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# Using TLM To Calculate Risk Of Wet Christmas Tree

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**Abstract**

Offshore facilities spend millions annually trying to ensure the integrity of their equipment. The challenge is determining where to apply the industry's always finite and limited resources to provide the greatest benefit. Risk-based inspection was developed in the petroleum industry to assist in identifying the highest risk equipment and to design an inspection program that not only identifies the most relevant failure modes, but also promotes activities that reduce their chances of occurrence. This paper is part of a project developed by LABRISCO/USP (Risk Analysis, Assessment and Management Laboratory of the University of São Paulo), which aims to develop a methodology for monitoring the integrity of equipment, optimizing inspection policies, based on the risk associated with the operation of subsea equipment in the oil and gas industry. The present paper describes, in a simplified way, the use of the TLM (Top Logic Model - equivalent fault tree) for risk calculation, which is generally applied in Risk Monitors in nuclear plants. The results include the study of a Wet Christmas Tree reference model, the evaluation of its FMECA and construction of the TLM through fault and event trees considering the production stoppage the event of interest, which can generate great economic impact for industries. These results contribute to more effective risk analyzes in the offshore industry, since data on this equipment is scarce in the literature. Furthermore, the main objective of this study is to contribute to the optimization of inspection plans proposing an efficient method to calculate the risk of the systems considered.

*Keywords*: Christmas Tree, Top Logic Model, TLM, risk monitor

## 1. Introduction

Offshore installations, both surface and underwater, refineries, petrochemical plants and others, spend millions of dollars annually trying to guarantee the integrity of their equipment. The challenge lies in determining where to apply the industry's always finite and limited resources to provide the greatest benefit. Therefore, it is vitally important for the oil sector (especially offshore production) to make an efficient choice regarding the application of resources, to keep the sector competitive and meeting satisfactory levels of safety.

Furthermore, it is important to highlight that in this type of industry, reliability and operational time are critical, since any interruption becomes extremely costly economically, as it not only affects production, but also generates high fines and fees for the operator. Therefore, maximizing operational availability should be a key concern (Rodrigues, 2019). In other words, it is important to understand events that can cause possible production stops, as the industry needs to invest in operational safety, in order to mitigate possible failures that could impact the environment, it also needs to worry about its profits (the higher the profit , the greater the capital available to invest), and events such as production stoppages cause a major financial impact.

Considering all the dangers that the offshore industry can bring, several approaches have been employed to manage offshore safety, which mainly consider organizational and human factors, safety culture and a risk-based approach. The latter was developed in the petroleum industry to assist in identifying the equipment at greatest risk (considering the respective failure modes) and to design an inspection program that not only identifies the most relevant failure modes, but also allows actions to be taken accordingly to mitigate the occurrence of failure modes (Zhaoyang et al., 2011).

Therefore, the present paper aims to calculate the risk of a reference model of the deepwater Wet Christmas Tree System (XT) focusing on the events that lead to a production stoppage. The proposal for calculating the risk is based on the simplified application of a TLM (Top Logic Model), a technique currently applied in nuclear plants, in which the risk is monitored in real time taking as reference the specific risk and the accumulated risk over a period interest, with risk monitors that allow the risk to be updated very quickly.

The risk monitor is an application of the PSA (Probabilistic Safety Assessment) methodology (Wang et al., 2015), which is one of the most useful methods of nuclear safety analysis and has been widely used to determine instantaneous risk based in the actual nuclear power plant configuration (Kafta, 1997). As the main method of PSA and risk monitor is a combination of Event Trees (ET) and Fault Trees (FTs) (OECD, 1975). FTA is commonly used for complex system safety and reliability analyses, including determining minimum cut sets (MCSs), key event probability, and component importance. However, the instantaneous risk model is generally very large and complex, difficult to be calculated and analyzed manually. 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 (normally within 1 or 2 minutes). Traditionally, it is not possible to perform this type of feat using a logical model based exclusively on Event Trees and Fault Trees, which make up PSA, for example. Therefore, the TLM, was used to reduce solution time, the model uses a fault tree that is logically equivalent to the set of fault trees and events trees. Furthermore, TLM, unlike PSA, makes it possible to activate or deactivate parts of the fault tree, with a view to representing the current state of the plant (Shepherd et al., 2004). 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 which will be described in the next sections of this article.

It is worth mentioning that this study has been prepared within the scope of a research project developed and carried out by members of the Risk Analysis Laboratory (***LabRisco***) – University of São Paulo (USP), whose general objective is to develop a methodology for monitoring integrity, optimizing the use of inspection, monitoring, testing techniques and their respective frequencies based on the risk associated with the operation of subsea oil and gas equipment.

## 2. Methodology for calculating risk using TLM

Initially, it is necessary to understand the plant where the system under consideration is located, including a description of the environment and operational procedures. It is also important to collect all information pertinent to the equipment under study, such as gathering associated performance information, as well as the hazard events to be considered in the risk calculation (using techniques such as APP – Preliminary Hazard Analysis – or HAZOP – Hazard and Operability Studies) and inspection methods for the equipment considered. Once the hazard events of interest have been selected, the construction of the probabilistic model in event trees and fault trees begins with a focus on quantifying the risk. The trees are quantified based on equipment performance data collected. The practices mentioned so far are usually applied in the offshore industry and for simplification, one of the main tools for risk analysis, FMECA (Failure Modes, Effects, and Criticality Analysis) – which is a natural evolution of APP or HAZOP – was used for most of the database to elaborate de events and fault trees.

Then it is possible to prepare the TLM, in which the event tree and fault tree models are converted to the TLM, through the grouping of basic events that are jointly affected by the interventions in relation to the inspection plans, so that changes to the plan have effect on the correct set of equipment. It is important to mention that a TLM can be developed for each risk dimension studied (such as personal, environmental or property), or, once there are risk equivalence relationships between dimensions, a single TLM can be constructed to the global risk calculation. In this situation, the TLM composes all event and failure trees, thus, in addition to considering the frequencies associated with the possible states of the plant, it considers the possible consequences of each state in each risk dimension (Shepherd et al., 2004).

The next sessions describe the steps to reach the TLM and the risk calculation. These steps involve studying the configuration of the system and associated equipment (in this case, the XT system), collecting all information pertinent to the equipment, such as, for example, description of the equipment itself and its operational procedures, survey of standards applicable to their installation, operation and maintenance, and the collection of performance information associated with these systems and equipment (preparation of the FMECA). There is also a survey of hazard events to be considered in the risk calculation, studying their causes, consequences, and classifications according to the risk acceptance criteria. Once the hazard events relevant to the risk are selected, the construction of the probabilistic model into an event tree and failure tree begins, focusing on risk quantification, and finally, the event and failure trees are converted in TLM.

### 2.1. Wet Christmas Tree (XT)

The Christmas Tree (XT) is one of the most important equipment for oil extraction and is designed to withstand high pressures and a wide range of operating and ambient temperatures. The XT is used in the well production phase, located at the wellhead, and is composed of valve systems and accessories that guarantee control of the entire operation (Santos, 2017). It is an intelligent set composed of valves that are operated remotely or hydraulically, with the function of controlling the flow of fluids produced or injected into the well (Petrobras, 2015).

To understand the studied system, know its equipment and components, a reference model of a deep water vertical XT (about 1,400m) was created according to the model presented at OREDA (SINTEF, 2015a, 2015b), literature searches and expert validation – which is more detailed in previous works (Moura et al., 2022). For this study, it is worth reviewing the structure and equipment considered, as well as their respective components. This model and the limit of the scope worked (subsea – submarine equipment) are demonstrated in the diagram in Figure 1 below.

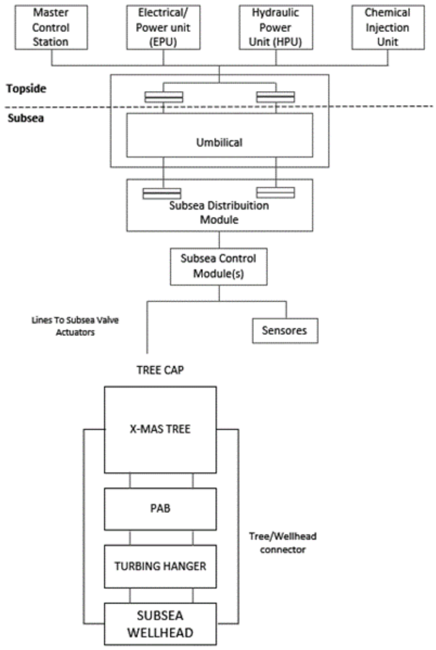


Figure 1. XT Reference model (Moura et al., 2022)

The XT deepwater system is complex, in terms of the number of components and associated failure modes, in the reference model used there are 11 pieces of equipment and 82 components. The main valves, such as Swab (responsible for ensuring vertical access to the well), Master (responsible for the entire flow of fluid that comes from the well) and Wings (known as production choke, in this case, one of the wings is used to control and isolate production and the other, located on the opposite side, is responsible for the service line) are in the XT equipment, in accordance with the concepts presented in the Oilfield Glossary (Schlumberger Oilfield Glossary, 2016). But there are important valves for the functioning of the system in BAP equipment as well, such as the Manual Gate Valve (Seal Test VGX). The Control System also houses very relevant components, given the nature of this system, such as existing sensors, which are very important for detecting the expected or unexpected (and unwanted) functioning of the entire XT system.

## 2.2. Input data

As previously mentioned, a large part of the database was consolidated into a FMECA spreadsheet, such as the list of equipment; function of each equipment and associated components; failure modes and causes of each component; phase of the mission or operational mode in which the failure occurs, local effect of the failures (involving the item's own functions), the effects on the next level (considering items that are part of the same group as the item under analysis) and the final effects (for the operation as a whole); fault detection method; compensation measures to overcome the effects of failures; severity class assigned to each failure mode; probability of failure associated with the occurrence of the failure mode; probability of the effect of the failure (conditional probability relating to the chance of the consequence being that predicted in the "severity class"); failure mode fraction (fraction of the item's failure rate that is associated with the failure mode under analysis); failure rates (in this study the data were taken from OREDA - but cannot be directly reproduced here for copyright reasons); and operating time.

In this study, each of this information was filled in according to the failure modes of each of the 82 components mentioned previously. Table 1 shows a partial view of the FMECA built with the main information used for the simplified TLM, such as equipment, component, severity class, failure mode, causes, associated effects, probability of not detecting the failure mode (for this article an approximation was used, it is foreseen in the scope of the project to update these numbers) and the probability of fail mode.

Table 1. Main data form FMECA considered to evaluate the TLM.

| Equipment | Component | Severity Class | Fail mode | Causes | Local effects (equipment) | Final effects (system) | Probability of non-detection | Probability of failure |
|---|---|---|---|---|---|---|---|---|
| Christmas Tree (XT) | W2 (Wing 2) | Catastrophic (V) | External leakage - process medium - ELP | Leakage through the seal; external impact; material failure | Hydrocarbon leak into the sea | Production stoppage and leakage of hydrocarbons into the sea | 5,0E-01 | 2,1E-03 |
| Christmas Tree (XT) | W1 (Wing 1) | Catastrophic (V) | External leakage - process medium - ELP | Leakage through the seal; external impact; material failure | Hydrocarbon leak into the sea | Production stoppage and leakage of hydrocarbons into the sea | 1,0E-01 | 2,1E-03 |
| Christmas Tree (XT) | S2 (Swab 2) | Catastrophic (V) | Fail to close on demand - FCD | Blocked by waste; stuck valve; hydrate formation | Unable to stop hydrocarbon flow | Loss of a barrier to flow | 8,0E-01 | 1,6E-03 |
| Christmas Tree (XT) | S2 (Swab 2) | Medium (III) | External leakage - utility medium - ELU | Sealing failure; valve corrosion; wear; material failure | Can't stop the flow | Possible hydrocarbon leak into the sea | 8,0E-01 | 2,6E-04 |
| Christmas Tree (XT) | S1 (Swab 1) | Catastrophic (V) | Fail to close on demand - FCD | Blocked by waste; stuck valve; hydrate formation | Unable to stop hydrocarbon flow | Loss of a barrier to flow | 8,0E-01 | 1,6E-03 |
| Christmas Tree (XT) | S1 (Swab 1) | Critical (IV) | Leakage in close position - LCP | Sealing failure; valve corrosion; wear; material failure | Can't stop the flow | Possible hydrocarbon leak into the sea | 8,0E-01 | 6,0E-03 |
| Christmas Tree (XT) | M2 (Master 2) | Catastrophic (V) | External leakage - utility medium - ELU | Leakage through the seal; external impact; material failure | Hydrocarbon leak into the sea | Production stoppage and leakage of hydrocarbons into the sea | 5,0E-01 | 7,9E-04 |

| Equipment | Component | Severity Class | Fail mode | Causes | Local effects (equipment) | Final effects (system) | Probability of non-detection | Probability of failure |
|---|---|---|---|---|---|---|---|---|
| Christmas Tree (XT) | M1 (Master 1) | Catastrophic (V) | External leakage - utility medium - ELU | Leakage through the seal; external impact; material failure | Hydrocarbon leak into the sea | Production stoppage and leakage of hydrocarbons into the sea | 1,0E-01 | 7,9E-04 |
| Christmas Tree (XT) | W2 (Wing 2) | Medium (III) | Control/Signal failure - SIG | Blocked by waste; electrical failure | Unable to stop hydrocarbon flow | It is possible to interrupt the flow using upstream (DHSV) and downstream (M1) valves | 8,0E-01 | 2,6E-03 |
| Christmas Tree (XT) | W1 (Wing 1) | Medium (III) | Control/Signal failure - SIG | Blocked by waste; electrical failure | Unable to stop hydrocarbon flow | It is possible to interrupt the flow using upstream (DHSV) and downstream (M1) valves | 8,0E-01 | 2,6E-03 |
| Christmas Tree (XT) | M2 (Master 2) | Medium (III) | Fail to function on demand - FTF | Blocked by waste; stuck valve; hydrate formation | Unable to stop hydrocarbon flow | It is possible to interrupt the flow using upstream (DHSV) and downstream (W1) valves | 8,0E-01 | 1,5E-02 |
| Christmas Tree (XT) | M1 (Master 1) | Marginal (II) | Fail to function on demand - FTF | Blocked by waste; stuck valve; hydrate formation | Unable to stop hydrocarbon flow | It is possible to interrupt the flow using upstream (DHSV) and downstream (W1) valves | 8,0E-01 | 1,5E-02 |

In addition to the information mentioned, for the TLM, redundancies in relation to components and two main sets of risk were considered: production stoppage (material risk) and external leakage (environmental risk), separating the failure modes according to the risk sets and their respective consequences (and severities). For this paper the focus will be on production stoppage, that is, material risk, and Table 2 shows the associated consequences according to the severities. It is important to mention that this article focuses on evaluating the potential benefits of TLM for this type of study, the complete analysis of this system is still under development and will include all hazard events mapped for the operation of this system.

Table 2. Consequences by severity – Production stop

| Risk set | Consequence | Severity class |
|---|---|---|
| Production stop | $t \geq 7$ days | Catastrophic (V) |
| Production stop | 3 days $\leq t < 7$ days | Critical (IV) |
| Production stop | 1 day $\leq t < 3$ days | Medium (III) |
| Production stop | 6h $\leq t < 1$ day | Marginal (II) |
| Production stop | $t < 6$h | Negligible (I) |

Table 2 it is possible to note the consequences for each severity of the failure mode, therefore, the catastrophic severity results from more than seven days of production stoppage, the critical one from three to seven days, the average from one to three days, marginal from six hours to a day and the negligible amount of less than six production stops.

### 2.3. Top Logic Model (TLM)

As mentioned previously, for risk analysis and assessment, a risk model of the problem under analysis must be developed, which allows the quantification of frequencies and associated consequences. In general, this model applies the Fault Tree and Event Tree techniques (Martins, 2013). Concerning to the TLM use, as an example, the TLM is created by aggregating each accidental sequence into a model like a fault tree, where each possible sequence makes up a branch combined with its respective damage by an “AND” gate. Thus, in TLM the risk is calculated by the sum of the frequencies “F” expected for damages multiplied by the respective consequences “C”. Thus, the possible damage “D” is associated with a risk portion $R_i$, as shown in (1).

$$R_i = F(D_i) * C(D_i) \tag{1}$$

Figure 2 shows an example of the simplified TLM elaborated, where the risk is composed by the environmental risk (in this case associated to an oil leak – which will not be explored in this paper due to space restrictions) and the material risk (in this case, associated to a production stoppage), being the latter is the focus of this paper. At the next level of the tree, there is the associated risk portion, in this section, the catastrophic risk portion, at the next level there is the frequency of events that cause a catastrophic production shutdown linked by gate “AND” to the consequence of these events (production stop for more than seven days – see Table 2). At the level below frequency there are events associated with XT System equipment, components, and their respective failure modes (basic events), the latter associated with their respective failures rates.

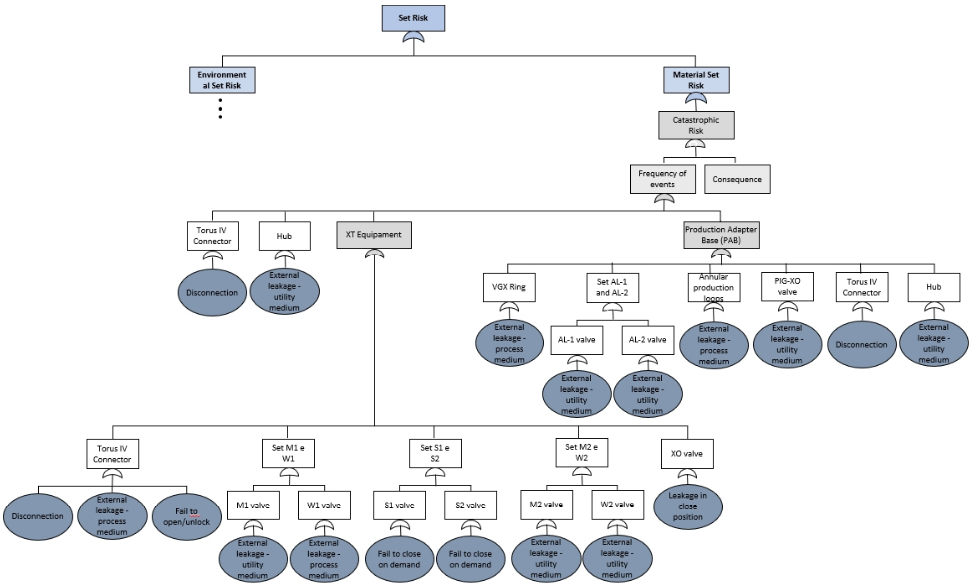


Figure 2. Part of the Simplified TLM developed.

It is worth note that, at this stage, only events associated to production stoppage were considered in the analysis, in other words, just a portion of the material risk was taken into account. This paper focuses on evaluating the potential benefits of TLM for this type of study, the complete analysis of this system is still under development and will include all hazard events mapped for the operation of this system. Table 2 shows the associated consequences according to the severities.

Solving the TLM occurs in a similar way to solving a FT (Shepherd et al., 2004). In this way, risk quantification (“event” at the top of the TLM) is done through sequences equivalent to the minimum cut sets of FTs.

To use TLM in the process of optimizing inspection plans, the effects of variations in these plans on the failure (and success) events present in the model must be considered. Therefore, it is necessary to prepare the TLM with this application in mind. An example of essential preparation for this study is the consideration in the model of the possible effects of inspection methods on basic events and their consequences. One way to prepare the model to consider these possible effects is to add an event related to the inspection method to the TLM for each basic event. This event can, for example, be used to consider the probability of not detecting the failure during the inspection, not preventing its consequences (once failures or degradations are identified, it is assumed that the component is repaired to “as good as new” condition). Therefore, **Błąd! Nie można odnaleźć źródła**

**odwołania.** shows a small example of how detection (inspection) methods were considered in the TLM of this study (see the basic events “Detection methods” in light blue in Figure 3). Some of the inspection methods that can be used to detect degradations and failures considered: visual inspection, magnetic particles, acoustic emission, ultrasound, functional test of valves, measurement of electrochemical potential and tightness test. Sets of inspection methods were also considered, such as visual inspection and electrochemical potential measurement applied simultaneously.

In future work will be used events in the TLM that allow the activation and deactivation of parts of the model, known as house events in FTs. Thus, for example, if a maintenance event leaves part of the modeled systems and equipment unavailable (for example, a security system that is being tested), the risk can be calculated

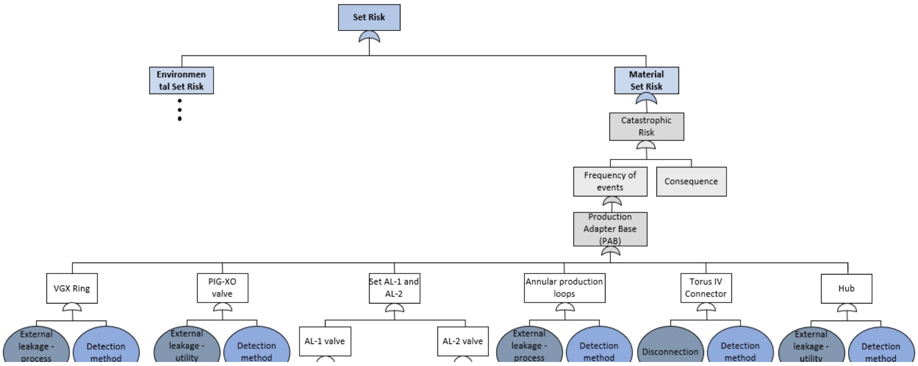


Figure 3. Part of TLM simplified with detection methods.

considering this scenario.

The TLM model carried out for all components of the XT described was created in the CAFTA software (Polestar, 2020). CAFTA is designed to meet the many needs of reliability analysts when performing fault tree/event tree analysis on a system or group of systems. Table 4 shows part of the cut sets defined from CAFTA considering catastrophic events (due to limited space for the paper, just a set of cut sets are represented here). Cut sets are a minimum combination of failures necessary to result in the occurrence of the event of interest (top of the tree event – in this case, production stoppage).

Table 4. CAFTA result

| Frequency | Consequence | Failure mode | Detection methods |
|---|---|---|---|
| 1,30E-02 | ANMPS-001-C-005 | ANMPS-001-EB-065 | ANMPS-001-MI-065 |
| 1,27E-02 | ANMPS-001-C-005 | ANMPS-001-EB-138 | ANMPS-001-MI-138 |
| 4,61E-03 | ANMPS-001-C-005 | ANMPS-001-EB-039 | ANMPS-001-MI-039 |
| 4,61E-03 | ANMPS-001-C-005 | ANMPS-001-EB-047 | ANMPS-001-MI-047 |
| 2,88E-03 | ANMPS-001-C-005 | ANMPS-001-EB-048 | ANMPS-001-MI-048 |
| 2,59E-03 | ANMPS-001-C-005 | ANMPS-001-EB-046 | ANMPS-001-MI-046 |
| 1,44E-03 | ANMPS-001-C-005 | ANMPS-001-EB-051 | ANMPS-001-MI-051 |
| 1,31E-03 | ANMPS-001-C-005 | ANMPS-001-EB-049 | ANMPS-001-MI-049 |
| 4,98E-04 | ANMPS-001-C-005 | ANMPS-001-EB-063 | ANMPS-001-MI-063 |
| 1,84E-04 | ANMPS-001-C-005 | ANMPS-001-EB-045 | ANMPS-001-MI-045 |
| 1,84E-04 | ANMPS-001-C-005 | ANMPS-001-EB-062 | ANMPS-001-MI-062 |
| 1,05E-04 | ANMPS-001-C-005 | ANMPS-001-EB-050 | ANMPS-001-MI-050 |
| 5,25E-05 | ANMPS-001-C-005 | ANMPS-001-EB-064 | ANMPS-001-MI-064 |

In the table above the “frequency” column shows the frequency data calculated by CAFTA, the consequence column refers, for this list, to the catastrophic consequence, failure mode are the basic events (e.g. ANMPS-001-EB-039 refers to External leakage - utility medium of the Al-2 valve of the BAP equipment). The detection methods column deals with events related to failure detection by the inspection method, for example, ANMPS-001-MI-039 refers to the detection method for the failure mode in question, which in this case would be the combination visual inspection and electrochemical potential measurement. Therefore, the combination of these two events: failure mode occurring and detection method not detecting the failure, results in the catastrophic consequence of a production stoppage.

Considering the consequences mentioned in Table 2, and generic values for the quantity of barrels produced per day by an ANM System of 150,000 and the barrel of oil $76.86 (USD), it was possible to calculate the financial risk of production stoppage according to the severities and (1), as shown in Table 5.

Table 5. Financial Risk.

| CAFTA | | Data base | | Stop time (days) | | Risk ($USD/day) | |
|---|---|---|---|---|---|---|---|
| Consequence | Frequency | Severity class | Consequence (stopped time) | Interval min. | Interval max. | Minimum | Maximum |
| ANMPS-001-C-005 | 4,42E-02 | Catastrophic (V) | $t \geq 7$ days | 7 | - | 0,00 | 3.564.126,94 |
| ANMPS-001-C-008 | 8,77E-02 | Critical (IV) | 3 dias $\leq t < 7$ days | 3 | 7 | 3.034.490,45 | 7.080.477,71 |
| ANMPS-001-C-006 | 1,43E-02 | Medium (III) | 1 dias $\leq t < 3$ days | 1 | 3 | 165.406,56 | 496.219,69 |
| ANMPS-001-C-007 | 7,04E-02 | Marginal (II) | 6h $\leq t < 1$ day | 0,25 | 1 | 202.939,22 | 811.756,89 |
| ANMPS-001-C-009 | 6,56E-03 | Negligible (I) | $t <$ 6h | 0,25 | - | 0,00 | 18.907,56 |

As you can see, in this case, the greatest risk (associated cost) is that of critical severity when it is considered the maximum associated risk, due to the higher frequency the maximum risk is even greater than the catastrophic severity.

## Conclusions

During the development of this paper, it was possible to note that the combination of the tools applied (FMECA, fault tree, event tree – TLM) can be very effective in providing innovative information for decision-making about the performance of the risk system.

According to the results obtained for this article, it is possible to note that the technique is efficient for calculating risk, where for the case study of the Wet Christmas Tree System, for the top production stop event, the severity of greatest financial risk was critical, which represents an interval of three to seven days of production stoppage. Therefore, with the database, it is possible to know which equipment, components, failure modes and respective detection methods are associated with critical severity for prioritizing mitigation measures.

Regarding the application of the TLM, it is possible to conclude that it is convenient due to the short time required to calculate the probability of the top event of interest and its effectiveness in probabilistic calculation. Currently a computational tool is under development in LABRISCO/USP (Risk Analysis, Assessment and Management Laboratory of the University of São Paulo) to generate TLMs and provide the results in an adequate format to the optimization process. In future work the computational tool developed to optimize the inspections plans will be combined with the computational tool under development to generate TLMs.


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