Development of a Novel approach for subsea pipeline failure analysis: A combined Fuzzy Analytic Hierarchy Process (FAHP) and Simple Addictive Weight (SAW) method.

ABSTRACT

This paper was undertaken to develop a decision-making model to minimize subsea pipeline failure. Furthermore, the study aimed to determine the prevailing criteria's/influencing factors contributing to the failure of subsea pipeline using a developed combined fuzzy analytic hierarchy process (FAHP), and Simple addictive weight method (SAW). From the findings of the study using FAHP and SAW, it was noticeable that the most influencing factors contributing to subsea pipeline failure was attributed to wrong installation (WI) and design error (DE) respectively. In addition, results from the SAW technique attributes subsea pipeline failure to wrong installation which may be cause by lack of competence of the operators or negligence of met-ocean conditions during installation phase. Thus, a comparative analysis from the decision tools with respect to the criterions was analysed which showed that wrong installation and design error are the prevailing factors or criteria's contributing to subsea pipeline during subsea processes. It is therefore of utmost interest that during subsea drilling process, more attention should be given to the installation phase and the process should incorporates experts to minimize failure modes and impending failures.

Keywords: Subsea pipeline, failure analysis, fuzzy analytic hierarchy process, simple addictive method, design error

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 in deep water areas. However, Gerrit et al. (2015) cited those subsea fluids (oil and gas) domain suffers from multifaceted and partly incomplete information flows. More so, Maryam and Marvin (2013) predicted that new systems and technologies in subsea industry are frequently met with uncertainty as some operators fear subsea systems failure frequencies and production losses. Technologies and equipment used for exploring and excavating the possessions of deep-sea regions which are buried under the seabed have gain positive momentum (Woo et al., 2014). The term "subsea" is particularly associated the development of resources concealed underground in coastal areas and the open sea. According to Woo et al., (2014), examples of subsea system include subsea well, subsea field, subsea project, and subsea development. Peter et al. (1994), stated that subsea production system can be improved if all designed facility needs are addressed in order to reduce capital and operating cost. Sirous (2012) argued that a subsea project can only be viable when drilling requirements, distances, location, fabrication, installation, and operational standards are met.

Subsea pipeline can be described as a prearrangement of piping and/or valves designed to combine, distribute, control, and repeatedly monitor fluid flow (Oseghale, 2019). By application, subsea systems are installed on the seabed within an array of wells to gather product or to inject water or gas into wells. According to Oseghale (2019), subsea systems have been applied in the development of oil and gas fields to ease the subsea system, minimalize the use of subsea pipelines and risers, and improve the fluid flow of production in the system (Sang et al., 2014). Paula (2001), lauds the role of subsea systems in subsea operations due to their easy maintenance and reduced impact of subsea interventions in production loss. Yingying et al., (2021) describe subsea manifold as the hub oil and gas transportation equipment which plays a vital role for the layout optimization of subsea production system. In time past, traditional manifolds used for subsea process were fixed on seabed by mean of its foundation which makes them difficult to discard and recover after use amidst its many advantage (Yinying et al., 2021).

Development of subsea cluster pipeline has been used in ultra-deepwater oil and gas fields (Yingying et al., 2016). However, piping system is responsible for satisfying the internal pressure, thermal loads, hydrostatic collapse and external operation loads in severe environmental situations. To improve the optimal performance of subsea pipeline, Sang et al., (2014) develop a numerical analysis of nonlinear finite element method and finite volume method using parametric studies. In addressing the contributing factors to subsea pipeline failure, Karan (2021), explained that material selection is one of the contributing conditions which influences reliability of subsea systems. Furthermore, karan (2021), cited that some of the environmental conditions influencing subsea systems utilization at sea are namely, corrosion risk, buckling effects, water hammer and erosion corrosion. Due to the high degree of hazards resulting in subsea system failure, risk assessment technique became necessary to examine the reliability of subsea systems (Zhaohui et al., 2021). According to Runar et al., (2001), low subsea reliability may impede production revenue loss and high cost of downtime and intervention. The authors further cited that lack of credibility to subsea conclusion will incur more risk and lack of competence. Hajar et al, (2023), investigated submarine pipeline failure accidents in deepwater using fuzzy analytic hierarchy process (FAHP). Results from the study revealed that the potential causes for submarine failure are corrosion, natural disaster, materials used and operation process. With harsh operating conditions and increasing complex system, the need for more research that is centred on improving subsea systems performance is paramount. However, the establishment of a decision tool which can help in determining the influencing nodes contributing to subsea systems failure is yet to be investigated. Adoption and development of decision tools will provide root cause detection for subsea systems, in order to reduce failure frequencies in subsea systems. Subsea production strategy has the possibility to deliver maximum production from low-energy reservoirs which may lead to significant cost saving (Mokhatab et al., 2006).

Subsea systems failure can be diagnose using different methods. Fault diagnosis based on artificial intelligence (AI) method involves incomplete data and incomplete input data set. Probability reasoning is a method to deal with uncertainty in information and Bayesian network as a tool that brings it into the real-world applications. According to Chen and Chien (2002), Bayesian network is a directed, acyclic graph (DAG), which embeds cause-effect relationship between variables (nodes). The representation framework of Bayesian network permit certain reasoning under incomplete knowledge. Component failure probability of a system is achieved by establishing evidence propagation inference among conditional probability distributions that have been specified at each variable (node).

2. MATERIALS AND METHODS

The methods applied in this paper include fuzzy analytic hierarchy process and simple addictive method. While primary and secondary data were sourced from internet sources, OREDA and questionnaire approach.

2.1 FUZZY ANALYTIC HIERARCHY PROCESS (FAHP)

Fuzzy analytic hierarchy process (FAHP) is the incorporation technique of qualitative and quantitative approaches. According to (Geng et al, 2021), the difference between FAHP and analytic hierarchy process (AHP) is the ability of FAHP to classify evaluation factors into target levels, criterion level and factor level. Hence, AHP can only classify evaluation factors into target level and factor level (Geng et al., 2021). Saaty (2003), posited that FAHP is applied to determine the eigenvectors of each judgement's matrix. Geng et al., (2021) applied FAHP in risk evaluation model. Results from the study revealed that the overall risk is at random level. However, the risk of feasibility and controllability index needs urgent attention. The paper contributed to knowledge by providing insights on the variable factors that affects work safety in land exploration. Septi et al., (2018) applied FAHP method to determine the quality of Gemstones. The findings generated from the study showed the best quality of gemstones to be Rubi with a weighed value of 0.152942. Likewise, Mahad et al., (2019) applied FAHP approach to solve multi-criteria decision-making problems. The findings deduced from the study revealed that service is the most preferable linguistic scale. Hence, FAHP was employed in this dissertation as a decision tool for determining the degree of influence of the criteria's that may contribute to subsea pipeline failure. The criteria were relatively ranked according to their order of importance. Procedure for utilizing FAHP includes:

1. Calculate the sum of elements in each row of the fuzzy judgement matrix
2. Calculate the square of M_i where "n" denotes the rank of matrix
3. Carry out normalization
4. Calculate the greatest eigenvalue of the judgement matrix

According to Sun et al. (2019), fuzzy triangular number is express as:

$$P = (l, \mu, m) \qquad (2.1)$$

Where:

L is the lowest value

m is the middle value and;

u is the upper value

The pairwise comparison matrix was transferred to FAHP using the triangular rule

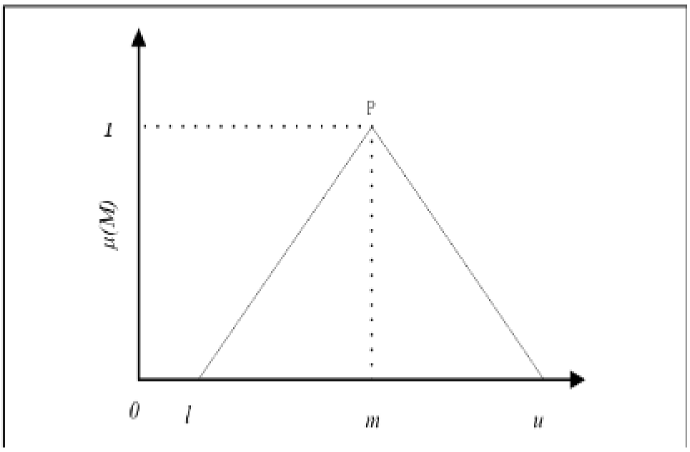

Fig. 1 Fuzzy triangular number

The simplified flowchart of the FAHP technique is shown in Fig. .2.

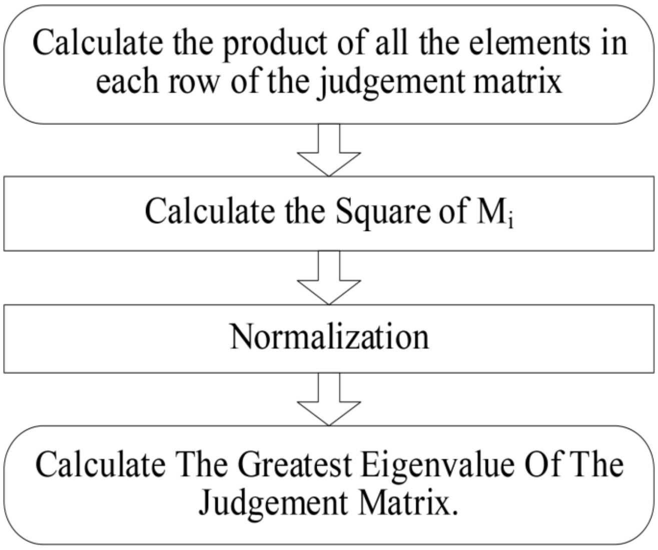

Fig. .2 Flowchart of the FAHP technique

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

$$\mu(x/M) = \begin{cases} 0\ (x < l) \\ \frac{x-l}{m-l}\ (l \leq x < m) \\ \frac{\mu - x}{\mu - m}\ (m \leq x < \mu) \\ 0(x \geq \mu \end{cases} \tag{2.2}$$

A judgment matrix F_{nxn} with the ratio of interval values is written in equation 2.3 as:

$$F_{nxn} = \begin{bmatrix} 1 & L & P1_n \\ M & O & M \\ P_{n1} & L & 1 \end{bmatrix} \tag{2.3}$$

Where the membership between triangular numbers is P1and express as:

$$P1 = (l_{1,} m_1 u_1) \tag{2.4}$$

The sum of element in each row of the fuzzy matrix judgement is express as:

$$M_i \sum_{j=1} ajj, i1 = 1,2 \ldots. \tag{2.5}$$

The square of M_i can be calculated using:

$$\overline{W_\iota} = \sqrt[n]{M_i} \tag{2.6}$$

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

$$W_i = \frac{\overline{W_\iota}}{\sum_{j=1}^{n} \overline{W_\iota}} \tag{2.7}$$

Eigenvectors in FAHP is express as:

$$W = [W_1, W_{2,} W_{3,} W_4]^T \tag{2.8}$$

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

$$\lambda_{max} = \sum_{i=1}^{n} \frac{AW_i}{nW_i} \tag{2.9}$$

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

To verify the consistency of FAHP, the ratio of consistency indicators to random consistency matrix is deduce, which is given as

Consistency ratio (CR) = $\frac{Consistency\ Indictaor\ (CI)}{Random\ consistency\ matrix\ (RI)}$ (2.10)

Where:

the consistency indicator (CI) is express as:

CI = $\frac{\lambda_{max} - n}{n-1}$ (2.11)

Where:

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

2.2 Simple addictive weighing Method

Simple addictive method is a multi-attribute decision tool that is based on the idea of weight summation where the highest weight value is considered as the “best or most influencing criteria”. This method was applied by Ibrahim and Surya (2018) to decide the best School, selection in Jambi. In addition, SAW technique has been helpful in determining the number of weighted performance ratings for each alternative on all attributes. However, it requires normalizing the decision matrix (X) to a scale that can be compared with existing alternatives. The summation of the criteria formula can be expressed as:

$r_{ijb} = \frac{r_{ij}}{Max\ (x_{ij})}$ 2.13

or

$r_{ijc} = \frac{r_{ij}}{Max\ (x_{ij})}$ 2.14

Where:

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

The weighted estimation can be deduced using:

$A_i = \sum_{j=i}^{m} W_j (x_{ij)normal}$ 2.15

Where:

A_i is the summation of each weighted attributes?

SAW involves few steps which include, performance score of an alternative using equation 2.1.5. Second steps involve normalizing of the criteria and the final step involves ranking of the weighted criteria.

3. RESULTS AND DISCUSSION

The analysis of the FAHP with respect to the criteria is shown in Table 1-.4 and Table.5 shows the results of di-fuzzified weight versus the criteria’s considered in this paper. Table .6-8 shows the analysis of the criteria using simple addictive method and Table .9-.10 shows the weighted mean with respect to the criteria's and ranking order of weighted criteria's.

Table 1: The pairwise comparison in FAHP form

Criteria(s)	DE	WI	C	F
DE	1,1,1	2,3,4	${}^{1}/_{4,5,6}$	2,3,4
WI	${}^{1}/_{2,3,4}$	1,1,1	${}^{1}/_{2,3,4}$	2,3,4
C	4,5,6	2,3,4	1,1,1	6,7,8
F	${}^{1}/_{2,3,4}$	${}^{1}/_{2,3,4}$	${}^{1}/_{6,7,8}$	1,1,1

Table .2: Fuzzy geometric mean

Criteria(s)	DE	WI	C	F	Fuzzy geometric mean value $(\tilde{r}_i)$
DE	1,1,1	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	$\frac{1}{6},\frac{1}{5},\frac{1}{4}$	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	0.3195, 0.3861, 0.595
WI	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	1,1,1	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	0.3536, 0.4387, 0.595
C	$\frac{1}{6},\frac{1}{5},\frac{1}{4}$	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	1,1,1	$\frac{1}{8},\frac{1}{7},\frac{1}{6}$	0.2761, 0.3124, 0.378
F	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	$\frac{1}{4},\frac{1}{3},\frac{1}{2}$	$\frac{1}{8},\frac{1}{7},\frac{1}{6}$	1,1,1	0.2973, 0.35495, 0.45180

With respect to the criteria', design Error (DE)

DE = $(1\ X\ \frac{1}{4}\ X\ \frac{1}{6}\ X\ \frac{1}{4})^{1/4}, (1\ x\ \frac{1}{3}\ x\ \frac{1}{5}\ x\ \frac{1}{3})^{1/4}, (1\ x\frac{1}{2}\ x\ \frac{1}{4}\ x\frac{1}{2})^{1/4},\ =\ (\frac{1}{96})^{0.25}, (\frac{1}{45})^{0.25}, (\frac{1}{8})^{0.25} = (0.3195), (0.3861), (0.595)$

For wrong installation (WI)

WI = $(\frac{1}{4}$ x 1 x $\frac{1}{4}$ x $\frac{1}{4})^{1/4}$, $(\frac{1}{3}$ x 1 x $\frac{1}{3}$ x $\frac{1}{3})^{1/4}$, $(\frac{1}{2}$ x 1 x $\frac{1}{2}$ x $\frac{1}{2})^{1/4}$, = $(\frac{1}{64})^{0.25}$, $(\frac{1}{27})^{0.25}$, $(\frac{1}{8})^{0.25}$ = (0.3536), (0.4387), (0.595)

For corrosion (C) = $(\frac{1}{6}$ x $\frac{1}{4}$ x 1 x $\frac{1}{8})^{1/4}$, $(\frac{1}{5}$ x $\frac{1}{3}$ x 1 x $\frac{1}{7})^{1/4}$, $(\frac{1}{4}$ x $\frac{1}{2}$ x 1 x $\frac{1}{6})^{1/4}$ = $(\frac{1}{172})^{0.25}$, $(\frac{1}{105})^{0.25}$, $(\frac{1}{48})^{0.25}$ = (0.2761), (0.3124), (0.37992)

Calculating for Fatigue (F) = $(\frac{1}{4}$ x $\frac{1}{4}$ x $\frac{1}{8}$ x $1)^{1/4}$, $(\frac{1}{3}$ x x $\frac{1}{3}$ x $\frac{1}{7}$ x $1)^{1/4}$, $(\frac{1}{2}$ x $\frac{1}{2}$ x $\frac{1}{6}$ x $1)^{1/4}$, = $(\frac{1}{128})^{0.25}$, $(\frac{1}{63})^{0.25}$, $\frac{1}{24})^{0.25}$ = (0.2973), (0.35495), (0.45180)

Hence, we determine according to the FAHP triangular rule, the lower value, middle value and upper value

Lower value (L) = 0.3195 + 0.3536 + 0.2761 + 0.2973 = 1.2465

Middle value (M) = 0.3861 + 0.4387 + 0.3124 + 0.35495 = 1.4967

Upper value (U) = 0.595 + 0.595 +0.37992 + 0.45180 = 2.02172

Table .3: Fuzzy weight deduction

				FUZZY weight ($\widetilde{w_i}$)		
DE	0.3195	0.3861	0.595	0.158000	0.2579	0.4770
WI	0.3536	0.4387	0.595	0.174900	0.29311	0.4770
C	0.2761	0.3124	0.378	0.136570	0.20873	0.3032
F	0.2973	0.35495	0.4518	0.147053	0.23716	0.3625

Geometrical mean (R.G.M) = $\frac{1}{2.02172}, \frac{1}{1.4967}, \frac{1}{1.2465}$

$\widetilde{A_1}$X $\widetilde{A_2}$ = $((l_1 m_1 u_1)$ x $(l_2 m_2 u_2)$

Where:

L is the lower value

M is the middle value

U is the upper value

By Di-fuzzified method,

centre of Area = $\widetilde{w_i} = \frac{l+m+u}{3}$

Applying fuzzy weight to determine the Di-fuzzified numerical weight

Table 4: Di-fuzzified weight before normalizing

Criteria (s)	Fuzzy weight ($\boldsymbol{w_i}$)	Weight (di-fuzzified numerical weight)
Design error	0.158, 0.2579, 0.4791	0.2976
Wrong installation	0.17490, 0.29311, 0.4789	0.315
Corrosion	0.13657, 0.20873, 0.3043	0.2162
Fatigue	0.147053, 0.23716, 0.3637	0.2489
		$\sum_{W} = \mathbf{1.0777}$

The numerical Di-fuzzified weight is not acceptable as the weight value is above 1,000. Hence, we normalize the weight by dividing each weight by the total Di-fuzzified weight

For DE

$\frac{0.2976}{1.0777}$ = 0.2761

For WI

$\frac{0.315}{1.0777}$ = 0.2923

For C

$\frac{0.2162}{1.0777} = 0.2006$

For F

$\frac{0.2489}{1.0777}$ = 0.231

Table .5: 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
	$\sum = \mathbf{1.000}$

Hence, the Di-fuzzified weight is acceptable. We therefore proceed to interpret the results for decision making process using weighted rank results.

Table .6: Normalize matrix of SAW method

WI	DE	C	F
0.88	0.3205	1	0.9393
0.84	1	0.333	0.7272
1	0.8589	0.2857	0.6060
0.76	0.6795	0.4	1

Table .7: Weight Estimation of the criteria from SAW method

WI	0.220000	0.080125	0.250000	0.234825	0.784950
DE	0.210000	0.250000	0.08325	0.181800	0.725050
C	0.250000	0.214725	0.0714250	0.151500	0.687650
F	0.190000	0.169875	0.100000	0.250000	0.709875

Table .8: 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

Table 9: Multi criteria decision methods results

Multicriteria methods	Wrong installation	Design Error	Corrosion	Fatigue
FAHP	0.2923	0.2761	0.2006	0.2310
SAW	0.784950	0.725050	0.687650	0.709875

Table .10: Ranking of the weighted value with respect to the multi-criteria Methods

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

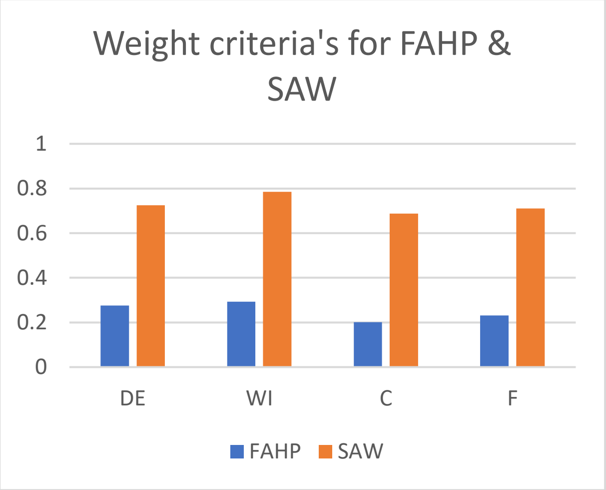

Fig. 3. comparative analysis of the combined weighted technique criteria's

3.2 Discussion of Results

From the FAHP analysis, it is noticeable that the most influencing factor contributing to subsea pipeline failure was attributed to wrong installation (WI) with weighted value 0.2923, followed by design error (DE) and fatigue (F) (see Figure 3.). From the analysis, Corrosion was observed to be the least contributing criteria as most challenges faced by subsea pipeline at the seabed are erosion related corrosion which subsea and material experts/ engineers have improved on by ensuring proper material selection are enforced by alloying with other metals. Hence, when considering the use of subsea pipeline at sea during subsea exploration process, it is necessary for the technical and administrative team to give special attention to the ways and manner subsea pipeline are installed and careful consideration should be given to the design specification and its safety factor to ensure it conform to standards without posing threat or challenges during use. Sufficient piping systems and valves of high capacity should be used during oil exploration to reduce the impact of fatigue. Also, overdue (pipeline aging) or longer period of subsea pipeline utilization during drilling at the sea should be reduced or incorporation of multi-stage pipeline or reinforced subsea pipeline should be encouraged to deplete the challenges of fatigue as it may results to fracture of the pipeline system, thereby affecting downstream and upstream production.

From Table .6-.8 using simple addictive method, wrong installation is observed to be have the highest weight value of 0.78495, followed by design error and fatigue with a value of 0.72505 and 0.70987 respectively. However, corrosion has the least weighted value of 0.68765. Thus, wrong installation is ranked as number one (1) followed by design error ranked as number two (2) respectively as the two most influencing criteria contributing to subsea pipeline failure.

A comparative analysis of the findings from the two methods applied in this paper with respect to the selected criteria's is shown in Fig 3.. Judging from Fig. 3. wrong installation was found to be the most influencing factor contributing to the failure of subsea pipeline from three methods namely, FAHP & SAW methods. Furthermore, design error was also considered as the second influencing factor contributing to subsea pipeline failure from FAHP and SAW analysis.

In conclusion from the analysis executed using FAHP, & SAW with the respects to the selected criteria's, wrong installation is revealed to be the most influencing criteria or factor contributing to subsea pipeline failure (see Table 4.). Likewise, design error (DE) was also another factor contributing to the failure of subsea pipeline

4. CONCLUSION

Subsea systems and their application have gain rapid momentum due to their vast utilization for various subsea processes. However, the challenges faced by these systems are manifested in different ways and manners. Hence, it becomes necessary to investigate or examine the underlying factors or conditions influencing failure in subsea pipeline.

Evidences from this dissertation in application of multi-attribute techniques, namely, FAHP and SAW method revealed that wrong installation, design error, fatigue and corrosion contribute to subsea pipeline failure. In terms of ranking of the criteria's applied in this study, using FAHP and SAW technique revealed that installation was observed to be the highest weighted value that should be given utmost priority. In addition, design was ranked to be the second weighted criteria from FAHP and SAW analysis. This implies that wrong installation and design error are the major criteria's or influencing factors contributing to the failure of subsea pipeline.

Findings from the study can be implemented in offshore and subsea systems to aid optimal performance and service long. It is of utmost significance that subsea systems should be properly aligned, positioned and incorporated at sea to minimize hazards, risk or production losses during subsea drilling processes.

5. RECOMMENDATIONS

In view of the findings from the study, the following recommendations were suggested:

1. Implementation of a maintenance approach should be considered in the early design of a subsea pipeline system
2. Installation of subsea pipeline should be executed by experts and environmental conditions should be properly observed.

Subsea pipeline structural design for steel pipeline system should be determined according to the ASME standards.

REFERENCES

Sang, E. L., Jeom, K. P., Yeon, C. H., Bong, J.K & Jung, K. S (2014). An efficient design methodology for subsea manifold piping systems based on parametric studies, *Ocean Engineering*, Volume, 84, pp: 273-282

Kaushik, R., Harish, S., Krishnamoorthy, B., & Satish N. (2017). Electrification of Subsea systems: requirements and challenges in power distribution and conversion, *CPSS Transactions on Power Electronic and Applications*, pp:259-266.

Gerrit, M., Damien, W., & Martin, M. (2015). Creating an A3 Architecture Overview; a case study in subsea Systems, INCOSE international symposium, vol. 25, pp:448-462

Maryam, R & Marvin, R. (2013). Prediction of failures rates for new Subsea systems: A practical approach and an illustrative example, Vol., 227, Iss: 06, *journal of risk and reliability*, pp:208-234

Peter, K., Brown, P. G., & Bloomer, R. A (1994). Lightweight Subsea Manifold Design, *Offshore Technology Conference,* Houston, Texas.

Karan, S. (2021). Optimized material selection for subsea valves to prevent failure and improve reliability, *Life cycle reliability and safety engineering,* Vol: 10, pp:173-182.

Zhaohui, S., Weidong, R., Hongdong, Q., & Yong, B. (2021). Study on risk assessment and numerical simulation method of subsea manifold system, *international conference on ships and offshore structures,* pp:245-255.

Paula, M.T.R., Labanca, E. L. L., & Paulo, C. (2001). Subsea Manifold Design Based on Life Cycle Cost, *Offshore Technology Conference,* Houston, Texas. https://doi.org/10.4043/12942-MS.

Karan, S. (2020). All electric subsea control systems and the effects on subsea manifold valves, *Journal of Marine science and Application,* Vol: 03, pp:465-472.

Yingying, W., Fangqiu, L.I, Menglan, D., Houfa, L., & Jiandong, G. (2016). Reliability Modelling of subsea cluster Manifolds based on the fault tree analysis, *international conference on offshore mechanics and Arctics Engineering, pp:234-256*

Yingying, Q., Hoaran, C., Nan, L., Weizheng, A., Frank L., Cong, W., & Segen F. (2021). The motion response and hydrodynamic performance comparisons of the new subsea suspended manifold with two mooring scenarios, *Journal of the Brazilian Society of Mechanical Sciences and Engineering, pp:1-16.*

Guan, F., Zhang, N., & Yuefeng, H. E (2021). Fuzzy reliability analysis of subsea manifold structure, *Advanced information Technology, Electronic and Automation Control Conference, pp:1566-1573*.

Runar, O., Ove, K & Idar, G. (2001). Subsea reliability- success factors for sustainable deepwater concept development, Offshore Technology Conference, April 2001. Doi: https://doi.org,/10.4043/13290-MS

Yongsheng, Y., Faisal K., Premkumar, T., & Rouzbeh, A. (2017). Corrosion induced failure analysis of subsea pipelines, *Reliability Engineering & system safety,* Vol. 159, pp:214-222.

Jong, H. W., Jong, H. N & Kwang, H. K. (2014). Development of a simulation methods for the subsea production system, Journal of computational design and engineering, Vol. 3, pp: 173-186.

Hajar, I., Mnasur, S.& Fidan, I (2023). Investigation of submarine pipeline failure accidents in deepwater based on the fuzzy analytical hierarchy process, *international conference on application of fuzzy systems, soft computing and artificial intelligence tools,* pp:391-398.

Sirous, Y. (2012). Subsea technologies selection using analytic hierarchy process, *international journal of the society for underwater technology*, Vol. 30, pp:151-164.

Guozheng, S., Pierluigi, S. R., Faisal, K., Nicola, P. & Ahmad, B. (2020). Model-based information fusion investigation on fault isolation of subsea systems considering the interaction among subsystems and sensors, Journal of loss prevention in the process industries, Vol. 67, pp: 104-267.

Cai, B., Hanlin, L., & Min, X (2016). A real-time fault diagnosis methodology of complex systems using object-oriented Bayesian networks, *Mechanical systems and signal processing*, Vol. 80, pp:31-44

Liu, Z., Yonghong, L., Boaping, C & Chao, Z (2015). An approach for developing diagnostic Bayesian network based on operation procedures, Expert systems with Applications, Vol. 42, pp:1917-1926.

Paul, A. B. (2010). Control's reliability and early life of field failure of subsea control modules, Subsea control and data acquisition conference, SUT-SCADA, UK.

Liangliang D& Miao Xian (2022). Analysis of Factors Affecting Sealing Performance of Subsea Wellhead Connector, World Journal of Engineering and Technology, pp:230-240

Mokhatab, S., Poe, W and Speight, J. (2006). Handbook of Natural Gas Transmission and Processing, pp.365–400. ISBN 0750677767; ISBN 9780750677769.

Geovana P. D., Ilson P.P., Bianca C. P., & Segen F.E (2018). Pipelines, risers and umbilical's failures: A literature review, Ocean engineering, Subsea Technology Laboratory, COPPE, Federal University of Rio de Janeiro, Brazil, pp:412-425.