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Influence of Inspections on the Risk Evaluation of a Subsea Manifold by a Top Logical Model

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We present a preliminary risk analysis of a typical subsea manifold for the Brazilian oil basin through a top logical model (TLM) developed by considering initiating events and their respective event trees. A total of seven initiating events have been identified, including: loss of containment in the section between the connector and the flowline, loss of containment in the section between valves, spurious valves closure, and pipe plugging in the sections between valves. For each of these initiating events, an event tree was developed, defining some barriers and identifying risk sequences. Additionally, for five initiating events, namely, Loss of containment in pipelines before valves, Loss of containment in at least one valve, Loss of insulation at Manifold input connectors, Loss of containment in ducts prior to manifold inlet connectors, and Structural Deficiency in the Manifold Protective Structure, no barriers were identified. From these event trees and using fault trees, the system TLM was developed, which is very useful for assessing the influence of inspection plans on equipment risk evaluation. This model allows for considering sensitivity analyses such as initially considering the existing standard inspection plan followed and no inspection plan. Other important variables to consider include failure detection probabilities associated with the inspection techniques used to assess the system. These results are valuable for decision-making regarding the definition of inspection plans.

Keywords: Offshore oil and gas industry, risk analysis, top logical model (TLM), initiating events, consequences, equipment inspection, detection probability.

1. Introduction

The search for integrity lies in every industry sector and the key problem is to identify the best way to invest the limited financial resources to provide the best inspection plans possible.

Considering all hazards involved in the offshore industry, several techniques and methodologies have been employed to manage offshore safety, which take into account organizational and human factors, safety culture and a risk-based approach. The latter was developed in the oil industry to help identify the equipment at the greatest risk and to design inspection programs that not only identify the most relevant failure modes, but also allow to mitigate their occurrence (Fullwood, 1999; BSEE/NASA, 2017).

The risk monitor is an application of the Probabilistic Safety Assessment (PSA) approach (Wang et al 2015), which is one of the methods of nuclear safety analysis and has been widely used to assess instantaneous risk based on the specific nuclear power plant configuration during its operation (Kafka, 1997). The key method of PSA and risk monitor is a combination of Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) (NRC, 1975). FTA is commonly used for complex system safety and reliability analyses, including determining minimum cut sets, key event probabilities, and component importance. However, the instantaneous risk model is generally very large and complex, difficult to be calculated and manually analyzed. Efficient analysis of large fault trees is a very complex problem, especially in instantaneous risk analysis (Wang, et al., 2016).

One of the main prerequisites for a Risk Monitor is its ability to produce a result in a short time (1 – 2 minutes) because the developed model is a dynamic one and the plant status must be known in a short interval for making decisions (NEA, 2004). Typically, it is not possible to perform this type of feature using a logical model based solely on Event Trees and Fault Trees, which makes up PSA, for example. Therefore, the Top Logical Model (TLM) was used to reduce the time of solution. The model uses a fault tree that is logically equivalent to the set of fault trees and event trees. Furthermore, TLM, unlike PSA, makes it possible to activate or deactivate parts of the fault tree, aiming at representing the current state of the plant (NEA, 2004). This feature will be discussed later. To construct a TLM, probabilistic modeling of the system considered is necessary, focused on the quantitative calculation of risk in the most usual way, that is, through event trees and fault trees.

This paper presents the preliminary results of the TLM development for a typical subsea manifold. Section 2 describes a typical subsea manifold. The methodology used is the subject of section 3. Preliminary results are presented and discussed in section 4. Finally, the conclusions reached are displayed in section 5.

2. Description of a Typical Subsea Manifold

The main function of a subsea manifold is to collect production from several subsea wells, gather flows from the individual wells through pipelines and direct them to a fixed platform or floating production, storage and offloading vessel (FPSO). Its operation is due to its various valves and control devices that allow the manifold to: regulate the production flow, separate fluids, measure production, and even inject chemicals, Bai & Bai (2019).

There are different types of subsea manifolds: production manifold - Collects production from wells and directs it to the platform or FPSO; Injection manifold: injects water, gas or other chemicals into wells; Test manifold: allows one to perform individual production tests on each well. Each type is made up of different types of valves, Guedes (1998).

In the preparation stage, it was observed that to develop event trees (ET), fault trees (FT) and TLM of the manifold equipment it was necessary to accurately identify a manifold model. For this purpose, the following manifold models were considered (Guedes, 1998):

- Garoupa atmospheric manifold (1978) Bonito manifold-template (diverless);
- Standard diver-assisted manifold;
- Manifold for deep waters – 1st generation;
- Manifold for deep waters – 2nd generation;
- Manifold for deep waters - 3rd generation.

Offshore operations are classified in one of three categories: a) shallow water operations (water depth is smaller than 1,000 ft); b) deep water (between 1,000 ft and 2,000 ft); and c) ultra-deep water (above 2,000 ft) [a].

It has been decided that the model to be used here would be the manifold for deep waters – 2nd generation (Figure 1) as it is the most representative of the population of manifolds that are the subject of analysis

It can be seen from Figure 1 that the manifold model used is composed of the valves: choke, control, check, utility isolation, process isolation and pigging, and pig modules (pigging module), chemical injection connection (Chemical injection coupling), hydraulic connection (hydraulic coupling), flow lines (Flowline).

Manifold Utility Isolation (UI) valves that control the amount of chemical injected or through a more complex dosing system (metering valve or metering valve) are specifically designed to precisely regulate the amount of chemicals, which are introduced into the process system, thus ensuring that the correct proportions are maintained for specific operational needs. They can be adjusted manually or controlled

[a] https://www.dnv.com/article/modelling different-upstream-oil-and-gas-operations-207958/, accessed on Feb, 2025.

automatically using a control system.

Concerning the 2nd generation manifold model, it was considered that this valve is controlled by the manifold control system and by remote action, since at such depth there would be no practical ways to operate with divers and/or or ROVs.

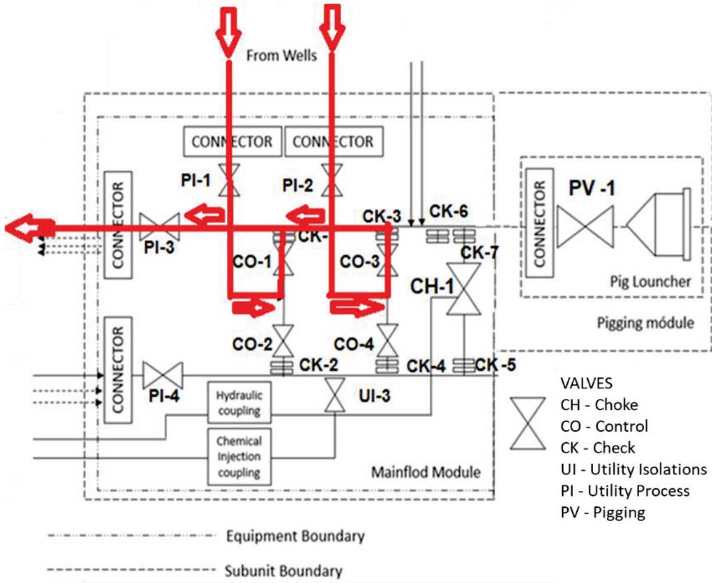

Fig.1. Manifold Diagram with Identification and classification of valves. Adapted from OREDA (2015)

It is usually a part of the manifold that allows direct introduction of chemicals into the main fluid flow in the system. This can be done using a specific valve (here called utility isolation valves) that controls the amount of chemical injected or through a more complex dosing system.

In a manifold used for pigging operations in pipeline systems, the main valve responsible for controlling the pigging process is known as pigging valve. This valve is specifically designed to facilitate the introduction and removal of pigs. This valve is essential in the pigging process, as it allows the pig to be launched or received into the pipeline system in a safe and controlled manner. It is generally positioned at strategic points on the manifold, where the pig is introduced into the system or removed from it. Furthermore, the pigging valve can be equipped with special features such as appropriate sealing and locking mechanisms to ensure that the process is safely conducted (Shang et al., 2021).

3. Methodology

Figure 2 displays the overall methodology employed in developing the analysis for building up the TLM for the subsea manifold (Maturana et al, 2024).

Step # I considers the study of the configuration of the field where the systems and equipment are installed. It includes information about the equipment such as: description of the equipment (see section 2), survey of standards applicable to their installation, and survey of performance information associated with these systems and equipment (for example: FMECAs – as in Nicolau et al (2022), human aspects – see Maturana et al (2021) and equipment performance data – such as OREDA (2015).

Five tasks are the subject of step II also and the first of them deals with hazard identification.

The hazard identification was prepared through Preliminary Hazard Analysis (PHA), (DNV, 2006). In addition to evaluating existing hazards, a qualitative assessment of risks is carried out by estimating the frequencies or probability of exposure to hazards and the severity of the consequences of accidents for the environment and workers' health.

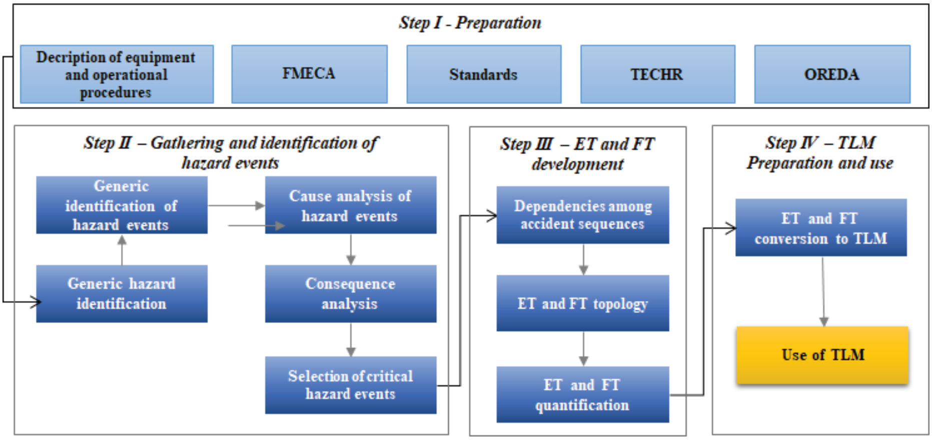

Fig. 2. Overall methodology description (adapted from Maturana et al, 2024)

PHA can be preventively used in operational areas, before tasks are carried out. Its main advantages are the possibility of involving a multidisciplinary group, resulting in a short period of time for analysis in most cases, in addition to its simplicity in application. However, its disadvantages are related to the dependence on the perception of those involved in identifying the hazards in the process or project, since the omission of a hazard can result in an accident if there is no adequate control or blocking action.

Step III deals with the development of event trees and fault trees. Two steps are important here: first, the event trees are developed for the initiating events identified. Next, they are quantified with the help of fault trees.

Finally, on Step IV, ET and FT are converted into a TLM, and it is prepared for use in risk monitoring. As an example of this preparation, we can mention the grouping of basic events that are jointly affected by operators' interventions with regard to inspection and maintenance plans.

A TLM can be developed for each outcome of risk (property, personal, environmental, etc.) or, when there are risk equivalence relationships between the dimensions, it is possible to construct a single TLM. In this case, the TLM aggregates all ET and FT that make up the model to calculate the risk so that besides considering the frequencies associated with plant states, the TLM considers the consequences of each state for each risk dimension.

In order to give an idea of a TLM, consider the event tree displayed in Fig. 3, hypothetically developed for a given initiating event IE and for which the fault trees of Fig 4 were developed. This example is adapted from Maturana et al (2024).

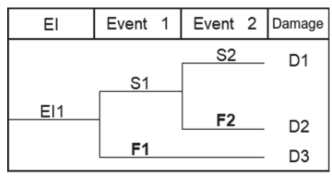

Fig. 3. An example of an event tree for a TLM (Maturana et al, 2024)

The problem represented in this set of trees refers to the calculation of the risk associated with the oil leakage (initiating event EI1) in a subsea manifold section (Section A), schematically represented in Figure 5.

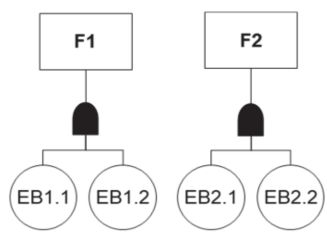

Fig. 4. Fault trees for the ET of Fig. 3 (Maturana et al, 2024)

Figure 3 displays the predicted event sequences, given that the initiating event EI1 occurs. This ET presents a sequence of two events

(1 and 2), with S representing success and F representing failure. Event 1 represents detection and alarm in the control room, which can be successful (S1) or not (F1). Event 2 represents the operator action, which may be successful (S2) or not (F2).

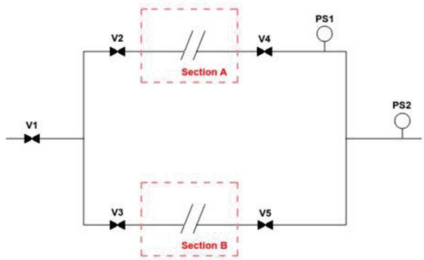

Fig. 5. Schematic manifold sections (Maturana et al, 2024)

Failure probabilities F1 and F2 (S1 and S2 are complementary probabilities to these latter, respectively) are calculated in the FT represented in Figure 3. To keep this example simple, it was considered that the failure of alarm systems and human errors have much greater probabilities than the remaining ones.

For illustrative purposes, we considered (in the development of the FT in Figure 3) just two basic events (EB) linked to their top events (F1 and F2) by AND gates. These EBs are as follows: EB1.1) failure of the alarm linked to the PS1 pressure sensor; EB1.2) failure of the alarm linked to the PS2 pressure sensor; EB2.1) human error in diverting the flow to Section B, and; EB2.2) human error in closing valve V1. In this example, the TLM is created by aggregating each accidental sequence into a model similar to a FT, where each possible sequence makes up a branch combined with its respective damage by an AND gate. Thus, in the TLM the risk is calculated by the sum of the expected frequencies F(D) for damages multiplied by the respective consequences C(D). Thus, the possible damage is associated with a portion of risk.

Figure 6 presents the TLM obtained in the way discussed so far for the ET presented in Figure 3, with FTs presented in Figure 4.

An important feature of a TLM is that it can activate or deactivate a fault tree branch in the context of risk monitoring. For example, if a valve can undergo test or maintenance, the branch where it is modeled cannot be considered because it is isolated. By means of a house event (connected to the failure events by an AND gate), the fault tree branch where failures of this valve are considered can be deactivated (the house event is assigned a "0" probability in this case).

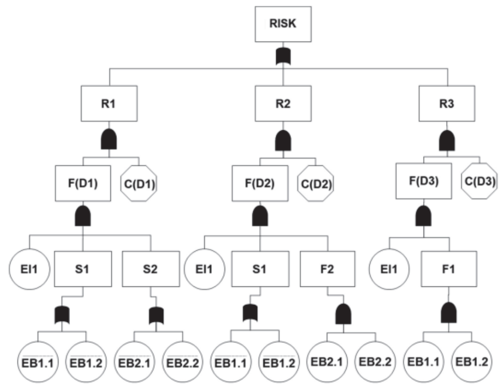

Fig. 5. TLM developed for the ET in Fig. 3 (Maturana et al, 2024)

One of the specific aspects of the model is the consideration of the probabilities of detecting failures, which were estimated considering equipment in deep waters. These probabilities are included in the composition of the FMECA. Consideration of the effects of failures is done through the assignment of consequences. Detailed discussion of the risk indices used for the failure modes that were raised in FMECA (and which involve the detection probabilities and the consequences) can be seen in Maturana et al (2024).

As to field data to be used in the TLM quantification, we could not find failure data for deep water equipment, so that we have used data from OREDA (2015).

4. Preliminary Results

The manifold model presented in Figure 1 was considered to build the PHA. It was assumed that all process control and isolation valves are accessed via the Manifold Control System by a hydraulic umbilical.

An initial set of 22 hazards were identified. From this initial set, 12 hazard scenarios that needed further investigation in order to define the initiating events for developing the event trees were identified.

Further consideration of the above

mentioned 12 initiating events showed that for 7 of them barriers were identified so that this allowed the development of events trees. Table 1 displays these initiating events (see Figure 1).

Table 1. Initiating events (IE) with identified barriers

#	Description
1	Loss of containment in the section between connector and flowline
2	Loss of containment in the section between valve PI-3 and valves CO-1 and CO-3
3	Loss of containment in the section between valves CO-1 and PI-1
4	Loss of containment in the section between valves CO-3 and PI-2
5	Spurious closure of valve PI-3
6	Spurious closing of Valves (PI-1 and PI-2) or (CO-1 and CO-3) or (PI-1 and CO-3) or (PI-2 and CO-1)
7	Pipe plugging in the section between valves PI-3 and CO-1 and CO-3

We take as an example the first initiating event of Table 1 for which 6 barriers were identified. The development of an event tree was performed by considering that each of these barriers could succeed or fail. Table 2 displays the identified barriers.

The development of the event tree for this initiating event starts by considering the first of the barriers. If the control system closes, the consequences are negligible. If this first barrier fails, the second one is considered, and so on. It is necessary to consider the possible consequences for each accident sequence defined. Table 3 summarizes these consequences.

With the help of Tables 1 – 3, it is possible to develop the event tree for the first initiating event. Figure 6 displays the event tree.

Sequence # 1 produces negligible effects. The failure of each barrier turns it necessary to check for the next one available until the extreme case for which the control system does not operate. This is the highest consequence sequence identified.

Table 2. Identified barriers for initiating event # 1

#	Description
1	Control system operates
2	Valve PI-3 closes
3	Valves PI-1 and PI-2 close
4	Valves CO-1 and CO-3 close
5	Valves PI-1 and CO-3 close
6	Valves PI-2 and CO-1 close

Table 3. Definition of consequences

#	Environmental	Assets	Personnel
D_1	NL	NLP	N
D_2	ML	MLP	N
D_3	AL	ALP	N
D_4	CiL	CiLP	N
D_5	CiL	CiLP	N
D_6	CaL	CaLP	N
D_7	CaL	CaLP	N

NL = Negligible leakage; ML = Marginal leakage; AL = Average leakage; CiL = Critical leakage; CaL = Catastrophic leakage; NLP = Negligible loss of production; MLP = Marginal loss of production; CiLP = Critical loss of production; CaLP = Catastrophic loss of production; N = Negligible

Regarding personnel consequences, they were identified as negligible because one has an offshore and subsea facility. This means that the social risk is negligible because individuals of the public are not exposed. On the other hand, occupational risk could be considered but risk analyses do not normally consider these risks.

The distinction between environmental and asset risks is performed in the event trees (Fig. 6). For each sequence a damage level is defined (D_i) and for each of these levels environmental, asset and human damages are defined also (this step is not shown in Fig 3 due to space limitations). Table 3 displays this classification.

A similar reasoning is applied to the remaining 6 initiating events of Table 1.

The next step in the analysis is the identification of initiating events for which no barriers are available, Table 4.

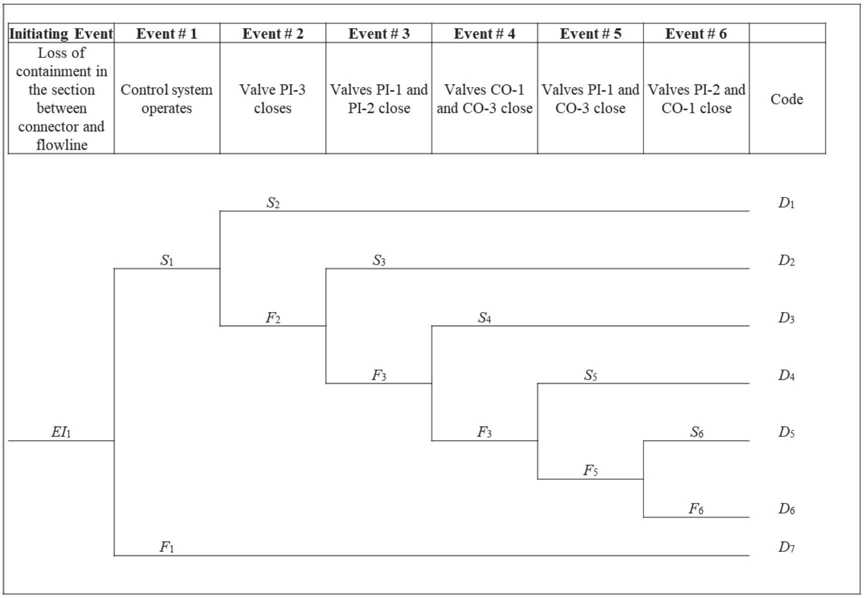

Fig. 6. Event tree for the first in initiating event of Table 1

Table 4. Initiating events without barriers

#	Description
8	Loss of containment in pipelines before valves
9	Loss of containment in at least one valve
10	Loss of insulation at manifold input connectors
11	Loss of containment in ducts prior to manifold inlet connectors
12	Structural deficiency in the manifold Protective Structure

Next, the TLM is developed by considering the 12 initiating events described earlier.

Initially, it is necessary to construct the TLM for each initiating event. For example, for the first IE of Table 1, there is a fault tree with top event "Risk for IE # 1", an OR gate under it with 12 branches, for all 12 IEs. For risk calculations, it is necessary to develop a branch for each IE considering its frequency and also its consequences because risk is the product of both. From Figure 3, it can be seen that the first branch considers the occurrence of the IE together with the successful operation of the control system and the closure of valve PI-3, and so on. Each of these branches is developed according to the available information.

Next, the complete TLM is developed for all initiating events. The initial development of this model is shown in Figure 7. Not all initiating events for which there were no available barriers are represented in this figure due to space limitations. AE in Figure 4 means Event Tree: AE N01 means Event Tree # 01.

The top event of the TLM in Figure 7 is related to the subsea manifold. All initiating events for which event trees were developed are considered (Table 1) besides those for which no barriers were identified. The complete development of this model is quite cumbersome because the number of events to be handled can reach the hundreds. Each branch under the top event in the TLM of Fig. 7 is related to each of the ETs whose initiating events are displayed in Table 1. The logic gate under the TLM top event is an OR gate because risks are additive. For each event tree considered (as AE N01) a new OR gate is added for considering the contributions of all tree damage sequences (see Fig. 6).

Once the TLM is developed for all IEs (with consequences), the next step is risk quantification. Failure data used is from OREDA (2015) as there is no available data bank on deep water equipment.

Fig. 7. TLM for the subsea manifold

5. Conclusions

The steps for developing a TLM for a manifold were discussed in a qualitative fashion. The details on the development were stressed and eventual difficulties for obtaining risk indices for optimization purposes were stated. The use of TLM allows for considering different system configurations (by turning on or off tree branches) and also by allowing for modifying quantitative data. The quantification processes will be pursued based on the findings shown in this article.

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