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A Methodology Proposal for Estimating the Costs Associated with Failure Effects of Subsea Equipment

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A proposed methodology is presented for estimating the costs associated with the failure effects in subsea equipment. The methodology takes into account the cost of operating losses when a failure mode inhibits the main function of the system and prevents the creation of value, as well as the costs of indirect losses, such as environmental costs caused by the degradation of the environment due to the emission of pollutants, human costs caused by human losses (injury, illness or death) and financial costs caused by the reduction of customer orders depending on the type of failure mode. The concept of Value of Statistical Life (VSL) is used to consider life losses. The development of this methodology is based on a systematic review of the literature, which uses the Scopus, Web of Science, Science Direct and Google Scholar databases. The review found that most literature focuses on modeling of the different types of costs involved in the equipment life cycle, rather than directly related to the costs of failure effects.

Keywords: Labor cost, material cost, opportunity cost, environmental cost, statistical value of life, failure.

1. Introduction

In recent years, research in the field of risk-based inspection (RBI) of subsea systems has been motivated by the complexity of these systems and the potential for equipment failures to cause significant material impacts. These impacts may include the loss or reduction of production, as well as the loss of the system or equipment itself. However, even more concerning is the potential for equipment failures to cause severe damage to the environment and pose threats to human life.

In a broader context, optimization problems related to inspection and maintenance of subsea equipment have long been a subject of interest. Various studies, including Ossai et al (2016), Liu et al (2018) and Rachman & Ratnayake (2019) have address RBI issues related to the purpose of this paper. On the other hand, Castanier et al. (2006) and Arzaghi et al. (2017) have dealt with maintenance-related optimization issues concerning subsea oil pipelines. Bucelli et al. (2018) discussed an integrated risk assessment approach for oil and gas facilities in sensitive areas. Optimization can also be considered from an equipment design perspective, as demonstraded by studies such as Zhang et al. (2017) and Zhang et al. (2022).

In a risk assessment project, it is crucial to consider the failure effects for each system and estimate the associated costs. This article proposes a methodology for estimate the costs associated with the failure effects in subsea equipment, which takes into account: the cost of operating loss when a failure mode inhibits the main function of the system and prevents the creation of value, and the costs of indirect losses, such as: environmental risks caused by the degradation of the environment due to the emission of pollutants, human risks caused by human losses (injury, illness or death) and financial risks caused by the reduction of customer orders depending on the type of the failure mode.

The development of this methodology was based on a systematic review of the literature using the Scopus, Web of Science, Science Direct and Google Scholar databases, where it was verified that most of the studies in the literature are concerned with the modeling of the different types of costs that involve the equipment life cycle and not directly related to the costs of failure effects. Therefore, this paper presents a systematic review of the literature and a methodology for estimating the costs of failure effects resulting from the review.

This paper is organized as follows. Section 2 presents the literature review on cost modeling. A proposal of a cost model for failure effects is presented in section 3. The model proposed is discussed in section 4. Finally, section 5 summarizes the conclusions reached so far.

2. Literature Review

This paper presents a systematic literature review for costs and methods for quantifying the effects of failures. The chosen search methodology was the Systematic Literature Review (SLR), which uses well-defined and rigorous criteria to identify, evaluate and synthesize the literature that has been searched (Cunha et al., 2019). The steps for using the SLR are the ones proposed by Thomé et al. (2016).

The failure effects were extracted from previous FMECAs (Moura et al., 2021, Nicolau et al., 2022) and general literature. Thus, the research problem can be described as the systematic search for specialized literature on the effects of failures for subsea equipment and their subsequent comparison in terms of cost classification, according to Badía et al. (2001).

In order to develop this phase of the project, extensive bibliographic research has been carried out, which aimed to identify publications such as scientific articles from journals, conferences, theses, and dissertations related to the review problem established in the research planning phase.

To conduct the bibliographical research, the following databases have been accessed:

- Scopus;
- Web of Science;
- Science Direct;
- Google Scholar (only theses and dissertations).

For the Scopus and Web of Science databases, no search restriction was imposed. In the case of the Science Direct database, the search was limited to research articles due to the large number of documents returned. Finally, the search for theses and dissertations was directed to the Google Scholar database, which was conducted separately, as this tool does not allow for the practical exporting of results like the other databases.

The keywords were grouped into two categories: (1) type of failure mode effect and (2) context, as presented in Tables 1 and 2.

Table 1. Keywords – Failure mode effect type

Number	Failure mode effect
1	Production interruption
2	Reduction in production
3	Leakage
4	Pollution
5	Environmental damage
6	Structural collapse
7	Installation delay
8	Sensor reading loss

Table 2. Keyword – Context

ID	Context
1	Failure effect
2	Subsea
3	Costs

Next, the search terms were defined. As an example, Table 3 shows the search commands used by gathering the keywords and context mentioned for Scopus and the number of documents found for each search command.

Table 3. Examples of search terms used in the Scopus search

Command	Number of results
Costs; AND Subsea; AND Failure effect; AND Production Interruption	11
Costs; AND Subsea; AND Failure effect; AND Reduction in production	179
Costs; AND Subsea; AND Failure effect; AND Leakage	98
Costs; AND Subsea; AND Failure effect; AND Pollution	104
Costs; AND Subsea; AND Failure effect; AND Environmental Damage	259
Costs; AND Subsea; AND Failure effect; AND Structural Collapse	93
Costs; AND Subsea; AND Failure effect; AND Installation delay	24
Costs; AND Subsea; AND Failure effect; AND Sensor reading loss	5
Total	773

Searches similar to those shown in Table 3 were made considering the information in Tables 1 and 2. In this phase, 1939 publications were found (all types) related to the search terms. The number of documents found in each database is shown in Table 4.

Table 4. Initial number of documents per search database

ID	Keyword	SC	WoS	SD	GS
1	Production Interruption	11	0	59	10
2	Reduction in production	179	1	286	5
3	Leakage	98	3	147	5
4	Pollution	104	1	100	8
5	Environmental Damage	259	5	257	4
6	Structural Collapse	93	1	87	2
7	Installation delay	24	0	103	4
8	Sensor reading loss	5	0	30	2
	TOTAL	773	11	1069	86

SC = Scopus; WoS = Web of Science; SD = Science Direct; GS = Google Scholar

It is worth noting that although a large number of documents were identified, only a few of them were found to be useful for the purposes of the study described in this paper, as will be discussed next.

The search for references to help clarify failure effects was not particularly useful, as most effective sources for the purpose of this work were found to be Moura et al. (2021) and Nicolau et al. (2022), in which FMECAs for subsea equipment are discussed.

Considering costs, Ferreira et al. (2017), for example, address risk prioritization in the context of an FMEA by considering the occurrence cost of failure modes in the detection stage. Mehrafrooz et al. (2019) discuss reliability analysis of subsea pipelines, specifically by considering failure modes from the cost point of view. It is seen that these are examples of papers that deal with cost but they not provide clear information to allow cost definition of failures effect of subsea equipment .

Concerning the development of a cost model, the works by Gilchrist (1993), Spencer & Rhee (2003), Von Ahsen (2008), Rhee & Spenser (2009), Guinot et al (2017) and Brennan (2017) address the problem, generally considering the life cycle cost of equipment, in different branches of industry, the automotive branch being common and, particularly, in two of them (Spencer & Rhee et al, 2003, and Rhee & Spencer, 2009) that of particle accelerators. However, no reference discussing a cost model for subsea equipment has been found.

It is noticed that there is a clear modeling of the different types of costs that involve the life cycle and that, in the case of very competitive industries, such as the automobile industry, this concern comes from the design of the equipment. These cost components are three: labor cost, material cost, and opportunity cost.

The works of Rhee & Spencer (2009) and Guinot et al. (2017), as well as relevant aspects discussed in Brennan (2017) are of particular interest to the present project. These works propose models that can be adapted to the project purposes, despite the fact the design phase of the subsea equipment under investigation (such as manifolds, PLET, PLEM, Christmas trees and emergency shutdown valves) is not the main focus.

It is important to note the need for considering environmental impacts of failures and their respective costs, as well as the fines and costs related to production interruption. In the literature, some works have addressed these issues, such as Luhichi et al. (2019). Additionally, it is important to consider the value of life in the context of production losses. The study of Viscusi (2004) is useful for modeling this feature.

3. Cost Model for Failure Effects

This section focuses not on life cycle costs, but specifically on the costs of failures effects. Therefore, the proposed model has been adapted from the models discussed in the references above. The reason for this is that the equipment under consideration in this project is already installed and in operation.

In the scope of this project, several definitions must be considered initially to understand the proposed model. Table 5 presents these definitions succinctly.

Table 5. Preliminary definitions

Concept	Definition
Detection time (t_d)	Time frame to notice and identify a particular failure mode that has occurred and diagnose its exact location and root cause.
Repair time (t_r)	Time range to fix each component. Redesign, remanufacturing and reinstallation are examples of activities that lead to this time.
Waiting time (t_y)	Time interval incurred for a non-value activity, such as waiting for technicians to respond, setup time, and mailing/shipping time.
Downtime (t_s)	Time interval during which the system was turned off and produced no value. Applies only to failure modes that occur during the operations phase. Downtime is the sum of detection, repair, and hold time.

According to Rhee & Spencer (2009), the expected cost of failures, $E(C_F)$, can be calculated by taking into account the number of failure scenarios (N), the probability of a particular failure occurring (p_i) and its respective cost, c_i:

$$E(C_F) = \sum_{i=1}^{N} p_i \, c_i \tag{1}$$

However, the focus of this study was on the system failure effects, taking into consideration their high degree of importance, in relation to local effects, unlike Eq. (1). More specifically, regarding the cost associated with each failure effect (c_i). The failure effects considered here were obtained through the development of a FMECA based on previous studies published in Nicolau et. al. 2022.

The formula for determining the cost of the failure effect (c_i), presented in Eq. (2) was developed based on the most frequently mentioned cost components in the literature, such as labor cost (c_l); cost of materials (c_m); cost of equipment (c_e); opportunity cost (c_o).

$$c_i = c_l + c_m + c_e + c_o \tag{2}$$

The labor cost can be obtained from Eq. (3):

$$c_l = t_r . l_r . n_o \tag{3}$$

where:

l_r: Individual cost of man-hour;

n_o: Number of team members for each cost share.

On the other hand, the cost of materials(c_m) can be estimated from Eq. (4):

$$c_m = \sum_{j=1}^{M} q_j . c_j \tag{4}$$

where:

q_j: number of parts of each type to be repaired or replaced;

c_j: is the cost of the material(s) involved in each case (it could be the cost of a whole part replaced or small parts replaced, or some material used in the repair, such as a lubricant, etc.).

The cost of equipment (c_e) can be estimated from Eq. (5):

$$c_e = \sum_{j=1}^{M} e_j . c_{j,h} \tag{5}$$

where:

e_j: number of equipment used to repair the failure;

$c_{j,h}$: hourly cost of the equipment(s) used in each case.

With regard to the opportunity cost, this can include costs related to operational losses (P_o), which are the costs incurred when a failure mode inhibits the main function of the system and prevents the creation of value (Rhee & Spencer, 2009). The opportunity costs also consider costs due to indirect losses, such as environmental costs (P_e) caused by the degradation of the environment due to the emission of pollutants, human costs (P_h) caused by human loss (injury, illness or death) and financial costs (P_f) caused by a decrease in orders from clients, depending on the type of failure mode (Louhichi et al., 2019).

One can calculate the opportunity cost using Eq. (6):

$$c_o = P_o + P_e + P_h + P_f \tag{6}$$

where:

$$P_o = t_s . c_{o,h} \tag{7}$$

where t_s is defined in Table 5 and $c_{o,h}$ is the hourly opportunity cost.

Therefore, Eq. (2) can be written as:

$$c_i = t_s . l_r . n_o + \sum_{j=1}^{M} q_j . c_j + \sum_{j=1}^{M} e_j . c_{j,h} + (P_o + P_e + P_h + P_f) \tag{8}$$

The environmental costs (P_e) associated with a failure scenario *i*, can be evaluated by using Eq. (9):

$$P_e = \left(\sum_{j=1}^{n} P_j V_j \rho_j D_{aj} \right) \tag{9}$$

According to Louhichi et al. (2019), a failure scenario can cause damage to the environment by emitting harmful pollutants. For a failure scenario *i*, consider:

- $P_j = (P_1, P_2, \ldots, P_n)$: the probability of emitting pollutants, so P_j is the probability of emitting chemical *j* during failure scenario *i*.
- $V_j = (V_1, V_2, \ldots, V_n)$: the emission volume of pollutants, so that V_j is the emission volume of chemical *j* during failure scenario *i*.
- $\rho_j = (\rho_1, \rho_2, \ldots, \rho_n)$: density vector of the chemicals, so that ρ_j,is the density value of the chemical *j* emitted during the failure scenario *i*.
- $D_{aj} = (D_{a1}, D_{a2}, \ldots, D_{an})$: cost of damage per ton of emission of pollutants, so that D_{aj} is the cost of damage per ton of emission of chemical *j* during failure scenario *i*.

According to Louhichi et al. (2019), assessing risks outside the financial domain can be challenging, as it is difficult to put a monetary value on something like a human life. To deal with this issue, economists have introduced the concept of Value of Statistical Life (VSL), which reflects the worker's willingness to pay for accepting a certain level of risk and pay for more safety.

The choice for using VSL was due to the literature used in the research for defining the methodology ((Viscusi et al, 1993), (Viscusi et al., 2003), (Viscusi, 2004), (Machina & Viscusi, 2014)) and the difficulty in measuring the term. VSL has attractive properties, according to (Machina & Viscusi, 2014): it provides a cardinal measure of the value of life instead of an ordinal measure. It is applied to estimate the value of the willingness to pay as well as the willingness to accept the risk value changes, p_k^d is the probability of death of person k in case of occurrence of failure scenario *i*.

The human cost (P_h) associated with a failure scenario *i* can be evaluated by considering the expected number of failures, and using the Eq. (10):

$$P_h = VSL \sum_{j=1}^{n_p} p_k^d \tag{10}$$

where, n_p is the total number of people that are possibly being impacted by failure scenario *i*. The summation in Eq. (10) has a similar interpretation to that of Eq. (9).

And finally, the financial cost can be calculated using the installments of fines on the operator, as mentioned in ANP (2015). In the event of a failure, its effect can directly affect the environment and the operator will be charged a fine, referred to here as M_a.

As a failure effect can also result in the interruption of the operations, causing delays in the delivery of a pre-agreed quantity of products, a penalty may be incurred depending on the terms of the contract. This penalty is referred to as the fine for non-delivery (M_e) in this study. Therefore, the financial cost can be calculated using Eq. (11):

$$P_f = M_a + M_e \tag{11}$$

4. Discussion

Here are some considerations regarding the data required to estimate the cost of the effect of each failure.

To estimate the cost of the effect of each failure, certain data must be collected. First, information about detection, repair, and waiting times is required. Detection times can be obtained from operational experience, while repair times can be estimated based on data available in databases, such as OREDA (Veritas, 2015). Waiting times also need to be collected based on operational experience.

The labor rate, which, in principle, is assumed to be constant, should be obtained from operational experience, especially for outsourced operations, where a company is hired to perform the repair or inspection. The number of operators required for each repair or replacement task should also be taken into account. The man-hour costs should also be obtained from field experience.

Regarding material costs, data on the number of parts replaced and the cost of each part are required. This data is also part of the operational experience.

Finally, the hourly opportunity cost, for each case, is also a data derived from operational experience.

It is important to note two aspects when estimating costs:

- the costs should be annualized;
- the input data required for the estimation are generally, random variables and, thus expected values must be obtained.

Furthermore, to model realistic cost estimates of failure effects, a significant amount of information is required. In addition to the data needed to estimate environmental and production interruption costs, such as statistical value of life, insurance information related to VSL may also need to be considered. However, this information is country-specific and turns out to be a great shortcoming.

5. Conclusion

This paper presents a cost model for evaluating the costs associated with the failure effects in the context of an FMECA for subsea equipment.

The failure effects have been identified based in previous FMECAs developed for subsea equipment.

However, while the proposed model is conceptually simple, obtaining the data necessary for its application to real cases is not a trivial task. This process requires field data from different sources, such as users, contractors, regulatory agencies, and so on.

The application of field data to the gathered failure effects will reveal the level of uncertainty associated with the data and identify any future needs for uncertainty analyses.

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