



INCORPORATING VIABLE METHODS IN FACILITATING FAILURE ANALYSIS OF SUBSEA MANIFOLD



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Abstract

This study was undertaken to develop a decision-making model that can be used to facilitate the minimization of rate of failure of subsea manifold. The prevailing criteria's/influencing factors that contributed to the failure of subsea manifold using a combined fuzzy analytic hierarchy process (FAHP), Bayesian Network, Simple additive weight method (SAW) and Entropy method (EM) were revealed. From the findings, wrong installation (WI) was the most influencing factors that contributed to the failure of the subsea manifold. The FAHP application in the study, revealed that WI is the major factor/failure mode of the subsea manifold failure. In BN analysis, the criteria were stated and defined, the posterior probabilities of the subsea manifold failing and working were revealed using the BN Genie software and their interdependency were observed as the states were varied respectively. The posterior probability of subsea manifold failure from BN analysis gave high possibility that WI was the key criterion that contributed to failure of the subsea system. The results from SAW technique also attributed the subsea manifold failure to WI. Evidence from Entropy method attributes subsea manifold failure to corrosion. Thus, a comparative analysis from the decision tools with respect to the criteria were analysed, and it showed that WI is the prevailing factor/failure mode that contributed to subsea manifold failure during subsea processes. It is therefore of utmost interest that during subsea production processes, more attention should be given to the installation phase, and the process should incorporate experts to minimize failure modes and impending failures.

Keywords:

Subsea manifold; Fuzzy Analytic Hierarchy Process (FAHP); Bayesian Network (BN); Simple Additive Weighting (SAW); Entropy Method (EM); Failure analysis.

1. Introduction

The discovery of significant numbers of new oil and gas fields located in deep water has made the subsea industry more predominant in recent years (Kaushik et al., 2017). According to Karan (2020), subsea development is constantly heading towards simplification and digitization due to the migration of oil and gas exploration into deep water areas. However, Gerrit et al. (2015) noted that subsea fluid domains suffer from multifaceted and partly incomplete information flows. Maryam and Marvin (2013) also predicted that new systems and technologies in the subsea industry are frequently met with uncertainty, as some operators fear subsea system failure frequencies and production losses. Technologies and equipment used for exploring and excavating the resources of deep-sea regions buried under the seabed have gained momentum (Woo et al., 2014). The term "subsea" is particularly associated with the development of resources concealed underground in coastal areas and the open sea, including subsea wells, subsea fields, subsea projects, and subsea developments. Peter et al. (1994) emphasized that subsea production systems can be improved if all design facility requirements are addressed, thereby reducing capital and operating costs. Sirous (2012) argued that a subsea project can only be viable when drilling requirements, distances, location, fabrication, installation, and operational standards are met. Subsea manifolds are arrangements of piping and valves designed to combine, distribute, control, and monitor fluid flow (Oseghale, 2019). They are typically installed on the seabed within an array of wells to gather production or to inject water or gas. According to Oseghale (2019), subsea manifolds have been applied in the development of oil and

gas fields to simplify the subsea system, minimize the use of pipelines and risers, and improve production flow (Sang et al., 2014). Paula (2001) highlighted their importance in subsea operations due to ease of maintenance and reduced impact of subsea interventions on production losses. Yingying et al. (2021) described subsea manifolds as hub equipment for oil and gas transportation that plays a vital role in layout optimization of subsea production systems. In earlier times, traditional manifolds were fixed on the seabed, making them difficult to discard or recover after use despite their many advantages (Yingying et al., 2021). Cluster manifolds have been developed for ultra-deepwater oil and gas fields (Yingying et al., 2016). However, subsea piping must withstand internal pressure, thermal loads, hydrostatic collapse, and operational loads in severe environments. Sang et al. (2014) applied nonlinear finite element and finite volume methods for performance analysis. Karan (2021) noted that material selection significantly influences reliability, while environmental conditions such as corrosion risk, buckling, water hammer, and erosion-corrosion are contributing factors. Due to the high hazards associated with subsea failures, risk assessment techniques are often applied to evaluate reliability (Zhaohui et al., 2021). Runar et al. (2001) cautioned that low subsea reliability leads to production revenue losses, high downtime costs, and credibility issues. Hajar et al. (2023) investigated submarine pipeline failures using FAHP and found corrosion, natural disasters, materials, and operations as major factors. With harsh operating conditions and increasing system complexity, the need for more research on subsea manifold performance is paramount. Establishing decision tools to determine

influencing nodes of manifold failure is still limited, although such tools can provide root-cause detection and minimize failure frequencies.

Subsea manifold failures are associated with site-specific conditions that not only result in production stagnation and economic losses but also promote environmental pollution that threatens marine life and human health (Yingying et al., 2016). Guan et al. (2021) observed that harsh working environments and stress during manifold installation challenge safety, while failures can also compromise connections with the Christmas tree and internal equipment. Complex sea conditions such as wave currents and earthquakes further reduce performance and lifespan. Yongsheng et al. (2017) noted that manifolds are prone to leakage and rupture, which can induce hazards and losses to human life, property, and the environment (Jong et al., 2014).

The persistent failure of subsea manifolds in diverse environments highlights the urgent need for a reliable decision-making model that can identify influencing factors and establish preventive measures. Wrong installation and design errors are among the most cited causes of failure, alongside corrosion and harsh environmental conditions. Such factors demand attention during design and installation phases to ensure reliability and performance. The present study therefore develops a novel model that integrates Fuzzy Analytic Hierarchy Process (FAHP), Bayesian Network (BN), Simple Additive Weighting (SAW), and Entropy Method (EM) as a multi-attribute decision-making tool for subsea manifold failure analysis. By determining posterior probabilities of critical factors, ranking their severity, and comparatively analyzing their impacts, the model aims to improve predictive capability, provide preventive strategies, and strengthen subsea equipment reliability under extreme marine conditions.

2. Literature Review

Historically, subsea manifolds have been integral to the development of oil and gas fields, primarily to minimize subsea flowline applications and reduce capital expenditure through fewer flowlines and umbilicals (Paula et al., 2001). Subsea manifolds serve as key nodes within subsea systems, controlling and directing the production flow. Their role in simplifying subsea infrastructure and improving operational efficiency has made them an attractive solution, yet failures remain a major concern in offshore operations.

Several studies have examined subsea manifold design, cost, and reliability. Paula et al. (2001) investigated the financial lifespan cost of Petrobras manifold applications in shallow and deepwater conditions, highlighting the cost advantages of subsea systems. Zhaohui et al. (2021) applied fault tree analysis and computational fluid dynamics for subsea manifold risk assessment, revealing improved valve flow characteristics and reliability enhancement opportunities. William and Hale (1998) explored design, testing, and installation challenges under extreme conditions, while Athanasios et al. (2017) introduced a fuzzy-TOPSIS-based decision-making methodology for prioritizing critical failure modes, demonstrating improvements over conventional FMEA techniques in

offshore reliability analysis. Other studies have emphasized subsea control reliability. Paul (2010) investigated subsea control module reliability and found early-life failures that lacked strong correlation with environmental conditions. Geovana et al. (2018) reviewed subsea failures across pipelines, risers, and umbilicals, with results indicating that mechanical damage, corrosion, natural hazards, and fatigue accounted for most failures. Flexible risers were particularly prone to collapse under external pressure, while umbilical failures were linked to tension, torsion, fatigue, and chafing. Liangliang and Miao (2022) used finite element modelling with ABAQUS to study wellhead connectors, finding that axial preload and material selection critically influence gasket sealing performance. Their results identified stainless steel 316L as more suitable than 304 or Inconel 625 for subsea applications.

Advanced approaches for subsea failure prediction have also emerged. Ashutosh (2016) proposed Bayesian Belief Networks (BBN) for failure rate prediction, building on Rahimi and Rausand's (2013) work to quantify Reliability Influencing Factors (RIFs) and failure causes. He et al. (2021) used analytic hierarchy process (AHP) combined with FMEA to assess failure modes in floating offshore wind turbines, identifying fifteen critical scenarios and proposing preventive measures. Alex et al. (2009) combined AHP and fault tree analysis to guide pipeline maintenance strategies based on failure likelihood and consequences. Wax deposition in subsea pipelines, a persistent challenge due to crystallization on cold pipe walls, was investigated by Abass (2021), who proposed predictive models and mitigation technologies.

Hybrid troubleshooting approaches have also been applied. Khairul (2016) used fishbone diagrams and "5-Whys" analysis to trace subsea equipment failures, emphasizing material hardness deviations in Inconel 718. Emerson et al. (2023) reviewed subsea installation modelling, focusing on safe, cost-effective lowering operations, while Chandima et al. (2015) examined subsea manifold failure using internal documentation and standards, offering a practical framework for reliability assessment. Fei et al. (2021) applied fuzzy fault tree models, demonstrating that failures of lifting and protective structures have high impact on subsea manifold reliability. Zhiwei et al. (2017) conducted motion analysis of deepwater manifold lifting operations, revealing high vessel and cable stresses during installation and highlighting the effectiveness of heave compensation. Risk-based methodologies have been widely deployed in subsea reliability analysis. FMEA (Zio, 2007), HAZOP (Andrews & Moss, 2002), fault tree analysis (Ericson, 2005), and event tree analysis (Bedford & Cooke, 2001) remain standard tools for identifying failure causes and assessing risks. Quantitative Risk Analysis (QRA) and ALARP principles have been applied to define acceptable risk thresholds (Vinnem, 2014; Sutton, 2010). Visualization techniques have also been developed to aid decision-making through graphical risk representations (Bostrom et al., 2008; Ale et al., 2015). Bow-Tie analysis (Saud et al., 2014) and Bayesian Networks (Nadkarni & Shenoy, 2001) have further expanded reliability modelling by capturing uncertainties and dependencies among variables.

Maintenance strategies play a critical role in mitigating subsea failures. Preventive, corrective, scheduled, reliability-centred, predictive, and routine maintenance approaches have been adopted to extend system life and reduce downtime (Moubray, 1991; Sullivan et al., 2004). Recent advances emphasize sensor-based predictive maintenance and condition monitoring as cost-effective alternatives to traditional approaches (Ebrahimipour et al., 2015). Subsea production systems comprise a wide range of interconnected components, including drilling systems, manifolds, jumpers, wellheads, trees, pipelines, umbilicals, risers, flowlines, control systems, and installation vessels (Gerald & Scott, 2022). Each subsystem presents unique challenges in design, installation, and reliability. Manifolds and jumper systems remain critical hubs for fluid control, while subsea trees and wellheads serve as pressure-containing interfaces. Flow assurance remains a persistent challenge due to wax, hydrate, and scale deposition, which can obstruct production flow under extreme temperature and pressure conditions.

Despite extensive research on subsea reliability and manifold performance, a clear gap persists. Most existing studies have focused on individual techniques such as FMEA, fault tree analysis, or Bayesian Networks. However, there is limited evidence of a combined decision-making framework that integrates FAHP, BN, SAW, and Entropy Method for subsea manifold failure analysis. Addressing this gap, the present study develops a comprehensive multi-attribute decision-making model capable of identifying critical influencing factors and supporting preventive strategies for subsea manifold reliability improvement.

3. Research Methodology

This study employed four decision-making techniques: Fuzzy Analytic Hierarchy Process (FAHP), Bayesian Network (BN), Simple Additive Weighting (SAW), and Entropy Method (EM), to analyse subsea manifold system failures. These approaches were selected due to their ability to integrate qualitative and quantitative factors, handle uncertainty, and provide structured rankings of influencing criteria. Data used in the analysis were obtained from subsea professionals with 10 – 15 years of experience as well as secondary sources such as the Offshore Reliability Data (OREDA) handbook.

3.1 Fuzzy Analytic Hierarchy Process (FAHP)

FAHP is an extension of the Analytic Hierarchy Process (AHP) that incorporates fuzzy logic to better capture human judgment under uncertainty. Unlike classical AHP, which only classifies evaluation factors into target and factor levels, FAHP introduces an additional criterion level (Geng et al., 2021). The technique involves constructing a fuzzy judgment matrix, calculating row sums, normalizing values, and determining eigenvectors to derive the relative importance of criteria.

A fuzzy triangular number is expressed as:

$$P = (l, m, u) \quad (1)$$

where l is the lower value, m the middle value, and u the upper value.

The membership function of $M(\mu)$ is defined as :

$$\mu(x/M) = \begin{cases} 0 & (x < l) \\ \frac{x-l}{m-l} & (l \leq x < m) \\ \frac{\mu-x}{\mu-m} & (m \leq x < \mu) \\ 0 & (x \geq \mu) \end{cases} \quad (2)$$

To normalize the process in FAHP, W_i is express as:

$$W_i = \frac{W_i}{\sum_{j=1}^n W_j} \quad (3)$$

The greatest eigen value of the judgment matrix can be express as:

$$\lambda_{max} = \sum_{i=1}^n \frac{AW_i}{nW_i} \quad (4)$$

Where:

A is the priority judgment matrix, and W_i represent the corresponding eigenvector, “ i ” is row and “ j ” is column of the judgment matrix

Consistency is tested using the Consistency Ratio (CR):

$$\text{Consistency ratio (CR)} = \frac{\text{Consistency Indictaor (CI)}}{\text{Random consistency matrix (RI)}} \quad (5)$$

Where:

the consistency indicator (CI) is express as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

Where:

“ n ” denotes the number of pairwise compared and “ λ_{max} ” maximum lambda value.

3.2 Bayesian Network (BN)

Bayesian Networks are probabilistic graphical models based on Bayes’ theorem, represented as directed acyclic graphs (DAGs) with nodes (variables) and arcs (dependencies). BN captures uncertainty by updating posterior probabilities as new evidence becomes available (Nadkarni and Shenoy, 2001).

In this study, subsea manifold failure was represented as the child node, while design error, wrong installation, corrosion, and fatigue were parent nodes (influencing criteria). Conditional Probability Tables (CPTs) were developed using expert judgment due to limited objective data.

The formula for determining the joint probability distribution of the four criteria is given by:

$$P[DE, WI, C, F] = P(DE | WI). P(WI | C). P(C | DE). \quad (7)$$

BN modelling was carried out using Genie software, which enabled evidence propagation and posterior probability computation.

3.3 Simple Addictive Weighing Method (SAW)

SAW is a multi-attribute decision-making method based on weighted summation, where the alternative with the highest total score is considered most critical. The normalized decision matrix is obtained using:

$$r_{ijb} = \frac{r_{ij}}{\text{Max}(x_{ij})} \quad (8)$$

or

$$r_{ijc} = \frac{r_{ij}}{\text{Max}(x_{ij})} \quad (9)$$

Where:

“ r_{ijb} ” can be described as benefit and r_{ijc} is cost attribute.

The weighted estimation can be deduced using:

$$A_i = \sum_{j=i}^m W_j(x_{ij})_{normal} \quad (10)$$

Where:

A_i is the summation of each weighted attribute

This technique was applied to rank the subsea failure criteria and validate FAHP results.

3.4 Entropy Weight Method (EM)

The Entropy Method was used to derive objective weights of criteria based on their degree of dispersion of information. The entropy value for criterion j is:

The eigen values of the criteria can be deduced using:

$$e_j = -h \sum_{i=1}^m r_{ij} \ln r_{ij} \quad (11)$$

Where $j = 1, 2, 3, 4, \dots$

After determining the eigen values, the di-fuzzified weight can be derived using:

$$d_j = 1 - e_j \quad (12)$$

The final weight of the criteria can be determined from the formula;

$$W_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (13)$$

3.5 Data Collection

Primary data were obtained through expert elicitation from subsea engineers and operators with 10 –15 years of deepwater drilling experience. Secondary data were retrieved from OREDA and technical literature. The experts provided pairwise comparisons of criteria, which were aggregated into a judgment matrix for FAHP analysis (Table 1).

Table 1 Pairwise comparison matrix in AHP form

Criteria(s)	Design Error	Wrong installation	Corrosion	Fatigue
Design Error	1	3	1/5	2
Wrong installation	1/3	1	1/3	4
Corrosion	5	3	1	7
Fatigue	1/3	1/4	1/7	1

Where:

DE = design error

WI = wrong installation

C = corrosion and

F = fatigue

4. Results and Discussion

4.1 Presentation of Results

The analysis of subsea manifold failure factors was conducted using four decision-making methods: FAHP, BN, SAW, and Entropy.

The FAHP normalized weights are presented in Table 2 and results are illustrated in Figure 1

Table 2: Di-fuzzified weight after normalizing

Criteria (s)	Di-fuzzified weight after normalizing
Design error	0.2761
Wrong installation	0.2923

Corrosion	0.2006
Fatigue	0.2310
$\sum = 1.000$	

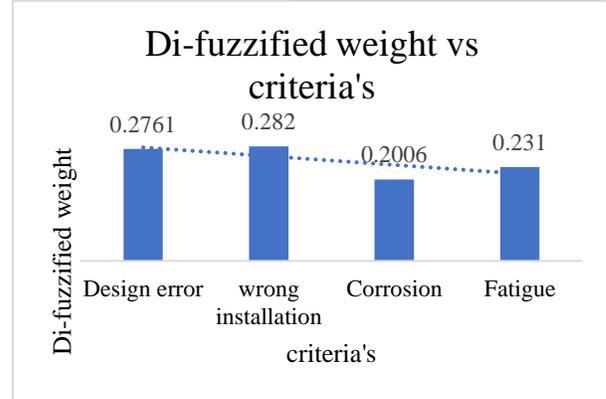


Figure 1: Di-fuzzified weight vs criteria's from FAHP analysis

Wrong installation (0.2923) emerged as the most influential factor, followed by design error (0.2761), fatigue (0.2310), and corrosion (0.2006).

Bayesian Network analysis was performed using Genie software, where influencing nodes were modelled as parent variables (wrong installation, design error, corrosion, fatigue). Posterior probabilities indicated that wrong installation (54%) and fatigue (50%) were the strongest contributors, while design error and corrosion accounted for 42% and 28%, respectively. The summarized results are shown in Table 3.

Table 3: Posterior probability results using BN Genie software

Criteria's/ (Influencing nodes)	Posterior Probability of subsea manifold failure by influencing nodes
1. Design error	42%
2. Wrong installation	54%
3. Corrosion	28%
4. Fatigue	50%

The SAW method produced normalized weights and ranking, presented in Table 4, placing wrong installation first (0.785), followed by design error (0.725), fatigue (0.710), and corrosion (0.688).

Table 4: Weight estimation and ranking order from SAW method

CRITERIA'S	A_i	RANK
WI	0.784950	1
DE	0.725050	2
C	0.687650	4
F	0.709875	3

The Entropy Method results are presented in Table 5, which assigned the highest weight to corrosion (0.4593) and

design error (0.4014), with fatigue and wrong installation ranked lower.

Table 5: Multi criteria decision methods results (Entropy weights)

Multicriteria methods	Wrong installation	Design Error	Corrosion	Fatigue
FAHP	0.2923	0.2761	0.2006	0.2310
BN	0.54	0.42	0.28	0.5
SAW	0.784950	0.725050	0.687650	0.709875
ENT	0.02991	0.40142	0.4593	0.1094

A comparative analysis across the four methods is summarized in Table 6 and illustrated in Figure 2. The integrated results indicate that wrong installation consistently ranked first in FAHP, BN, and SAW, while Entropy weighted corrosion highest. Nevertheless, considering the convergence of results across three independent methods, wrong installation and design error are established as the dominant factors driving subsea manifold failure.

Table 6: Ranking of the weighted value with respect to the multi-criteria Methods

Criteria's	FAHP	SAW	BN	EM
Wrong installation	1	1	1	4
Design Error	2	2	3	2
Corrosion	4	4	4	1
Fatigue	3	3	2	3

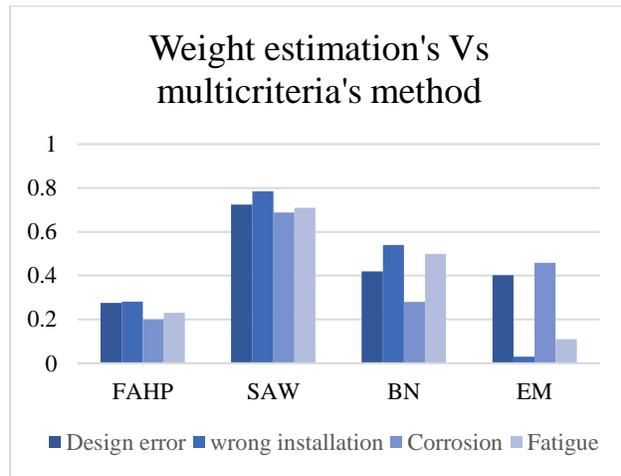


Figure 2. Weight estimation versus multi-decision models

4.2 Discussion of Results

From the FAHP analysis (Table 2; Figure 1), wrong installation was identified as the most influential factor (0.2923), followed closely by design error (0.2761). Fatigue (0.2310) and corrosion (0.2006) contributed less significantly.

BN results (Table 3) confirmed these findings, showing wrong installation (54%) and fatigue (50%) as dominant,

while design error (42%) and corrosion (28%) had lower probabilities. Simulations further revealed that combinations of high fatigue and corrosion increased failure likelihood up to 91%, while setting all factors low reduced failure to 19%.

The SAW method (Table 4) reinforced the prominence of wrong installation and design error, ranking them first and second, while Entropy (Table 5) placed corrosion as the leading factor.

When integrated (Table 6; Figure 2), three methods (FAHP, BN, SAW) consistently highlighted wrong installation and design error as the prevailing causes of subsea manifold failure. This suggests that practical interventions should prioritize strict installation protocols and rigorous design validation.

Operationally, poor installation practices, linked to operator competence and neglect of met-ocean conditions, pose the greatest threat. Design errors, particularly those affecting stress distribution, exacerbate fatigue-related failures. Although corrosion ranked lower in most models, it remains critical due to its role in accelerating fatigue and material degradation.

Integrating FAHP, BN, SAW, and Entropy provides a robust framework for reliability assessment. Wrong installation and design error emerge as the dominant contributors to subsea manifold failure, underscoring the need for better training, adherence to standards, and quality assurance in subsea projects.

5. Conclusion

The analysis of subsea manifold failure using FAHP, BN, SAW, and Entropy revealed that wrong installation and design error are the most critical factors affecting manifold reliability. Across three of the four methods applied, wrong installation consistently ranked first, highlighting its dominant influence on system performance. Design error followed closely, while fatigue and corrosion, though relevant, were secondary contributors. The Entropy method diverged slightly by emphasizing corrosion, yet the overall comparative analysis confirmed that installation quality and design specifications are the prevailing causes of subsea manifold failure.

These findings underscore the importance of strict adherence to design standards, proper alignment of manifold structures, and the deployment of competent professionals during installation. Poor installation practices, often linked to inadequate expertise or neglect of environmental conditions, present the highest risk of operational failure, while design errors amplify fatigue and reduce long-term service life. The study therefore provides a practical decision-support framework for offshore operators, offering a systematic means of ranking and prioritizing risk factors in subsea systems.

Beyond academic contributions, this work offers direct industrial implications. By integrating multi-criteria decision-making techniques, operators can enhance reliability assessment, optimize subsea manifold design, and reduce downtime and associated costs. The framework also provides a roadmap for preventive action, guiding subsea engineers toward improved training, quality assurance, and material selection in harsh marine environments. In this way, the study contributes both to

advancing subsea reliability research and to strengthening best practices in offshore oil and gas operations.

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