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Research Article

A Three-Stage Hybrid Multi-Criteria Model for Material Selection in Subsea Pipeline Design

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Abstract

Subsea pipelines are such a crucial part of offshore oil and gas production, therefore their design and construction should be as efficient and cost-effective as possible. Proper material selection is critical for a successful operation and a longer pipeline lifespan. For the selection of a design material with the highest reliability under a dynamic environment as the one obtained in the oil and gas industry, a three-stage hybrid multi-criteria model has been proposed. The hybrid multi-criteria model, which is based on an integrated Analytical Hierarchy Process (AHP) model and the VlseKriterijumskaOptimizacija I KompromisnoResenje (VIKOR) model, is used for the evaluation and selection of a suitable and high reliability-based design material for the subsea pipeline design by considering several operational and environmental scenario the pipes might encounter in the field. With the vast amount of engineering materials available to the design engineer, selecting a suitable and high reliability-based material for the subsea pipeline design is a tedious and demanding task, especially in a dynamic environment and scenario. In this paper, ten subsea pipeline material alternatives of different types, with seven criteria, have been critically examined under a three-case scenario. Results from the evaluation show that for the first case study scenario -sour service hydrocarbon transport in deep waters-, 22% Cr stainless steel is found to be the best choice material, for the second case study scenario, Carbon Fiber Reinforced Polymer is selected as the best. While for the third case study scenario, carbons steel and polymers material is found to be the most reliable material choice.

Keywords: Three-stage hybrid multi-criteria model, AHP model, VIKOR model, subsea pipelines

Denizaltı Boru Hattı Tasarımında Malzeme Seçimi İçin Üç Aşamalı Hibrit Çok Kriterli Bir Model

Öz

Denizaltı boru hatları, açık deniz petrol ve gaz üretiminin çok önemli bir parçasıdır, bu nedenle tasarımları ve inşaatları mümkün olduğunca verimli ve uygun maliyetli olmalıdır. Doğru malzeme seçimi, başarılı bir operasyon ve daha uzun boru hattı ömrü için kritik öneme sahiptir. Petrol ve gaz endüstrisinde elde edilenden daha dinamik bir ortamda en yüksek güvenilirliğe sahip bir tasarım malzemesinin seçilmesi için, üç aşamalı hibrit çok kriterli bir model önerilmiştir. Entegre bir Analitik Hiyerarşi Süreci (AHP) modeline ve VlseKriterijumskaOptimizacija I KompromisnoResenje (VIKOR) modeline dayanan hibrit çok kriterli model, boruların sahada karşılaşabileceği çeşitli operasyonel ve çevresel senaryolar göz önünde bulundurularak denizaltı boru hattı tasarımı için uygun ve yüksek güvenilirliğe dayalı bir tasarım malzemesinin değerlendirilmesi ve seçilmesi için kullanılmaktadır. Tasarım mühendisi için mevcut olan çok miktarda mühendislik malzemesi ile, denizaltı boru hattı tasarımı için uygun ve yüksek güvenilirliğe dayalı bir malzeme seçmek, özellikle dinamik bir ortamda ve senaryoda sıkıcı ve zorlu bir iştir. Bu yazıda, yedi kritere sahip farklı tipte on denizaltı boru hattı malzemesi alternatifi, üç vakalı bir senaryo altında eleştirel olarak incelenmiştir. Değerlendirmeden elde edilen sonuçlar, ilk vaka çalışması senaryosu için - derin sularda ekşi hizmet hidrokarbon taşımacılığı - için% 22 Cr paslanmaz çeliğin en iyi seçim malzemesi olarak bulunduğunu, ikinci vaka çalışması senaryosu için Karbon Fiber Takviyeli Polimerin en iyisi olarak seçildiğini göstermektedir.

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Üçüncü vaka çalışması senaryosu için, karbonlar çelik ve polimer malzemesinin en güvenilir malzeme seçimi olduğu bulunmuştur.

Anahtar Kelimeler: Üç aşamalı hibrit çok kriterli model; AHP modeli; VIKOR modeli; denizaltı boru hatları.

1. Introduction

Subsea pipelines are one of the most important aspects of the offshore industry. Due to the rapid growth of the oil and gas industry, exploration and production are tending into deeper waters with harsher conditions. It is a well-known fact that corrosion is a common and costly issue in the oil and gas industry and even more costly in the offshore sector. The use of metals such as carbon steel has been the norm and the go-to for most offshore pipeline projects over the better part of the century, this is mainly because of its excellent mechanical properties and high pressure and thermal resistance. However, in harsher corrosion environments, carbon steel has proven to be inadequate and resulted in billions of dollars in repair costs. According to a study done by the National Association of Corrosion Engineers (NACE), the cost of corrosion had reached more than US$ 600 billion in 2001, accounting for roughly 4%–6% of the country's gross national product [20].

In corrosive environments, intensive corrosion control methods, such as inhibitors, cathodic protection, and coating, are required to maintain the integrity of the pipes, insufficiency or inadequate measures can even result in the need for early replacement [18]. A more corrosion-resistant pipe technology, such as Corrosion-resistant alloys (CRA) and polymer composites, should be chosen to reduce pipeline corrosion. CRA such as duplex stainless steel, and nickel-based alloy have proven to be effective in harsher corrosion environments, however, they are significantly more costly than carbon steel and are mostly used to clad or line carbon steel pipes [9]. In the petroleum industry, the financial benefits from employing materials that are lighter, stiffer, stronger, and more corrosion resistant than carbon steel are significant. In this category, composite materials are a major contender. As exploration and production continue to extend globally into deeper waters and harsher environments, the spotlight is shifting to lightweight fiber-reinforced plastic (FRP) solutions as replacements for steel [10]. This is made possible with the approval of new industry standards DNV OS C501. Fiber-reinforced thermoplastics are ideal candidates for subsea applications across multiple sectors, including underwater vehicles, marine construction, and offshore oil and gas, due to several desirable characteristics including high specific strengths and moduli and excellent corrosion resistance [10].

Considering all these different materials, material selection is crucial to any engineering design. In the area of material selection where there are numerous choices and various influencing criteria, a more precise mathematical approach is required. It is observed that choosing the most appropriate material for a specific product from a finite set of alternatives is an example of multi-criteria decision-making (MCDM) problem [2, 14, 22]. To make the best decision on MCDM problems, the analytical hierarchy process (AHP) model, which has widely been used in literature is applied [1, 3, 8, 22]. This research addresses the problem of material selection of subsea pipelines. Material failure is the leading issue in offshore pipelines leading to billions of dollars in loss. In the design and development of any structural elements, material selection is one of the most challenging issues and it is also critical for success and to meet the demands of cost reduction and better performance [5].

Designers should have a clear understanding of the functional requirements for each component and detailed knowledge of the considered criteria for a specific engineering design when choosing the most appropriate material from an ever-increasing array of viable alternatives, each with its characteristics, applications, advantages, and limitations. Improper selection of material may often lead to huge cost involvement and ultimately drive towards premature component failure [12]. Variations in national standards, legislative requirements, operator procedures, and risk tolerance also play a substantial role in the materials selection process. These challenges require different approaches to pipeline materials selection, which may vary strongly between different nations and operators. The most important factor to ensure the integrity of subsea pipelines is an excellent material selection process. Corrosion-resistant alloys, although known to be an excellent alternative to conventional carbon steel materials, carry a limitation when the factor of the cost is put into play. In this sense, non-metallics are gaining more and more appeal and attention, given their potential to minimize the cost of both corrosion management and material [16].

With the innovation of new non-metal materials that are well suited for subsea pipelines and the expensive limitations of current metal materials, the growing need for companies to re-evaluate their material choices is inherent. Although metals can undergo processes to combat the high requirements of corrosion environments, it is a costly and difficult process. Therefore, a more cost-effective solution is required which lies with materials with inherent corrosion resistance such as composite or polymers. Composite pipes are strong, durable, flexible, lightweight, and have low installation and maintenance costs but they have a higher material unit cost than carbon steel [17]. This is one of the reasons why it is attractive to use carbon steel, because of the high cost of operating the lay barge, the installation of a submarine pipeline accounts for the majority of the total cost. The faster the pipe can be welded, the faster it can be installed, and the lay barge may be used for a shorter period. This cost can be reduced in the case of Thermoplastic composite pipes (TCP), which are spool-able and are produced to be several kilometers in length.

As earlier stated, the problem of material selection arises in subsea pipelines due to the vast array of materials that can be used and the standards governing these materials. This research is aimed to develop a novel approach using numerical methods to guide the selection process based on the following criteria; corrosion resistance, thermal resistance, fatigue resistance, cost, ease of installation and manufacture, density, and hardness under a three case scenario that has been carefully examined for the material selection and evaluation [15, 23, 24]. These scenarios, which are related to the fluid passing through the pipe and the environmental conditions of the pipes, affect the weighting of the criteria used. The case study scenario includes sour service hydrocarbons transport in CO_2 environments, aggressive chemicals in deep waters, and non-corrosive fluids -industrial water lines- [7].

To address the aim of the study, a three-stage hybrid fuzzy multi-criteria decision model has been proposed for selecting suitable and reliable materials for the design of the subsea pipeline by considering cost, efficiency, and reliability with the view to meet the full requirements of the various international standards such as DNV-OS-F10, NORSOK M-001, ASME B36, and API codes.

The hybrid multi-criteria model is based on an integrated Analytical Hierarchy Process (AHP) model and the VlseKriterijumskaOptimizacija I KompromisnoResenje (VIKOR) model. The study contributes to material selection literature, by providing a new model that allows various material types such as metals, polymers, alloys, and composites to be selected depending on the operational and environmental scenario considered. This is completely novel, as previous researches and evaluation approaches presented in the literature are limited to the selection of a single type of material. The combination of the two models is based on the following advantages of the models. The AHP approach provides the weighting step of the criterion, as well as the consistency test to determine if the weight gained is consistent. The weighting process is only handed away by the experts without confirming the weighting consistency, which is a flaw in the VIKOR approach. The AHP approach, on the other hand, suffers from a flaw in the cracking process. If more and more options are added to the AHP cracking process, it becomes more difficult. The VIKOR approach, on the other hand, offers advantages in the cracking process due to its preference values for cracking and its ability to readily overcome many alternatives.

The remaining section is organized as follows, in Section 2, the methodology that comprises the three-stage hybrid multi-criteria model is introduced. This is followed by the application of the model for a real-life case study in Section 3. Finally, in Section 4, some concluding remarks are presented, as well as the limitations of the study.

2. Methodology

The proposed methodology consists of three basic stages; identification of criteria, AHP computations, and ranking of the alternative materials using the VIKOR model. Figure 1 shows the flow diagram of the proposed methodology. The proper criteria and materials are selected and analyzed in the first stage, and the decision hierarchy is framed, this hierarchy is then approved. After the approval, the criteria are assigned weight using the analytical hierarchy process (AHP) in the second stage. The third stage will consist of using the VIKOR method to rank the alternative materials. The result gives the best candidate material.

2.1. Criteria Definition

The following criteria are created to meet the objective for the material selection of subsea pipelines;

I. Corrosion resistance (CR): the ability to withstand the destructive action of corrosive mediums.
II. Thermal resistance (TR): the heat property and a measurement of a temperature difference by which an object or material resists heat flow.

III. Fatigue resistance (FR): the highest stress that a material can withstand for a given number of cycles without breaking.
IV. Cost (C): The value of money that has been used to purchase the material.
V. Manufacture and installation (MI): The ease at which the material is manufactured and installed, including time, and cost.
VI. Density (D): a measurement of how much mass is in a given volume.
VII. Hardness (H): resistance to plastic deformation, penetration, indentation, and scratching.

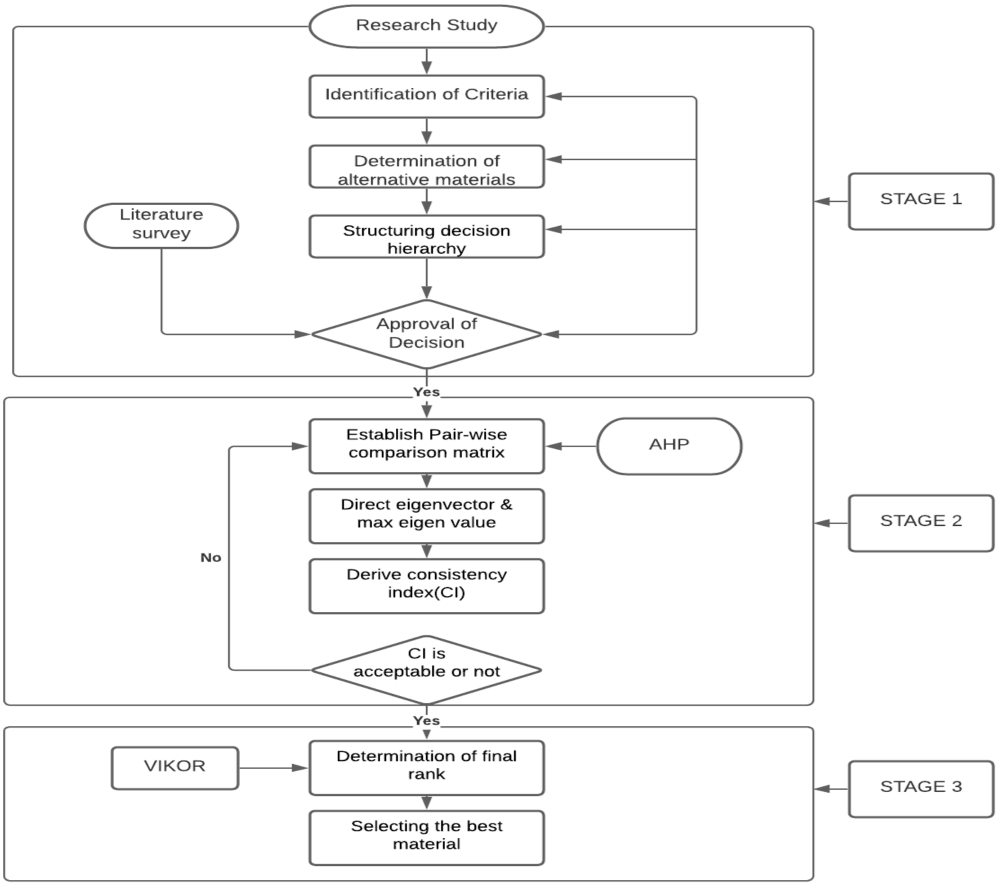

Figure 1. Schematic Diagram for Proposed Model for Material Selection

2.2. Alternative Materials

There is a wide range of engineering materials to choose from according to the certified codes and standards. Among these materials, the primary materials used for pipelines include metallic materials and non-metallic materials.

2.2.1. Metallic Materials

Traditionally, metals are the materials of choice in the offshore oil and gas sector because of the following advantages;

I. Their performances have been well documented over the years in various design conditions.
II. Can be used over a wide range of temperatures and pressures to meet a variety of design requirements.

III. Adequate standards governing the use of the materials.

The most common metallic materials used in subsea pipeline applications are steels and corrosion-resistant alloys (CRA). Amongst the steels, carbon steel has been used as the go-to material for pipelines, but one of the limitations of carbon steel is the lack of inherent corrosion resistance, which is vital in subsea pipelines. To combat the problem of corrosion, corrosion-resistant alloys have been found adequate, although not without their limitations. Examples of CRAs include stainless steels (e.g., austenitic, ferritic, martensitic, and duplex) and nickel-based alloys.

2.2.2. Non-Metallic Materials

Non-metallic materials offer the most appropriate choice for fluid services and process conditions that are very aggressive to commonly used metallic materials (such as steel), or as an economically attractive option between the use of steel and the relatively more expensive materials such as CRAs. Non-metallic materials used in offshore oil and gas applications are of two types, Polymers, and composites.

The use of polymers and composites in subsea pipelines is due to their high resistance to corrosion and also the economic advantages over CRAs. Polymers used in pipelines are of three types; Thermoplastic, thermosets, and Elastomers. The two common types of composites used in pipelines are Carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP).

2.2.3. Materials Selected

In this study, ten alternative materials will be evaluated and selected for the three different case study scenarios, the materials are as follows; Carbon steel (CS), 13% Cr martensitic stainless steel, 22% Cr Duplex stainless steel, 25% Cr Super Duplex stainless steel, 316L austenitic stainless steel, High-density Polyethylene (HDPE), ACETAL (Polyoxymethylene POM-C), Polyamide 12 (PA12), Glass fiber reinforced epoxy (GRE), and Carbon Fiber-reinforced polymer (CFRP). Table 1, highlights the materials, their type, capabilities, and limitations. From research and analysis, the material properties used for the different case scenarios were rated by a group of five (5) material engineering experts specially selected from the academia to evaluate and give their opinion on the materials considered by using the criteria rating (Likert) scale as presented in the Table. Finally, their evaluated results and opinions are then aggregated based on the scale, and the results are shown in Table 2.

Table 1. Material Capability

Material	Type	Capability	Limitations
Carbon Steel	Steel	High ductility, toughness, machinability and weldability, low cost	Low corrosion resistance
13% Cr Martensitic SS	CRA	good ductility and corrosion resistance, easily forged and machined	Costly, Requires PWHT
22 % Cr Duplex SS	CRA	High corrosion resistance, temperature ranges from -50^{o}C to 300^{o}C	Expensive
25%Cr Super Duplex	CRA	Higher Mechanical strength, corrosion resistance, good temperature range	Expensive
316L	CRA	Good corrosion resistance is easily machined and welded.	Moderate cost to high cost
HDPE	Thermoplastic	High impact resistance, resistance to C0$_2$ and H$_2$S, low cost	Low strength, max temp of 90^{o}C.
Acetal	Thermoplastic	Good mechanical properties, good fatigue strength	Not resistant to Hydrocarbons over 80^{o}C.
PA12	Thermoplastic	Good chemical and corrosion resistance, flexibility, and durability.	Maximum temp of 80^{o}C.
GRE	Composite	Excellent corrosion resistance, good thermal resistance	High initial cost
CFRP	Composite	Excellent chemical and corrosion resistance, low maintenance.	High initial cost

<table>
<tr><th colspan="5">Criteria rating (Likert) scale</th></tr>
<tr><th>Very Good</th><th>Good</th><th>Moderate</th><th>Poor</th><th>Very Poor</th></tr>
<tr><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td></tr>
</table>

Table 2. Material Properties with Respect to the Criteria

Materials	Criteria						
	CR	TR	FR	C	MI	D	H
Carbon Steel (CS)	1	5	4	5	3	3	4
13% Cr Martensitic SS	4	4	4	3	2	3	5
22 % Cr Duplex SS	5	5	5	2	3	3	5
25% Cr Super Duplex SS	5	5	4	1	3	3	5
316L	4	4	5	3	3	3	5
HDPE	4	3	3	5	5	5	2
Acetal	4	3	3	4	5	5	2
PA12	4	3	4	4	5	5	3
GRE	5	4	4	3	4	5	3
CFRP	5	3	4	3	5	5	3

2.3. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is an MCDM method introduced by Thomas Saaty in 1980 [6]. This method is an Eigenvalue approach to pair-wise comparisons. The AHP method can be applied to analyze qualitative data quantitatively. It is used to transform complex and multi-criteria problems into a structural hierarchy [4].

Steps for implementing the AHP model

Step 1: Define the goal of the problem.

Step 2: Structure the problem in a hierarchy of different levels constituting goal, criteria, and alternative as shown in Figure 2.

Step 3: Perform a pair-wise comparison using the predefined Saaty's nine-point scale listed in Table 3. The pair-wise comparison generated say Matrix A

Step 4: Normalize matrix A and transform it into matrix B. Each element of matrix B is computed as,

$$b_{ik} = \frac{a_{ik}}{\sum_{i=1}^{n} a_{ik}} \tag{1}$$

Then calculate eigenvector $= w_i$, which is known as the criteria weight vector w, is built by averaging the entries on each row of matrix B, i.e.

$$w_i = \frac{\sum_{i=1}^{n} b_{ij}}{n} \tag{2}$$

Calculate the maximum eigenvalue according to the following equation on each row of matrix B, i.e.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(Aw)_i}{w_i} \tag{3}$$

Where λ_{max}= maximum eigenvalue of the comparison matrix.

Step 5: Calculate consistency matrix CI

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

Step 6: Find the Consistency ratio CR, which can be calculated as the ratio of the consistency index (CI) of the matrix to the consistency index of a random-like matrix (RI). The value of RI is taken from the Consistency indices for the randomly generated matrix in Table 4.

$$CR = \frac{CI}{RI} \tag{5}$$

Usually, a CR of 0.1 (10%) or less is considered acceptable.

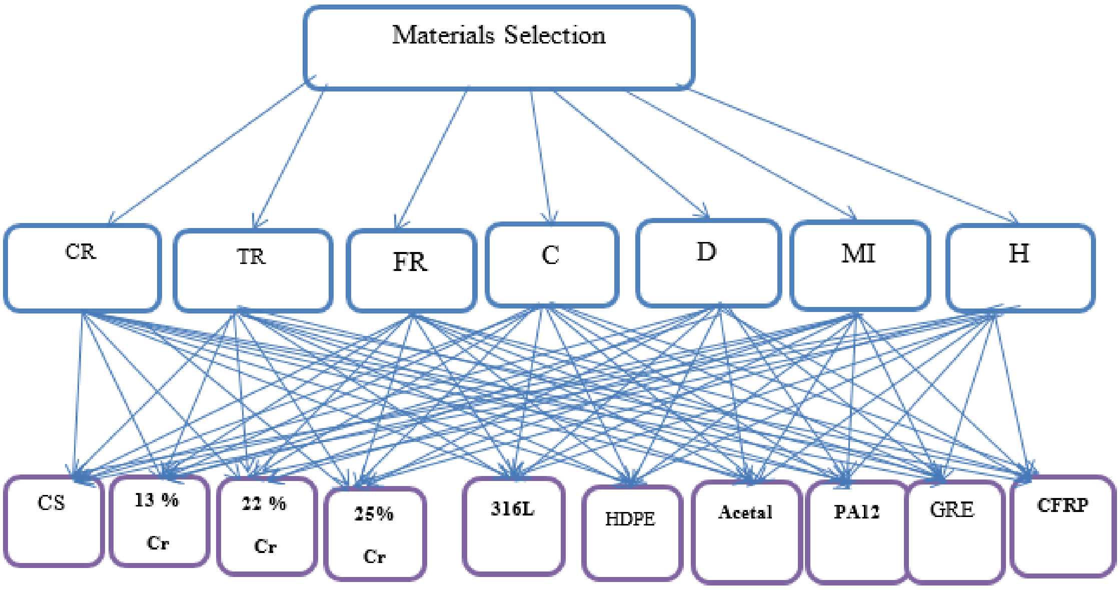

Figure 2. Decision Hierarchy for Material Selection for Subsea Pipelines.

Table 3. Saaty's Nine-point Scale

Importance scale	Definition
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely important
2,4,6,8	Intermediate values

Table 4. Consistency Indices for the Randomly Generated Matrix of the seven criteria N=7

Random Index RI							
Criteria Number (N)	1	2	3	4	5	6	7
RI	0	0	0.58	0.9	1.12	1.24	1.32

2.4. VIse Kriterijumska Optimizacija kompromisno Resenje (VIKOR)

VIse Kriterijumska Optimizacija kompromisno Resenje method was developed by Opricovic in 1998 to solve complex multi-criteria decision-making problems [13]. It assumes that compromise can be accepted for resolving the conflict and the feasible solution would be closest to the ideal solution and the alternatives are evaluated based on all the considered criteria [11].

Steps for implementing the VIKOR model are as follows:

Step 1: Identify the pivotal selection criteria and shortlist the alternatives depending on those criteria.

Step 2: In the decision matrix, determine the best, $\left(x_{ij}\right)_{max}$ and the worst, $\left(x_{ij}\right)_{min}$ values of all the criteria.
Step 3: Determine utility values (S_i) and regret values (R_i).

$$S_i = L_{1,i} = \sum_{j=1}^{m} \frac{w_i[\left(x_{ij}\right)_{max} - x_{ij}]}{[\left(x_{ij}\right)_{max} - \left(x_{ij}\right)_{min}]} \tag{6}$$

$$R_i = L_{\infty,i} = max^m\ of \left\{ \frac{w_j\left[\left(x_{ij}\right)_{max} - x_{ij}\right]}{\left[\left(x_{ij}\right)_{max} - \left(x_{ij}\right)_{min}\right]} \right\}, j = 1,2, \dots\dots\dots, n \tag{7}$$

Step 4: Introduce v as the weight of the strategy for 'the maximum group utility'. The value of v ranges between 0 and 1, and usually, its value is taken as 0.5
Step 5: Calculate VIKOR index (Q_i)

$$Q_i = \frac{v(S_i - S_{i\,min})}{(S_{i\,max} - S_{i\,min})} + \frac{(1-v)(R_i - R_{i\,min})}{(R_{i\,max} - R_{i\,min})} \tag{8}$$

Step 6**:** Arrange the alternatives in ascending order, according to Q_i values. The best alternative is the one having the minimum Q_i value.

3. Results and Disscussion

In this paper, as previously stated, three different dynamic operating and environmental conditions in which the subsea pipeline designs are expected to operate in are examined and included in the evaluation model. The case study scenarios which include, sour service hydrocarbons transport in CO_2 environments, aggressive chemicals in deep waters, and non-corrosive fluids (industrial water lines) are studied in detail in the proceeding sub-sections.

3.1. Case Study Scenario 1

This case study describes the subsea pipeline material selection for sour service hydrocarbon transport in CO_2 environments. As stated earlier, the following criteria will be used for this study that is the corrosion resistance (CR), thermal resistance (TR), fatigue resistance (FR), cost (C), manufacture and installation (MI), density (D), and hardness (H). In applying the AHP model, a questionnaire was designed for collecting data of pairwise comparisons, which is used to determine the priority weight of each criterion. For each pair of criteria, the decision-maker (Expert) is asked to respond to a question like 'How important is criterion A in relation to criterion B?, and so on, then they rated using the Saaty's nine-point scale in Table 3. A pairwise comparison matrix for the seven criteria was formed according to step 3 of AHP as shown in Table 5.

Table 5. Pairwise Comparison Matrix for Criteria in Case Study Scenario 1

Criteria	CR	TR	FR	C	MI	D	H
CR	1.000	4.000	6.000	5.000	7.000	7.000	3.000
TR	0.250	1.000	3.000	2.000	6.000	5.000	0.500
FR	0.167	0.333	1.000	0.333	6.000	5.000	0.200
C	0.200	0.500	3.000	1.000	5.000	5.000	0.500
MI	0.143	0.167	0.167	0.200	1.000	0.333	0.143
D	0.143	0.200	0.200	0.200	3.000	1.000	0.167
H	0.333	2.000	5.000	2.000	7.000	6.000	1.000

The normalized matrix with criteria weights is solved using equation (1), then the criteria weight is calculated by using equation (2) as illustrated in Table 6. According to the results from Table 6, the most important criteria for sour service hydrocarbon transport (case study 1) is corrosion resistance (CR), with a value of 0.387, and the Hardness (H) has a value of 0.205. Hydrocarbons tend to be transported at high temperatures, so thermal resistance is also an important criterion, which ranked third in the criteria weight list.

Table 6. Normalized Matrix for Criteria in Case Study Scenario 1

Criteria	CR	TR	FR	C	MI	D	H	Criteria weights
CR	0.447	0.488	0.327	0.466	0.200	0.239	0.544	**0.387**
TR	0.112	0.122	0.163	0.186	0.171	0.170	0.091	**0.145**
FR	0.075	0.041	0.054	0.031	0.171	0.170	0.036	**0.083**
C	0.089	0.061	0.163	0.093	0.143	0.170	0.091	**0.116**
MI	0.064	0.020	0.009	0.019	0.029	0.011	0.026	**0.025**
D	0.064	0.024	0.011	0.019	0.086	0.034	0.030	**0.038**
H	0.149	0.244	0.272	0.186	0.200	0.205	0.181	**0.205**

The next step in AHP analysis is to find the maximum eigenvalue $\boldsymbol{\lambda_{max}}$, using equation (3). Table 7 shows the consistency calculations which are obtained according to equation (4) and by using the random index (RI) value 1.32 as shown in Table 4 above. The consistency ratio calculated is given as 0.08999 which is less than 0.1, therefore it falls within the acceptable range. The consistency ratio result is presented in Table 8.

Table 7. Consistency Calculation for Case Study Scenario 1

Criteria	**CR**	**TR**	**FR**	**C**	**MI**	**D**	**H**	**Weighted Sum**
CR	0.387	0.580	0.498	0.580	0.175	0.266	0.615	3.101
TR	0.097	0.145	0.249	0.232	0.150	0.190	0.103	1.165
FR	0.065	0.048	0.083	0.039	0.150	0.190	0.041	0.615
C	0.077	0.073	0.249	0.116	0.125	0.190	0.103	0.932
MI	0.055	0.024	0.014	0.023	0.025	0.013	0.029	0.183
D	0.055	0.029	0.017	0.023	0.075	0.038	0.034	0.271
H	0.129	0.290	0.415	0.232	0.175	0.228	0.205	1.674

Table 8. Results obtained from AHP Analysis in Case Study Scenario 1

Criteria	**Weights**	**λ_{max}, C.I, R.I**	**Consistency Ratio**
CR	0.387	λ_{max} = 7.713 C.I = 0.11879 R.I = 1.32	0.08999
TR	0.145		
FR	0.083		
C	0.116		
MI	0.025		
D	0.038		
H	0.205		

Similarly, the VIKOR model is applied to evaluate the materials presented in Table 3 above. The values of the weights obtained from the AHP analysis are introduced into the matrix and normalized using step 2 of VIKOR as shown in Table 9. The S_i and R_i values were determined using equations (6) and (7) respectively. From the result, the value of Q_i was calculated using equation (8), and the obtained values are ranked and tabulated as shown in Table 10.

Table 9. Normalized Decision Matrix of VIKOR Analysis in Case Study Scenario 1

Material	**Criteria and weights**						
	CR	**TR**	**FR**	**C**	**MI**	**D**	**H**
Criteria weights	**0.387**	**0.145**	**0.083**	**0.116**	**0.025**	**0.038**	**0.205**
Carbon Steel	0.387	0.000	0.042	0.000	0.017	0.038	0.068
13% Cr Martensitic SS	0.097	0.073	0.042	0.058	0.025	0.038	0.000
22 % Cr Duplex SS	0.000	0.000	0.000	0.087	0.017	0.038	0.000
25% Cr Super Duplex SS	0.000	0.000	0.042	0.116	0.017	0.038	0.000
316L	0.097	0.073	0.000	0.058	0.017	0.038	0.000
HDPE	0.097	0.145	0.083	0.000	0.000	0.000	0.205
Acetal	0.097	0.145	0.083	0.029	0.000	0.000	0.205
PA12	0.097	0.145	0.042	0.029	0.000	0.000	0.137
GRE	0.000	0.073	0.042	0.058	0.008	0.000	0.137
CFRP	0.000	0.145	0.042	0.058	0.000	0.000	0.137

Table 10. Results Obtained from VIKOR Analysis in Case Study Scenario 1

Material	**S_i**	**R_i**	**Q_i**	**Rank**
Carbon Steel	0.552	0.387	0.991	**10**
13% Cr Martensitic SS	0.332	0.097	0.244	**4**
22 % Cr Duplex SS	0.142	0.087	0.000	**1**
25% Cr Super Duplex SS	0.212	0.116	0.133	**2**
316L	0.282	0.097	0.184	**3**
HDPE	0.530	0.205	0.662	**8**
Acetal	0.559	0.205	0.697	**9**
PA12	0.449	0.145	0.465	**7**
GRE	0.317	0.137	0.293	**5**
CFRP	0.381	0.145	0.384	**6**

In the sour service hydrocarbon transport pipe case scenario, the main criteria that affect the material selection process are found to be the corrosion resistance, hardness, and thermal resistance criteria as shown in the AHP results presented in Table 8. Similarly, with the VIKOR computed results as presented in Table 10, it is not hard to see that, out of ten materials evaluated, the 22 %Cr duplex stainless steel is selected as the most suitable material and with the highest reliability-based potential to be used for the subsea pipeline design. In Figure 3 below, the overall ranking results of the ten materials for Case Study Scenario I are presented. Where the ranking order is given as; 22 %Cr duplex SS, 25 %Cr super duplex SS, 316L SS, 13 % Cr martensitic SS, Glass reinforced epoxy (GRE), Carbon fiber reinforced polymer (CFRP), PA12, HDPE, Acetal, and Carbon steel.

This result shows that corrosion-resistant alloys (CRAs) are the materials of choice for sour service hydrocarbon transport. Carbon steel is ranked last, although it can be lined or cladded with CRAs for better performance. Composites also prove themselves as a contender for this application. The advantage of composites is that they can be designed specifically for a particular application. The results are consistent with the one presented by Sotoodeh (2018), whom they analyzed the improvement of the material selection process for piping systems in the offshore industry, the study concluded that 25% Cr super duplex SS is a good material of choice material for applications where high corrosion resistance and high strength is needed.

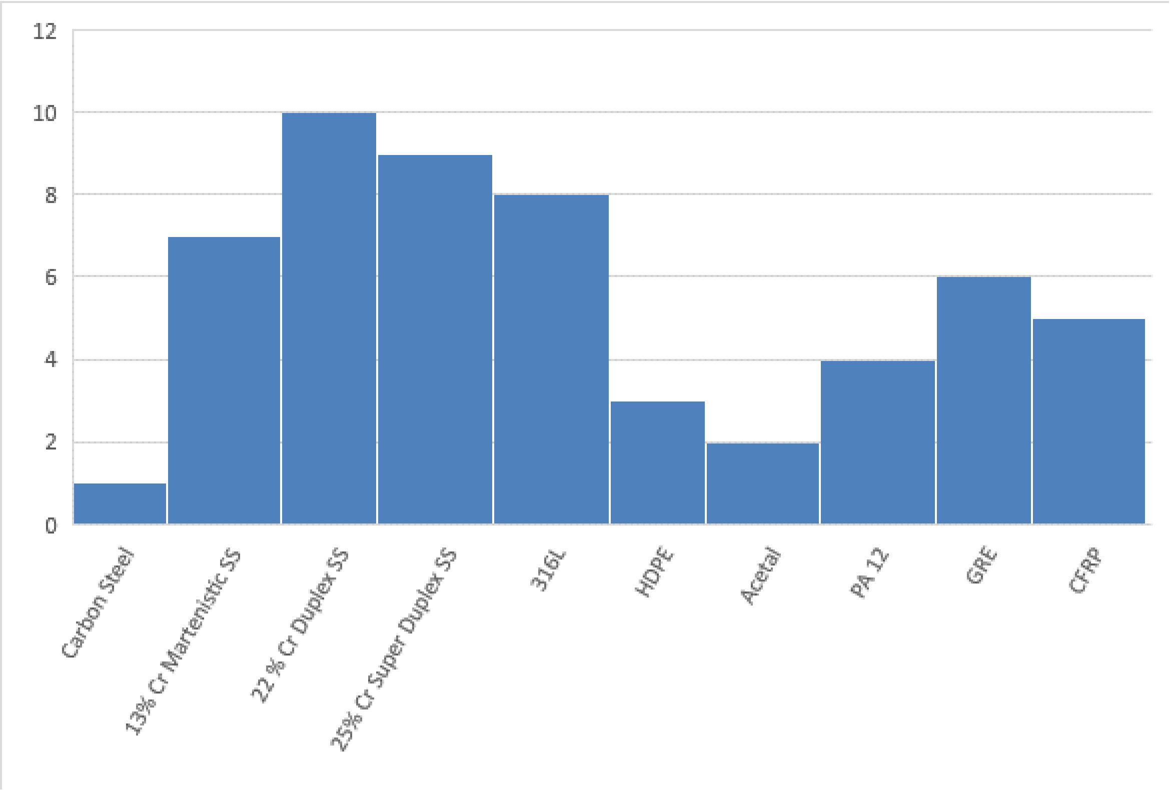

Figure 3. Material Rankings in Case Study Scenario 1

3.2. Case Study Scenario 2

This case study scenario describes the subsea pipeline design material selection for aggressive chemicals in deep waters. Since aggressive chemicals are highly corrosive, it is important that the materials used needs to have high corrosion and chemical resistance. In the following, the same steps are used in Case Study Scenario 1 above. The AHP results for the determination of the criteria weight have been presented in Table 11, where the corrosion resistance (CR) criterion is found to be the most important criteria for the aggressive chemical transport in deep waters scenario with a weight value of 0.382, while the Cost (C) is found to be the closest most important criteria with a weight value of 0.247. Aggressive chemicals tend to be transported at normal temperatures, so thermal resistance isn't an important criterion, which ranked last in the criteria weight list. The consistency ratio was calculated to be 0.07882 which falls within the acceptable range.

Table 11. Results obtained from AHP analysis in Case Study Scenario 2

Criteria	Weights	λ_{max}, C.I, R.I	Consistency Ratio
CR	0.382	λ_{max} = 7.624 C.I = 0.10405 R.I = 1.32	0.07882
TR	0.031		
FR	0.078		
C	0.247		
MI	0.052		
D	0.055		
H	0.155		

Similarly, the VIKOR model is applied to evaluate the design materials just as in the Case Study Scenario 1. Here, the values of the weights obtained from the above AHP analysis in Table 11 are used for the matrix and normalization computation. The VIKOR model results for the S_i and R_i values as well as that of the Q_i value have been presented in Table 12. Ranking results for the evaluation shows that Carbon fiber reinforced polymer (CFRP) is the most suitable and highest reliability-based material for the subsea pipeline design when aggressive chemicals in deep waters are considered.

Table 12. Results from the VIKOR model for Case Study Scenario 2

Material	S_i	R_i	Q_i	Rank
Carbon Steel	0.562	0.382	1.000	**10**
13% Cr Martensitic SS	0.381	0.124	0.220	**6**
22 % Cr Duplex SS	0.275	0.185	0.147	**5**
25% Cr Super Duplex SS	0.376	0.247	0.433	**9**
316L	0.324	0.124	0.122	**4**
HDPE	0.360	0.155	0.240	**7**
Acetal	0.421	0.155	0.347	**8**
PA12	0.331	0.103	0.097	**3**
GRE	0.299	0.124	0.078	**2**
CFRP	0.297	0.124	0.074	**1**

In the subsea pipeline design for transporting aggressive chemicals in deep waters, the criteria evaluation from the AHP model shows that corrosion resistance is the most important criterion. This further confirms that the inherent corrosion resistance characteristic is of great value when designing subsea pipes. Some deep-water pipes also need to have a low specific weight that as in the case of risers. The results from the VIKOR computations also show that the ranking order for the most suitable and highest reliability-based materials are the Carbon fiber reinforced polymer (CFRP), Glass-reinforced epoxy (GRE), PA12, 316L SS, 22 %Cr duplex SS, 13 % Cr martensitic SS, HDPE, Acetal, 25 %Cr super duplex SS and Carbon steel. The study can therefore conclude that composite materials are the materials of choice for aggressive chemical transport for deepwater applications. Some polymers such as PA12 are also equipped to handle this condition. The overall ranking results of the ten materials evaluated for the Case Study Scenario 2 have been presented in Figure 4.

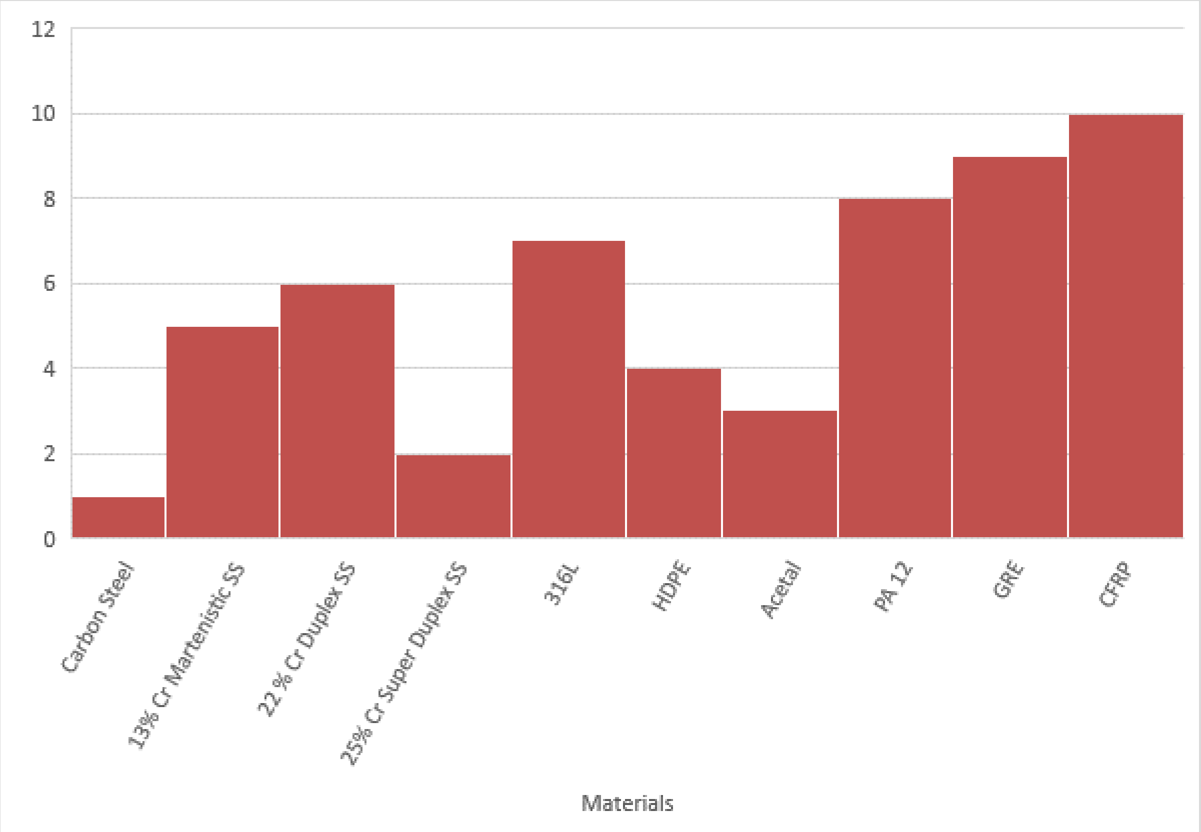

Figure 4. Material Rankings in Case Study Scenario 2

3.3. Case Study Scenario 3

In this case study scenario 3, subsea pipeline design materials are selected for non-corrosive fluid transport pipes such as those used in industrial water lines for transporting cooling water in environments of little to no H_2S content. Since corrosion wouldn't be a major problem in this case study scenario, the major concern here however is shifted to deal with the price and 'ease of use' criteria of the material. In the following, the same steps are used in the Case Study Scenarios above. The AHP results for the determination of the criteria weight have been presented in Table 13, where the cost (C) criteria with a weight value of 0.416 are found to be the most important criteria for the non-corrosive fluid transport pipes scenario. While hardness (H), with a weight value of 0.181 is found to be the closest most important criterion. The consistency ratio was calculated to be 0.04411 which falls within the acceptable range.

Table 13. Results obtained from AHP Analysis in Case Study Scenario 3

Criteria	Weights	λ_{max}, C.I, R.I	Consistency Ratio
CR	0.036	λ_{max} = 7.349 C.I = 0.05822 R.I = 1.32	0.04411
TR	0.029		
FR	0.149		
C	0.416		
MI	0.096		
D	0.093		
H	0.181		

Similarly, the VIKOR model is applied to evaluate the design materials just as in the other Case Study Scenarios. Here, the values of the weights obtained from the above AHP analysis in Table 13 are used for the matrix and normalization computation. The VIKOR model results for the S_i and R_i values as well as that of the Q_i value have been presented in Table 14. The ranking results for the evaluation shows that Carbon steel is the most suitable and highest reliability-based material for the subsea pipeline design when non-corrosive fluid transport is considered.

Table 14. Results obtained from VIKOR Analysis in Case Study Scenario 3

Material	S_i	R_i	Q_i	Rank
Carbon Steel	0.328	0.093	0.000	**1**
13% Cr Martensitic SS	0.495	0.208	0.439	**8**
22 % Cr Duplex SS	0.469	0.312	0.560	**9**
25% Cr Super Duplex SS	0.648	0.416	1.000	**10**
316L	0.389	0.208	0.273	**4**
HDPE	0.368	0.181	0.199	**3**
Acetal	0.472	0.181	0.362	**6**
PA12	0.337	0.121	0.057	**2**
GRE	0.450	0.208	0.369	**7**
CFRP	0.432	0.208	0.341	**5**

The subsea pipeline is designed for transporting non-corrosive fluids and is very common in the oil and gas industry. The criteria evaluation approach using the AHP model shows that cost is the most important criterion. While the results from the VIKOR computations as presented in Table 14 shows the following ranking order; carbon steel, PA12, 316L, HDPE, CFRP, 13 % Cr martensitic SS, GRE, Acetal, 22 %Cr duplex SS and 25 %Cr super duplex SS.

It can be concluded from the results that, carbon steel is the most suitable and highest reliability-based design material for the subsea pipe design when non-corrosive fluids are considered. Similarly, polymer materials like the PA12 and HDPE are close alternatives that can be used for the design. If cost is a major factor in the material selection process, cheaper materials like carbon steel and polymers should be considered as they are cheaper than CRAs and Composites. The overall ranking results of the ten materials evaluated for the Case Study Scenario 3 have been presented in Figure 5.

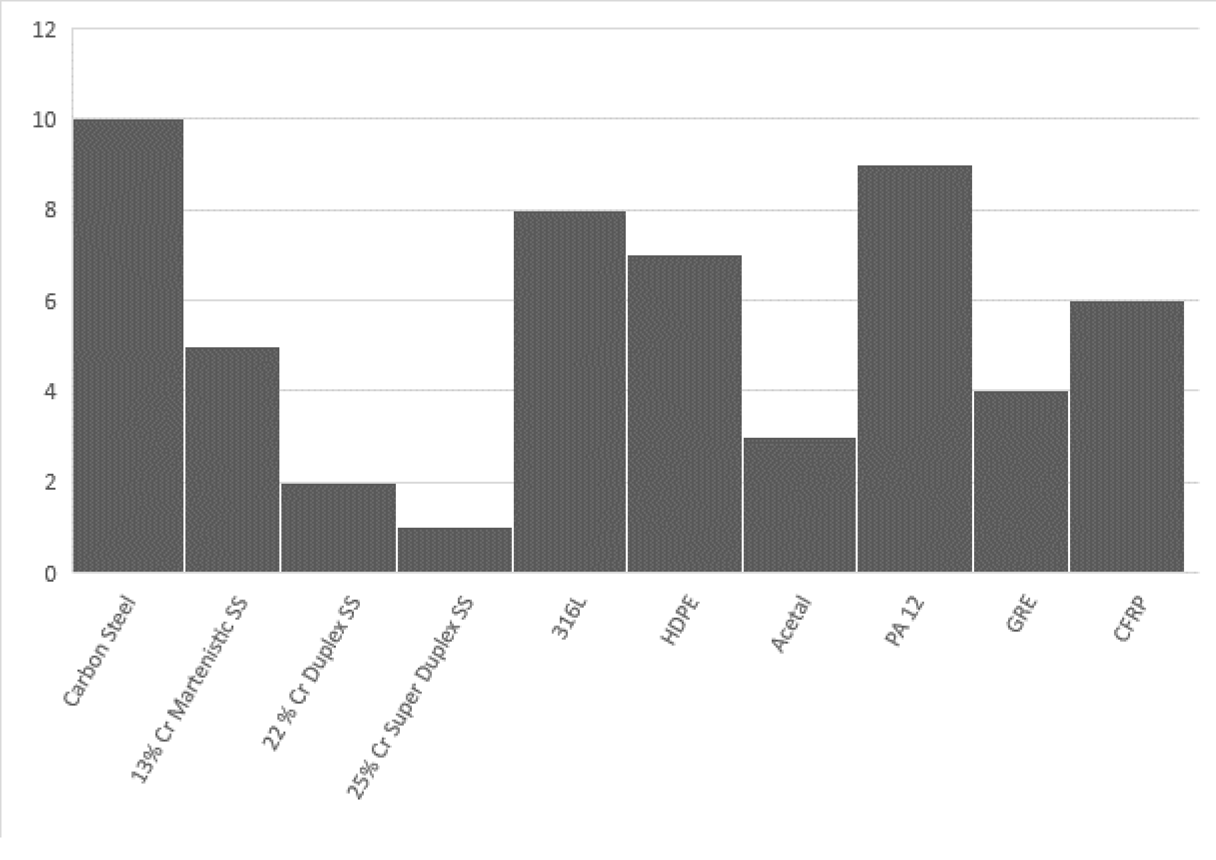

Figure 5. Material Rankings in Case Study Scenario 3

4. Conclusion

Subsea pipelines are a very important aspect of offshore oil and gas production, therefore their design and construction should be reliable and efficient as possible. Proper material selection plays a vital role in an efficient operation and a longer lifespan for the pipelines. This study presented a three-stage hybrid model that is based on an integrated Analytical Hierarchy Process (AHP) model and the VlseKriterijumskaOptimizacija I KompromisnoResenje (VIKOR) model for the evaluation and selection of a suitable and high reliability-based design material for the subsea pipeline design by considering three operational and environmental scenario (three offshore application) that the pipes might encounter in the field.

Ten subsea pipeline design materials were examined critically with respect to seven criteria. The AHP model was applied in the different case study scenarios to determine the weight values of the different criteria. It was noticed for each case study scenario that the resulting weight values calculated were different and can affect the entire application. The results of the VIKOR analysis show that for sour service hydrocarbon transport in deep waters, 22% Cr Stainless steel is the best, most suitable, and highest reliability-based material for the subsea pipe design, for aggressive chemical transport, Carbon Fiber Reinforced Polymers are the best materials. While for the non-corrosive fluids, carbons steel and polymers are the material of choice.

Although Carbon steel may need to undergo some processes for protection against saltwater corrosion before use, the obtained results from the model, however, are in agreement with the previous research study of non-corrosive fluids. For a more efficient and cost-effective pipeline production, it is recommended that offshore oil-producing companies should adopt the use of the best fit and the highest reliability-based material for the design and construction of subsea pipes by considering the results obtained from a dedicated and a good research case study scenario. This research was limited in scope to just ten common materials, but with the variety of engineering materials that can be chosen, the research could be extended and further developed to suit other applications not examined.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

Author Contributions

All the authors were involved in designing the study, collecting data; evaluation of results and in the writing of the article.

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