	Represents a very low probability or negligible impact of an event occurring or its consequences.
2	Rarely happening	Small	0.1; 0.2; 0.4; 0.5	Indicates low probability or impact, but slightly higher than "rare/almost impossible".
3	It Could Happen	Currently	0.3; 0.4; 0.6; 0.7	Represents the average level of probability or impact, where the event or consequence is neither low nor high.
4	Very Likely to Happen	Big	0.5; 0.6; 0.8; 0.9	Indicates a high probability or significant impact, requiring attention and action to mitigate the risk.
5	Almost certain to happen	Very large	0.8; 0.9; 1.0	Represents a very high probability or catastrophic impact, requiring immediate action and strong mitigation.

3.3 Data Collection for Probability and Impact

The probability and impact of each identified risk factor were collected from respondents, including experts and stakeholders related to the subsea pipeline project. The data collection process involved a survey in which respondents provided qualitative assessments of the probability and impact of each risk factor, using a rating scale as in Tables 2 and 3, in consultation with expert advice and literature references.

3.4 Fuzzy Logic - Risk Analysis

Fuzzy Theory of Thesis. After fuzzy data is collected, risk factors are ranked based on their relative probability and impact using fuzzy logic. Fuzzy systems, also known as fuzzy-rule-based, fuzzy expert, fuzzy model, and fuzzy logic controller, consist of four components: rules, fuzzifiers, inferences, and defuzzifiers. In the context of a risk matrix, this system makes inferences based on the criteria shown in Table 5, which refers to Muhammad Yusuf (2024). Fuzzy risk analysis is used to calculate risks based on previously compiled probabilities and impacts. The defuzzification process produces values for all risks, allowing for more comprehensive risk identification. This stage is important for determining the most critical risks that require immediate attention, as a basis for effective decision-making in risk management. The equation used to calculate traditional analysis risk is:

$$R_i = P_i \cdot I_i, \qquad [15]$$

Where Ri is the risk score, Pi is the fuzzy probability, and Ii is the fuzzy impact of the i-th risk factor. Herecan be seen in Table 5, which describes the risk matrix, which has values and levels of interpretation for defuzzification of the fuzzy and traditional analysis processes as follows:

Table 5
Risk Impact and Probability Matrix [15]

RISK VALUE							
PROBABILITY	Almost Certain	5	5	10	15	20	25
	Likely	4	4	8	12	16	20
	Moderate	3	3	6	9	12	15
	Unlikely	2	2	4	6	8	10
	Rarely/Almost Impossible	1	1	2	3	4	5
			1	2	3	4	5
			Insignificant	Minor	Moderate	Significant	Catastrophic
			IMPACT				

The results of the risk assessment process with high risk factors are ranked and prioritized. The following are the main risk rankings listed in Table 6.

Table 6
Risk Rating

Code	Variables	Sub-Code	Risk Factor Description	Probability	Impact	Fuzzy Risk Value	Traditional Risk Value	Var	Risk Category	Risk Rating
X1	Field Conditions	X1.1	Extreme weather conditions that result in transportation and installation being stopped/disrupted	4	4	18,500	16	16%	High	1
		X1.2	The occurrence of free span in pipes is due to the pipe being on an uneven seabed contour.	4	4	18,500	16	16%	High	2
X2	External	X2.1	Delays in licensing approval from government agencies	3	4	15,423	12	29%	High	4
X3	Technical	X3.4	Delays in arrival of ships and materials/equipment for construction activities	3	4	14,125	12	18%	High	8
		X3.6	Damage/failure of lifting operations using a crane during construction	3	4	15,773	12	31%	High	3
		X3.7	Equipment damage/mechanical breakdown occurs during construction	3	4	15,773	12	31%	High	3
		X3.10	Fatal accident conditions for technicians working at heights	3	4	15,167	12	26%	High	6
		X3.12	Damage to existing underwater facilities (pipes, cables) due to being pulled by anchors	3	4	14,500	12	21%	High	6
		X3.16	Condition of inaccuracy in engineering design calculation and analysis process	3	4	14,214	12	18%	High	7
		X3.17	Significant increase in material take off (MTO) or bill of quantity (BOQ) from	3	4	14,125	12	18%	High	8

Code	Variables	Sub-Code	Risk Factor Description	Probability	Impact	Fuzzy Risk Value	Traditional Risk Value	Var	Risk Category	Risk Rating
			detailed engineering study results							
		X3.18	The quality of the materials sent to the field does not meet the requirements	3	4	15,167	12	26%	High	6
		X3.23	Buckle damage to pipes (buckle/overstress) during pipe laying	3	4	15,167	12	26%	High	6
		X3.26	Pipe Indicated to Leak During Precommissioning Testing	3	4	15,773	12	31%	High	3
		X3.31	Repetition of construction/installation work (rework) due to design, fabrication or construction method errors	3	4	15,423	12	29%	High	5
		X3.32	Delay in completion of construction/installation	3	4	14,125	12	18%	High	8

3.5 Risk Factor Relationship Model

After conducting normality tests, Spearman analysis, and expert validation, a model of the relationship between variables was obtained a significant and strong relationship between risk variables. Based on the positive and perfect correlation value, it shows that if there is a change in a certain variable, it will affect or be followed by other risk variables consistently. The following can be seen in Figure 5: the relationship model of field condition risk factors, external, and technical factors. Risk variable X1.1 affects X3.4, X3.6, X3.7, X3.10, X3.12, X3.23, X3.31, and X3.2. Risk variable X1.2 affects X3.23, while X2.1 affects X3.32. Risk variable X3.4 affects X3.32, and X3.6 affects X3.31 and X3.32. Risk variable X3.7 affects X3.12, X3.16, X3.23, X3.26, X3.31, and X3.32. In addition, X3.10 affects X3.32, and X3.12 affects X3.26, X3.31, and X3.32. Risk variable X3.16 affects X1.2, X3.17, X3.18, X3.23, X3.26, X3.31, and X3.32, while X3.17 affects X3.32. Risk variable X3.18 affects X3.17, X3.31, and X3.32, and X3.23 affects X3.26, X3.31, and X3.32. Finally, X3.26 and X3.31 also affect X3.32.

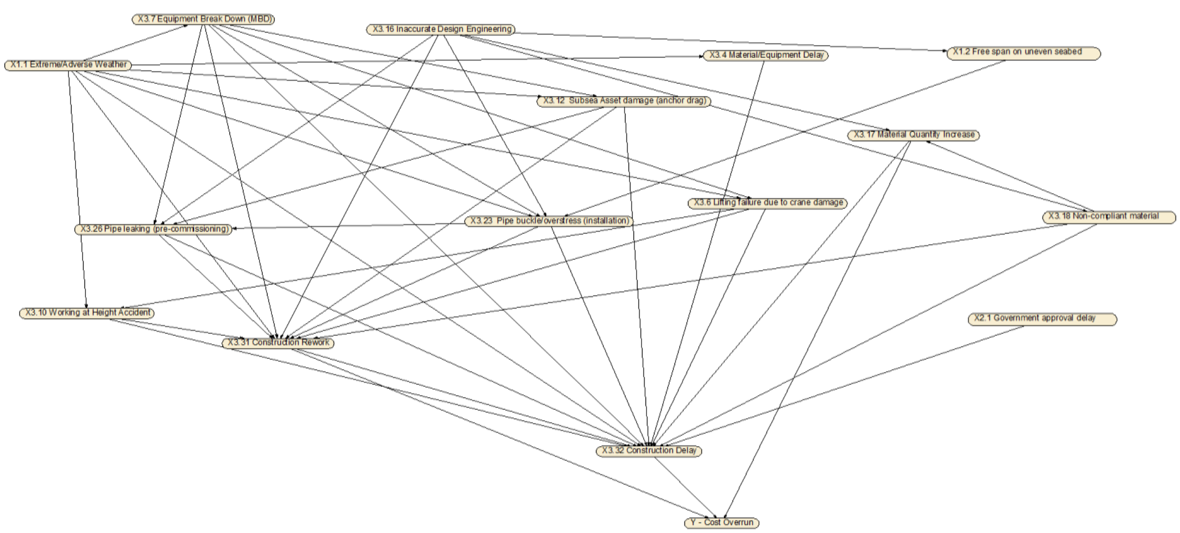

Figure 5. Risk Factor Relationship Graphics

3.6 Corrective Action Identification and Corrective Action Cost Estimation

Based on the analysis of the relationship between risk variables, the next stage is to determine corrective actions for the risk impacts that have occurred. Table 7 presents a tabulation of the impacts and corrective actions for 15 dominant risk factors identified through fuzzy analysis, which affect the accuracy of contingency costs in the subsea pipeline construction project.

Table 7
Risk Impact Corrective Action Costs

No	Indicator Code	Influence (Causes)	Risk Code	Corrective Action	Impact Correction Cost Estimate			Notes
					Minimum	Realistic	Maximum	
1	X1.1	–	X3.4	Additional charges for additional barge rental duration	USD 6,000	USD 12,000	USD 24,000	
2	X1.1	–	X3.6	Additional costs for crane hydraulic system repair duration	USD 87,500	USD 175,000	USD 350,000	Assuming a repair duration of 3-5 days. The cost impact is duration x daily rate
3	X1.1	–	X3.7	Additional costs for the equipment spare part replacement process	USD 43,750	USD 87,500	USD 175,000	Ok. Assuming the repair duration is not more than 1 day
4	X1.1	–	X3.10	Medical expenses and compensation	USD 2,000	USD 3,000	USD 5,000	From the compensation side, it's ok. But from the company's credibility side, the impact is very big. More than USD 5 million (ie blacklisted and cannot participate in tenders)
5	X1.1	–	X3.12	Additional costs for the addition and installation of pipe materials and mechanical connectors	USD 250,000	USD 500,000	USD 750,000	More than USD 2 million dollars. (environmental issue, investigation, punishment to CTR, black listed)
6	X1.1	–	X3.23	Additional costs for additional installation time & replacement pipe materials	USD 200,000	USD 400,000	USD 500,000	Rectification takes about 5-7 days per point. Max impact is about USD 1 million.
7	X1.1	–	X3.31	Additional time allocation/contingency for operational costs of installation vessels	USD 87,500	USD 175,000	USD 350,000	0.2% of the contract value per day, maximum 5% of the contract value
8	X1.1	–	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 100,000	USD 200,000	USD 300,000	0.2% of the contract value per day, maximum 5% of the contract value
9	X1.2	–	X3.23	Additional costs for additional installation time & replacement pipe materials	USD 200,000	USD 400,000	USD 500,000	
10	X2.1	–	X3.32	Additional mitigation costs for installation vessel duration costs due to delays in hydrotest approvals	USD 43,750	USD 87,500	USD 175,000	Same as above
11	X3.4	–	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 200,000	USD 400,000	USD 700,000	

No	Indicator Code	Influence (Causes)	Risk Code	Corrective Action	Impact Correction Cost Estimate			Notes
					Minimum	Realistic	Maximum	
12	X3.6	–	X3.31	Additional time allocation/contingency for repeat work	USD 31,250	USD 62,500	USD 125,000	
13	X3.6	–	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 300,000	USD 500,000	USD 1,000,000	
14	X3.7	–	X3.12	Additional costs for additions, installation of pipe materials and mechanical connectors and repair of installation equipment.	USD 240,000	USD 300,000	USD 360,000	
15	X3.7	–	X3.23	Additional costs for additional installation time & replacement pipe materials and repair of installation equipment	USD 240,000	USD 300,000	USD 360,000	
16	X3.7	–	X3.26	Additional costs for repair/replacement time of damaged equipment for pre-commissioning testing.	USD 31,250	USD 62,500	USD 125,000	
17	X3.7	–	X3.31	Additional costs for repair/replacement time of damaged equipment and repeat work	USD 31,250	USD 62,500	USD 125,000	
18	X3.7	–	X3.32	Allocation of additional costs for repair/replacement time for damaged equipment and anticipation of delays in completion/penalties	USD 200,000	USD 400,000	USD 700,000	
19	X3.10	–	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 300,000	USD 500,000	USD 1,000,000	
20	X5.12	–	X3.26	Additional costs for repair/replacement time of flange connection	USD 240,000	USD 300,000	USD 360,000	
21	X3.12	–	X3.31	Additional costs for additional installation time & replacement pipe materials	USD 240,000	USD 300,000	USD 360,000	
22	X3.12	–	X3.32	Additional costs for additional installation time & replacement pipe materials	USD 240,000	USD 300,000	USD 360,000	
23	X3.16	–	X1.2	Contour correction intervention work for free span correction	USD 50,000	USD 150,000	USD 250,000	
24	X3.16	–	X3.17	Additional costs for additional pipe materials	USD 240,000	USD 300,000	USD 360,000	
25	X3.16	–	X3.18	Allocation of replacement materials in accordance with the	USD 240,000	USD 300,000	USD 360,000	

ISSN: 2454-2261

No	Indicator Code	Influence (Causes)	Risk Code	Corrective Action	Impact Correction Cost Estimate			Notes
					Minimum	Realistic	Maximum	
				following requirements and their delivery				
26	X3.16	–	X3.23	Additional costs for additional installation time & replacement pipe materials	USD 240,000	USD 300,000	USD 360,000	
27	X3.16	–	X3.26	Additional costs for repair/replacement time of flange connection	USD 240,000	USD 300,000	USD 360,000	
28	X3.16	–	X3.31	Additional time allocation/contingency for operational costs of installation vessels	USD 62,500	USD 125,000	USD 250,000	
29	X3.16	–	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 300,000	USD 500,000	USD 1,000,000	
30	X3.17	–	X3.32	Allocation of additional costs for additional materials that cause work delays	USD 200,000	USD 400,000	USD 700,000	
31	X3.18	–	X3.17	Allocation of replacement materials in accordance with the following requirements and their delivery	USD 240,000	USD 300,000	USD 360,000	
32	X3.18	–	X3.31	Additional time allocation/contingency for operational costs of installation vessels	USD 62,500	USD 125,000	USD 250,000	
33	X3.18	–	X3.32	Allocation of additional costs for delivery of replacement materials that cause work delays	USD 200,000	USD 400,000	USD 700,000	
34	X3.23	–	X3.26	Additional costs for additional installation time & replacement pipe materials	USD 240,000	USD 300,000	USD 360,000	
35	X3.23	–	X3.31	Additional costs for additional installation time & replacement pipe materials	USD 240,000	USD 300,000	USD 360,000	
36	X3.23	–	X3.32	Additional costs for additional installation time & replacement pipe materials	USD 240,000	USD 300,000	USD 360,000	
37	X3.26	–	X3.31	Additional costs for repair/replacement time of flange connection	USD 240,000	USD 300,000	USD 360,000	
38	X3.26	–	X3.32	Additional costs for repair/replacement time of flange connection	USD 240,000	USD 300,000	USD 360,000	
39	X3.31	–	X3.32	Additional costs for repair/replacement time of flange connection and to anticipate delays in completion/penalties	USD 240,000	USD 300,000	USD 360,000	

3.7 Determining Contingency Costs

The final stage in the process is to determine the project contingency cost by multiplying the corrective action cost by the probability of each risk factor in the construction of the underwater pipeline. The following are the results of the analysis in Table 8 as follows:

Table 8
Contingency Fee

No	Indicator Code	Influence (Causes)	Risk Code	Corrective Action	Contingency Cost (Corrective Cost x Probability)		
					Minimum	Realistic	Maximum
1	X1.1	_	X3.4	Additional charges for additional barge rental duration	USD 24,000	USD 48,000	USD 96,000
2	X1.1	_	X3.6	Additional costs for crane hydraulic system repair duration	USD 350,000	USD 700,000	USD 1,400,000
3	X1.1	_	X3.7	Additional costs for the equipment spare part replacement process	USD 175,000	USD 350,000	USD 700,000
4	X1.1	_	X3.10	Medical expenses and compensation	USD 8,000	USD 12,000	USD 20,000
5	X1.1	_	X3.12	Additional costs for the addition and installation of pipe materials and mechanical connectors	USD 1,000,000	USD 2,000,000	USD 3,000,000
6	X1.1	_	X3.23	Additional costs for additional installation time & replacement pipe materials	USD 800,000	USD 1,600,000	USD 2,000,000
7	X1.1	_	X3.31	Additional time allocation/contingency for operational costs of installation vessels	USD 350,000	USD 700,000	USD 1,400,000
8	X1.1	_	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 400,000	USD 800,000	USD 1,200,000
9	X1.2	_	X3.23	Additional costs for additional installation time & replacement pipe materials	USD 800,000	USD 1,600,000	USD 2,000,000
10	X2.1	_	X3.32	Additional mitigation costs for installation vessel duration costs due to delays in hydrotest approvals	USD 131,250	USD 262,500	USD 525,000
11	X3.4	_	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 600,000	USD 1,200,000	USD 2,100,000
12	X3.6	_	X3.31	Additional time allocation/contingency for repeat work	USD 93,750	USD 187,500	USD 375,000
13	X3.6	_	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 900,000	USD 1,500,000	USD 3,000,000
14	X3.7	_	X3.12	Additional costs for additions, installation of pipe materials and mechanical connectors and repair of installation equipment.	USD 720,000	USD 900,000	USD 1,080,000
15	X3.7	_	X3.23	Additional costs for additional installation time & replacement pipe materials and repair of installation equipment	USD 720,000	USD 900,000	USD 1,080,000
16	X3.7	_	X3.26	Additional costs for repair/replacement time of damaged equipment for pre-commissioning testing.	USD 93,750	USD 187,500	USD 375,000
17	X3.7	_	X3.31	Additional costs for repair/replacement time of	USD 93,750	USD 187,500	USD 375,000

No	Indicator Code	Influence (Causes)	Risk Code	Corrective Action	Contingency Cost (Corrective Cost x Probability)		
					Minimum	Realistic	Maximum
				damaged equipment and repeat work			
18	X3.7	_	X3.32	Allocation of additional costs for repair/replacement time for damaged equipment and anticipation of delays in completion/penalties	USD 600,000	USD 1,200,000	USD 2,100,000
19	X3.10	_	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 900,000	USD 1,500,000	USD 3,000,000
20	X5.12	_	X3.26	Additional costs for repair/replacement time of flange connection	USD 720,000	USD 900,000	USD 1,080,000
21	X3.12	_	X3.31	Additional costs for additional installation time & replacement pipe materials	USD 720,000	USD 900,000	USD 1,080,000
22	X3.12	_	X3.32	Additional costs for additional installation time & replacement pipe materials	USD 720,000	USD 900,000	USD 1,080,000
23	X3.16	_	X1.2	Contour correction intervention work for free span correction	USD 150,000	USD 450,000	USD 750,000
24	X3.16	_	X3.17	Additional costs for additional pipe materials	USD 720,000	USD 900,000	USD 1,080,000
25	X3.16	_	X3.18	Allocation of replacement materials in accordance with the following requirements and their delivery	USD 720,000	USD 900,000	USD 1,080,000
26	X3.16	_	X3.23	Additional costs for additional installation time & replacement pipe materials	USD 720,000	USD 900,000	USD 1,080,000
27	X3.16	_	X3.26	Additional costs for repair/replacement time of flange connection	USD 720,000	USD 900,000	USD 1,080,000
28	X3.16	_	X3.31	Additional time allocation/contingency for operational costs of installation vessels	USD 187,500	USD 375,000	USD 750,000
29	X3.16	_	X3.32	Allocation of additional costs to anticipate delays in completion/penalties	USD 900,000	USD 1,500,000	USD 3,000,000
30	X3.17	_	X3.32	Allocation of additional costs for additional materials that cause work delays	USD 600,000	USD 1,200,000	USD 2,100,000
31	X3.18	_	X3.17	Allocation of replacement materials in accordance with the following requirements and their delivery	USD 720,000	USD 900,000	USD 1,080,000
32	X3.18	_	X3.31	Additional time allocation/contingency for operational costs of installation vessels	USD 187,500	USD 375,000	USD 750,000
33	X3.18	_	X3.32	Allocation of additional costs for delivery of replacement materials that cause work delays	USD 600,000	USD 1,200,000	USD 2,100,000
34	X3.23	_	X3.26	Additional costs for additional installation time & replacement pipe materials	USD 720,000	USD 900,000	USD 1,080,000
35	X3.23	_	X3.31	Additional costs for additional installation time & replacement pipe materials	USD 720,000	USD 900,000	USD 1,080,000
36	X3.23	_	X3.32	Additional costs for additional installation time & replacement pipe materials	USD 720,000	USD 900,000	USD 1,080,000

No	Indicator Code	Influence (Causes)	Risk Code	Corrective Action	Contingency Cost (Corrective Cost x Probability)		
					Minimum	Realistic	Maximum
37	X3.26	_	X3.31	Additional costs for repair/replacement time of flange connection	USD 720,000	USD 900,000	USD 1,080,000
38	X3.26	_	X3.32	Additional costs for repair/replacement time of flange connection	USD 720,000	USD 900,000	USD 1,080,000
39	X3.31	_	X3.32	Additional costs for repair/replacement time of flange connection and to anticipate delays in completion/penalties	USD 720,000	USD 900,000	USD 1,080,000

3.8 Implications for Risk Management

The findings of this study indicate that:
Increasing the accuracy of contingency cost estimates can be achieved through risk identification and calculation. First, identifying dominant risks allows the project team to understand the factors with the greatest impact, such as environmental conditions, external risks and technical risks that help the project manager estimate costs.

a) Risk calculations using fuzzy analysis methods produce more accurate estimates of the potential impact of risks, so that the team can set relevant cost contingencies based on concrete analysis.
b) With a thorough understanding of the risks and their realization, the team can plan the necessary mitigation actions to reduce budget constraints.

The implication for risk management is the need for a systematic approach in identifying and calculating risks for accurate contingency cost estimates, so that project cost estimates become more detailed.

4 Conclusion

The analysis results identified 38 significant risk factors affecting the contingency cost of the subsea pipeline construction project, consisting of 3 field condition risk factors, 3 external factors, and 32 technical factors. This identification provides a strong foundation for planning an effective risk mitigation strategy. The fuzzy-based qualitative analysis revealed 15 main factors, including 2 field condition risks (extreme weather and free span on the pipeline), 1 external risk (delay in permit approval), and 12 technical risk factors (delays in the arrival of ships and materials/equipment for construction activities, damage/failure of lifting operations using cranes during construction, damage to equipment/mechanical breakdown during construction, fatal accidents involving technicians working at heights, damage to existing underwater facilities (pipes, cables) due to being pulled by anchors, inaccurate conditions in the calculation and analysis process of engineering design, significant increase in the quantity of material take off (MTO) or bill of quantity (BOQ) from the results of detailed engineering studies, the quality of materials sent to the field does not meet the requirements, buckling damage to pipes (buckle/overstress) during pipe deployment, pipes indicated to be leaking during precommissioning testing, repetition of construction/installation work (rework) due to design, fabrication or construction method errors, and delays in completion of construction/installation). All these factors are supported by literature and fuzzy analysis, providing a solid foundation for more effective risk mitigation strategies. Correlation tests and validation of the variable relationship model indicate the presence of a number of factors that contribute to project delays and losses. Corrective actions applied to dominant risk factors require additional project costs and time allocations, emphasizing the importance of good risk management to keep the project budget within budget.

Future Study
As a development, further research is suggested to analyze other variables that can be integrated with field condition, external, and technical variables as the cause of risk factors in the construction of submarine pipelines. Variables

include financial risk factors and management risk factors, which influence each other and can cause cost overruns and delays in project completion.

Conflict of interest statement
The authors declared that they have no competing interests.

Statement of authorship
The authors have a responsibility for the conception and design of the study. The authors have approved the final article.

Acknowledgments
We are grateful to two anonymous reviewers for their valuable comments on the earlier version of this paper.

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