Use of Bayesian Network to Support Risk-Based Analysis of LNG Carrier Loading Operation

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Abstract: This paper presents a methodology for risk analysis of LNG carriers operations aiming at defining the most critical pieces of equipments as for avoiding LNG leakage during loading and unloading operations. The pieces of equipment considered critical for loading and unloading operations are identified and the Cause-Consequence diagram is built. The probability of occurrence of each event listed in the diagram is calculated based on Bayesian network method. The consequences associated with those scenarios are estimated based on literature review. Based on the calculated risk profile some maintenance and operational recommendations are presented aiming at reducing the probability of occurrence of the critical failure scenarios.

Keywords: LNG, Cause-Consequence diagram, Risk analysis, Bayesian networks.

1. INTRODUCTION

The increasing worldwide demand for Liquefied Natural Gas (LNG) has corroborated its importance as a component of the world's supply of energy. Once the great consumers (concentrated in Asia, Europe and North America) of natural gas are not the great worldwide producers (concentrated in the Middle East, Africa and Central America) the need for transportation of that hydrocarbon has still increased [1].

Natural gas can be transported in its liquid form by large LNG carriers between liquefaction plants at exporting countries (where LNG is loaded into the tank ship) and regasification plants at importing countries (where LNG is unloaded from the tank ship).

As well as any other industrial activity, the natural gas industry is not free from accidents, which can cause serious consequences to the integrity of people and properties. For this reason, it is necessary to develop studies to determine what are the possible causes and scenarios of these faults specifically in the area of LNG transportation [2].

Considering the high quantity of equipments involved in the LNG carriers loading and unloading operations and also the large volume of flammable liquid that is transferred during these proceedings, the use of risk analysis techniques available in the literature are recommended to avoid accidents during such procedures.

Based on the Formal Safety Assessment (FSA) guidelines proposed for petroleum industry [3], this paper presents a risk-based method to analyze the failure scenarios and associated consequences that may happen during the cargo handling operation of a LNG carrier. The paper determines the possible leakage causes and classifies their consequences. The risk involved in loading and unloading operations is described considering the probability of occurrence of each failure mode and the consequences of the leakage based on a risk matrix method. Recommendations to avoid the occurrence of LNG leakage are discussed.

2. METHODOLOGY

The method used for LNG carrier operation analysis is a risk-based approach based on Formal Safety Assessment (FSA) guidelines proposed for petroleum industry [3]. The first step is to identify and to select the pieces of equipment and components which are part of the loading and unloading system.

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The functional tree is developed to explain the functional relation between the pieces of equipment aiming at the reliable operation of the system.

The second step is called hazard identification, which applies the Preliminary Hazard Analysis, and is used to identify the hazards associated with loading and unloading operations, related to the failure of pieces of equipment. The Cause-Consequence Diagram is used to identify the failure scenarios associated with a given hazard occurrence and the control and alarm systems used as barriers to avoid failure propagation. The probability of each of the events listed in the cause-consequence diagram is calculated based on Bayesian network method. That method is an alternative for the use of Fault Tree Analysis to define the probability of occurrence of a specific event.

The third step is the development of the risk analysis in order to obtain a quantitative value of risk which allows the classification of the risk associated with a given hazard as low, acceptable and unacceptable, in accordance with a risk matrix. Finally, the recommendations to reduce the occurrence of the events that may cause a given failure scenario can be proposed. In Figure 1 a flowchart is used to illustrate each step of the proposed method.

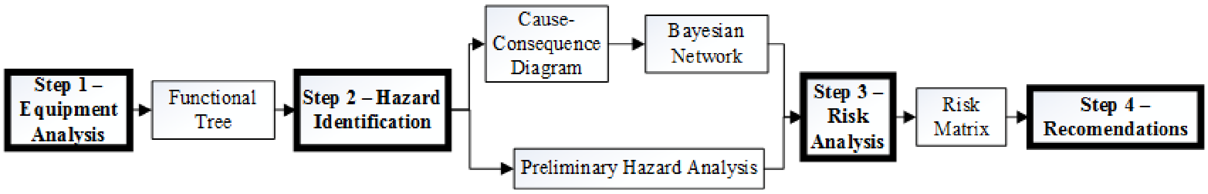


Figure 1 - Flowchart of the Proposed Method

3. APPLICATION OF THE METHOD

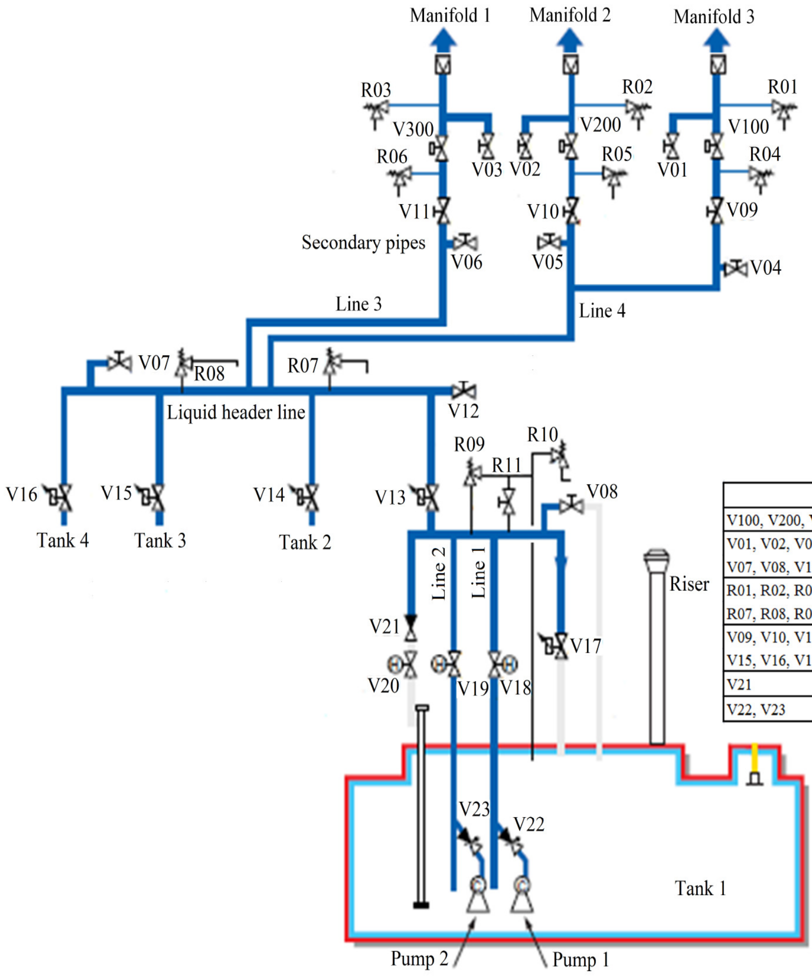
The present study analyzes the loading and unloading operations of a Mark III LNG carrier with four storage tanks and cargo capacity of 138,000 m3. The loading and unloading system is composed by subsystems, as for example: pumping, storage, distribution, relief system and the manifold. The main components used in the cargo handling system are shown in Fig 2.

During loading operation, LNG is loaded through the manifold and it is carried through two secondary pipelines to the liquid header line, which distributes it to each tank. Loading is completed when all tanks are loaded with 98,5% of its full capacity. After that, LNG is drained from the valves and pipelines and sent to a cargo tank, avoiding the presence of methane in the inactive lines.

The LNG is unloaded with the use of one main cargo pump for each tank which is submerged inside the respective tank. The main cargo pumps discharge the LNG to the main liquid header and then this fluid is transferred to the terminal through the manifold connections. Each tank is not fully discharged leaving a volume of LNG corresponding to a level of about 0,1m. On completion of discharge, the loading arms and pipelines are purged and drained into one cargo tank and the loading arms are then also disconnected

The loading and unloading system has a liquid header line that have two relief valves which function is to transfer the LNG relief to the cargo tanks when the liquid pressure is higher than 10 bar (relief valves set-up pressure). Usually, the pressure inside the pipelines is 1 bar. In the loading and unloading piping system are installed relief valves to avoid the raise in liquid pressure.

The storage system consists of four insulated cargo tanks, separated from each other by transverse cofferdams, and from the outer hull of the vessel by wing and double bottom ballast tanks. The insulation covers the entire primary barrier which purpose is to maintain the cryogenic temperature and to prevent the generation of the boil-off gas. According to [3], the LNG carriers have a secondary barrier that is used to contain the LNG in the case of primary barrier failure and to avoid the contact of the ship's structure with the low temperatures of the cryogenic substance.



Symbol	Component
	Main cargo pump
	Swing check valve
	Globe valves
	Butterfly valves
	Lift check non-return valve
	LNG tank
	Liquid secondary pipeline
	Liquid main pipeline
	Butterfly valve shutdown of ESD
	Safety valve

LEGEND	
V100, V200, V300	Butterfly valves activated by the ESD
V01, V02, V03, V04, V05, V06, V07, V08, V18, V19, V20	Globe Valves
R01, R02, R03, R04, R05, R06, R07, R08, R09, R10, R11	Relief valves
V09, V10, V11, V12, V13, V14, V15, V16, V17	Butterfly valves
V21	Lift check non-return valve
V22, V23	Swing check valves

Figure 2 - LNG Circuit for Loading and Unloading Operations [14]

3.1. Functional Tree

The functional tree (Figure 3) is used to describe a system, determining its functions and the contribution of each of its components to the system performance. The cargo handling system is divided in five subsystems: pumping, storage, distribution, manifold and relief. Those subsystems are divided in components each of one performing a specific function linked with subsystem main function. A failure in a component at the bottom of the tree affects the performance of the subsystem above it, causing a possible interruption in loading or unloading operations, including LNG leakage.

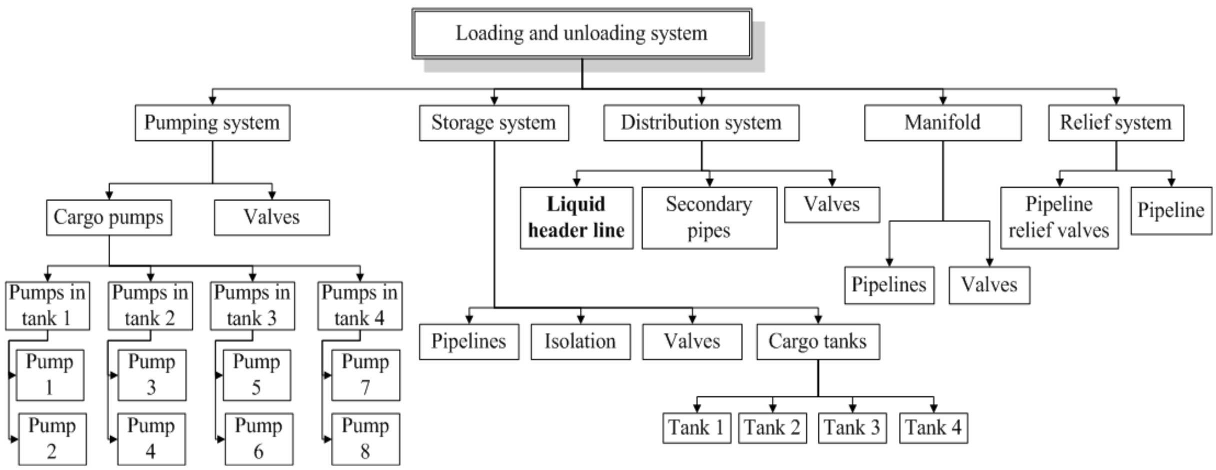


Figure 3 - Functional Tree of the Loading and Unloading System [14]

3.2. Preliminary Hazard Analysis

The Preliminary Hazard Analysis (PHA) is used to identify those accidental events that will be subject to the further risk analysis. The PHA technique was chosen to be applied here because it can be used in any period of the equipment lifecycle, including design and operation.

The present analysis studies the hazard LNG leakage during the loading and unloading operations. The causes of occurrence, consequences and safeguards associated with that hazard are identified and analyzed to develop the PHA table. This analysis is shown in the Table 1. The causes of LNG leakage considered in the PHA associated with the valves are structural deficiency, external leakage (process medium), and valve leakage in closed position. In the case of the cryogenic pumps the failure mode considered in the analysis is fail to stop on demand. In pipelines the main failure modes are presence of a through thickness crack, partial and total pipe cross section rupture.

3.3. Cause-Consequence Analysis

The Cause-Consequence Analysis is used to identify and evaluate the sequence of events that can happen given a initiating event. The analysis aims at determining if the initiating event can induce an accident or if the accident is avoided by the protection barriers of the system. In this paper, the analysis begins with the failure of the components of the cargo handling system and is centered in the occurrence of LNG leakage. Considering LNG leakage in the loading/unloading system, a series of events can happen, as shown in the Cause-Consequence Diagram presented in Figure 4.

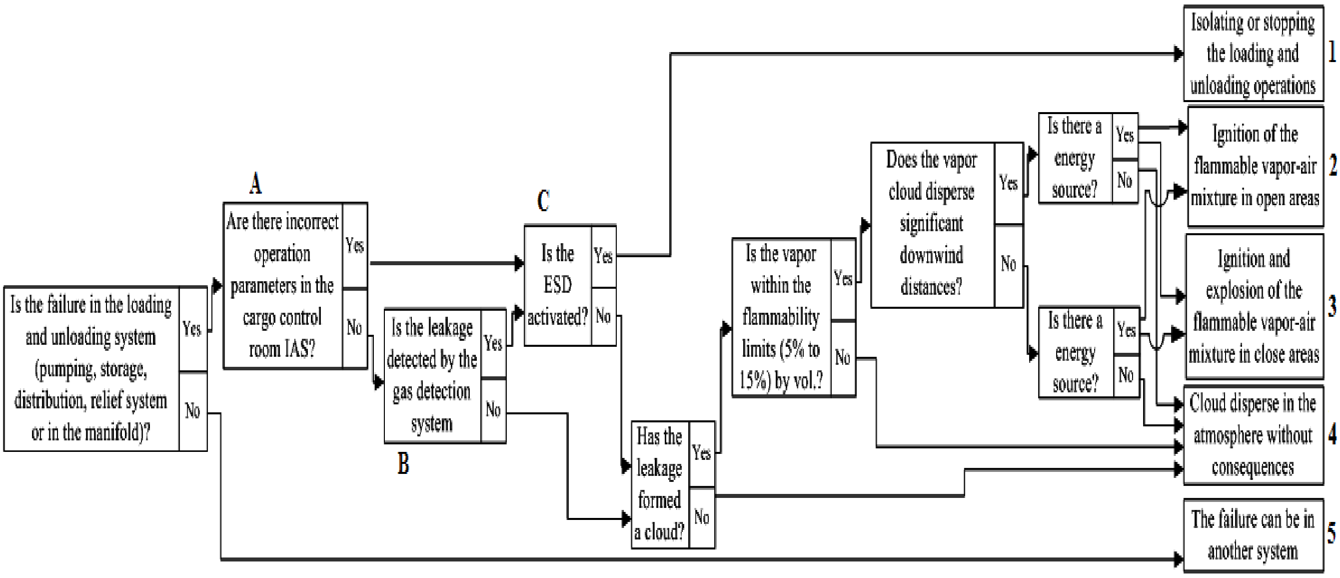


Figure 4 - Cause-Consequence Diagram

The safety barriers are designed to stop the loading/unloading operation and to avoid the continuous LNG leakage. These barriers ideally should not fail because any failure can cause major consequences.

The first barrier is the Cargo Control Room, which remotely controls and monitors the cargo handling operations. All major valves such as the manifold valves, also called ESD Manifold valves, and individual tank loading and discharge valves, are remotely operated from the IAS, so that all normal cargo operations can be carried out from the cargo control room.

The second barrier is the Gas Detection System, which detects the presence of gas, especially in spaces where gas is not normally expected to be presented. Various sensors monitors both hazardous and non-hazardous gas zones. If gas is detected, alarms are activated, indicating the occurrence of a leakage. The entire cargo piping system and cargo tanks are considered gas hazardous zones.

The third barrier is the Emergency Shutdown System (ESD). During the loading and unloading operations in case of LNG leakage, the emergency shutdown (ESD) system can be used to isolate the leaking pipe section and to stop the primary pumps and to close the ESD valves to avoid a large liquid spill. The ESD system is automatically activated in response to hazard detectors (gas and fire detectors), process alarms (pressure loss in pipe) or an operator pushing an ESD button, as defined by [4]. This system acts in response to a liquid release, interrupting the duration of the release and so affecting the consequences associated with that leakage. In case of LNG leakage, the ESD system can automatically isolate the cargo handling system or stop the process by shutting down the primary pumps and/or closing the ship-side valves located in the manifold V100, V200, V300 showed in Figure 2.

The possible scenarios for the LNG leakage are listed in the sequence, according to Figure 4 and described in Table 1.

The first scenario is the failure in the cargo handling system but the IAS works not causing important consequences once the ESD operated. In this case the failed line must be isolated, controlling the leakage, and the operation must be stopped. The second scenario occurs when after the LNG leakage the IAS does not detect the variation of the main process parameters like pressure, temperature, or flow. If a variation of these parameters is not detected by the IAS the ship has a gas detection system which works and consequently the ESD is activated, causing the stop of the loading or unloading operation.

The third scenario takes place if no one of those safety systems activates the ESD. In the place where leakage occurs a pool can be formed with a vapor cloud which concentration can be between the low and upper flammability limit but in the absence of an ignition source the vapor disperse into the atmosphere without causing effects to the ship or to the terminal. The downwind distance that flammable vapors might reach is a function of the volume of LNG spilled, the rate of the spill, and the weather conditions. The last scenario has the same sequence of the third scenario but the difference is that the vapor cloud is ignited by an energy source from the ship or from the terminal. The result is an ignition of the flammable vapor-air mixture in open areas and an ignition with explosion in close areas. The flame will burn back to the vapor source possibly causing a pool fire, according to [5].

3.4. Bayesian Network

According to [6, 7], a Bayesian Network (BN) consists of a directed acyclic graph in which each node is annotated with quantitative probability information. Each node corresponds to a random variable, which may be discrete or continuous. A set of directed links or arrows connects pairs of nodes. If there is an arrow from node X to node Y, X is said to be a parent of Y. To each node Y with parents $X_1, ..., X_n$, a conditional probability table $P(Y|X_1, ..., X_n)$ is attached, quantifying the effect of the parents on the node.

BNs have become a widely used formalism for representing probabilistic systems and have been applied in a variety of areas, especially in Artificial Intelligence. In dependability and risk analysis, however, other techniques, like Fault Tree Analysis (FTA), are yet more employed for evaluations of safety-critical systems. But the modelling flexibility of the BN formalism can accommodate various kinds of statistical dependencies that cannot be included in the FTA, for example, obtaining a more precise result [8].

In this paper, BNs are built to obtain the reliability of the barriers presented in the Cause-Consequence Diagram. Although three barriers are described, only the BN from the ESD system (third barrier), is shown (Figure 5). Databases [9] and [10] are used to define the reliability of the different components of the barriers. Table 2 shows the calculated reliabilities of the barriers, for one year of operation.

Table 1 - Preliminary Hazard Analysis

N°	Hazard	Cause	Consequence	Safeguards
1	LNG leakage	Failure in the connection of the loading arms with the ship's manifold.	Structural damage of the ship's structure due to the LNG leakage. There is the possibility of vapor cloud formation. Stopping the loading or unloading process. Activation of the emergency system.	Drip tray is installed in the manifold areas in order to collect any spillage and drains it overboard. The ship has a monitoring system that monitors and indicates which are the internal conditions of the circuit of LNG and an alarm system that indicates the occurrence of natural gas leakage allowing the interruption of the transfer process.
2		Structural deficiency in the valves.	Structural damage of the ship's structure due to the LNG leakage. There is the possibility of vapor cloud formation. Stopping the loading or unloading process. Activation of the emergency system.	The ship has a monitoring system that monitors and indicates which are the internal conditions of the loading and unloading system and an alarm system that indicates the occurrence of natural gas leakage allowing the interruption of the transfer process.
3		Valve leakage in closed position allowing that LNG can circulate in other systems such as the relief system, the emergency system or the spray system.	Entry of LNG into the spray system. Entry of LNG into the relief system. Stopping LNG transfer process.	There are valves to contain the LNG preventing the flow of LNG to a line where it should not be as for example the emergency pipelines or the pipes that are used for the spray operation. The ship has a monitoring system that monitors and indicates which are the internal conditions of the loading and unloading system and an alarm system that indicates the occurrence of natural gas leakage allowing the interruption of the transfer process.
4		Crack or rupture in the liquid header line, in the secondary pipelines or in the relief pipelines.	Damage in the ship's structure. Possibility of vapor cloud formation . Freezing in the surrounding areas. Possibility of entry of atmospheric air into the LNG system and breaking the inert environment. Stopping the LNG transfer process.	The ship has an emergency system that stops the loading and unloading process in case of a leakage. The ship has a monitoring system that monitors and indicates which are the internal conditions of the loading and unloading system and an alarm system that indicates the occurrence of natural gas leakage allowing the interruption of the transfer process.
5		Crack or rupture in the primary cargo tanks.	Damage in the ship's structure. Possibility of vapor cloud formation. Freezing in the surrounding areas. Possibility of entry of atmospheric air into the LNG system and breaking the inert environment. Stopping the LNG transfer process.	The ship has a monitoring system that monitors and indicates which are the internal conditions of the loading and unloading system and an alarm system that indicates the occurrence of natural gas leakage allowing the interruption of the transfer process. There is a secondary tank that has the function of containment the LNG in case of any leakage from the primary tank. There is an emergency system that stops the loading and unloading process.
6		Failure of the alarm level inside the LNG storage tanks that will cause the overfilling of one or more storage tanks.	Stopping of the loading or unloading transfer process. Damage to the ship's structure. Freezing in the surrounding areas. Possibility of vapor cloud formation.	There are three levels of alarms that paralyze the cargo pumps. The ship has a monitoring system that monitors and indicates which are the internal conditions of the loading and unloading system and an alarm system that indicates the occurrence of the natural gas leakage and allow the suspension of the transfer process.
7		Pressure increase within the loading and unloading system due to high output discharge pressure in the cargo pumps.	Rupture or crack in the LNG circuit due to high pressure inside it. Stopping of the LNG transfer process. Possibility of vapor cloud formation.	The ship has a monitoring system that monitors and indicates which are the internal conditions of the loading and unloading system and an alarm system that indicates the occurrence of the natural gas leakage allow the suspension of the transfer process.

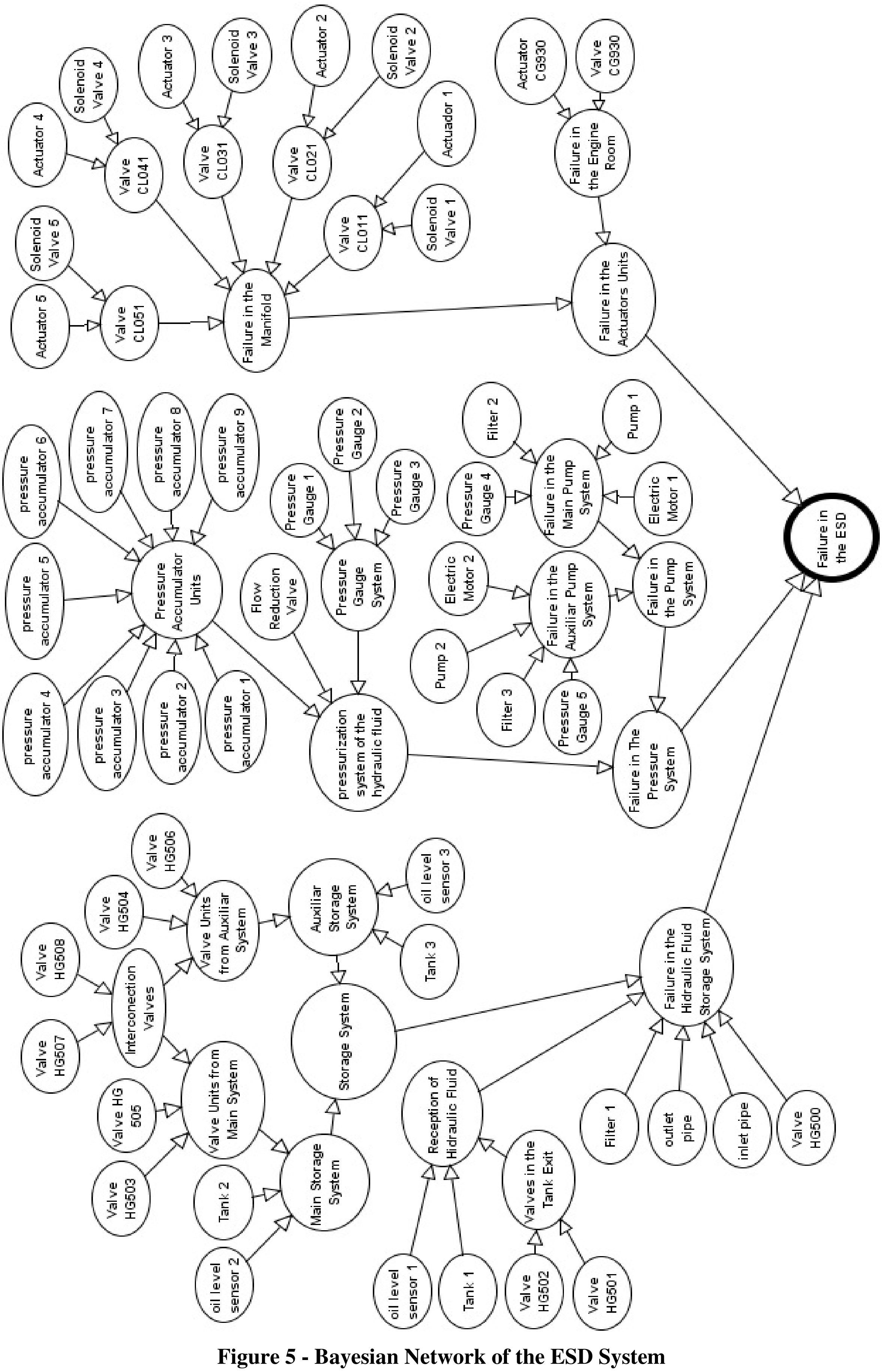


Figure 5 - Bayesian Network of the ESD System

Table 2 - Calculated Reliabilities of the Barriers

Barrier	Reliability (for one year)
Cargo Control Room (CCR)	R = 0,99
Gas Detection System (GDS)	R = 0,93
Emergency Shutdown System (ESD)	R = 0,83

In order to compute the probability of the scenario 1, "Isolating or stopping loading and unloading operations", in the Cause-Consequence Diagram, it is necessary take into account all the possibilities that lead to this scenario given a leakage. In this case, there are two possibilities:

- Cargo Control Room detects a incorrect operational parameter (A) and the ESD is activated (C);
- Cargo Control Room doesn't detect a incorrect operational parameter (A'), the Gas Detection System detects a leakage (B) and the ESD is activated (C).

The probability of occurrence of the first scenario is, then, given by:

$$P(Sc\ 1) = A*C + A'*B*C = 0{,}99*0{,}83 + 0{,}01*0{,}93*0{,}83 = 0{,}829 \quad (1)$$

The high probability of occurrence of the first scenario shows that the three barriers have an important role in preventing accidents given an LNG leakage in the loading/unloading system. The evaluation of the probability of occurrence of scenarios 2 to 5 are not discussed in the present paper once it involves cloud dispersion analysis which is not focus of the paper. Nevertheless, the barriers reliability has influence on those scenarios development. Clearly the loading/unloading operations can be considered safe due to the presence of reliable barriers. The ESD system presents the lowest reliability among the safety barriers once it presents a great number of components that must be working to keep system functionality.

3.5. Risk Analysis

Risk is defined as the evaluation of the probability of occurrence of an event and consequences associated with the occurrence of this event. The risk must be calculated based on the failure analysis of each component that can cause LNG leakage.

To classify the probability of occurrence of an event as well as its consequences, the technical standard N2784, which corresponds to the Petrobrás risk classification [11], is used. The Risk Matrix used is also extracted from [11].

Table 3 shows the frequency categories used in this study. The probability of occurrence is defined by the number of occurrence of an event in one year. To calculate the probability of occurrence, databases [9] and [10] are used to define the failure rate of the different components of the loading and unloading system.

The probability of occurrence of a given number of events in a period of time is determined by the use of the Poisson's distribution, once all components reliability is modeled with exponential distribution. The following equation shows the expression for the calculation of that probability:

$$P(n) = \frac{(\lambda t)^{n} . e^{-\lambda t}}{n!} \quad (2)$$

The number of occurrence for all cases during the operational time is n=1 which represents one event occurrence during that time. The failure rate selected in the databases was the upper value which represents the most conservative approach for this analysis. To allow the frequency category classification according to Table 3, the operational period considered for the analysis is 8760 hours (one year). This period refers to the effective operation of the cargo handling system and not to the calendar year.

Table 4 shows the consequence categories used in this study. The consequence is measured as the impact that the LNG leakage can cause, such as injures of people (crew or third parts) or material damages (in the LNG carriers or in the terminal). The environmental impact is not analyzed in this paper.

Table 5 shows the frequency and consequence categories of certain components. The list of components in Table 5 was extracted from the Preliminary Hazard Analysis (Table 1). The probability of occurrence was calculated using the equation above.

Table 3 - Frequency Categories

Category	Denomination	Range (occurrence/year)	Description
A	Extremely remote	Less than 1 in 10^6 years	Conceptually possible but extremely unlikely to occur during the lifetime of the facility. There is no reference to historical occurrence
B	Remote	Between 1 in 10^4 years and 1 in 10^6 years	Not expected to occur during the lifetime of the facility, even though this may have occurred somewhere in the world
C	Less probable	Between 1 in 10^2 years and 1 in 10^4 years	Likely to occur once during the lifetime of the facility
D	Probable	Between 1 in a year and 1 in 10^2 years	Expected to occur a few times during the lifetime of the facility
E	Frequent	Over to 1 in a year	Expected to occur many times during the lifetime of the facility

Table 4 - Consequence Categories

Consequence category		Description	
		Personal safety	Safety of the facility
I	Negligible	Do not cause injuries or deaths of employees or third parts; and/or neighbour community; the maximum consequences are cases of first aid or minor medical treatment	No damage or minor damage to equipment or in the facility
II	Marginal	Minor injuries in employees and/or in third parts	Slight damage in the equipments or in the facility (damages are controllable and/or low-cost repair)
III	Critical	Minor lesions in third parts. Lesions of moderate severity in employees, contractors and/or people from outside the facility (remote probability of death of employees and/or other people)	Severe damage in the equipment or in the facilities
IV	Catastrophic	Causes death or serious injuries to one or more people (employees, contractors and/or third parties)	Irreparable damage in the equipment or in the facilities (repair is slow or impossible)

Having Tables 3, 4 and 5, it is now possible to analyse the risk of the loading/unloading system using a Risk Matrix. According to [12], the risk matrix approach, combining the likelihood of occurrence of an event and the consequence, defines risk as a pair located in a given matrix. Risk matrices have been used extensively for screening of risks in many industries. The risk matrix used in the present study is presented in Table 6, according to [11]. Risk increases in the direction of the upper-right side of the matrix and the category changes from NC (non critical) through M(moderate) and C (critical).

For each event listed in Table 5 a risk analysis is performed considering the probability of failure and the consequences of failure, according to the scenarios developed in the Cause-Consequence diagram. In case of the failure mode in the pump corresponding to 'fail to stop on demand' and in case of butterfly valves activated by the ESD failure mode 'fail to close on demand' the risk is classified as C (Critical) once if those components fail, there can be a large leakage because the loading and unloading operations are not interrupted by ESD.

On the other hand, the risk value associated with the majority of components is classified as M (Moderate). In case of total rupture of the pipelines cross section or primary tank barrier failure, the risk is considered M (moderate) once the probability category for those events is extremely remote (according to Table 5), although the occurrence of those events can cause serious consequences due to the enormous quantity of LNG leaked if the ESD system fails.

Table 5 - Probability of Occurrence and Consequence for Failures

Component	Nº	Failure Modes	Failure Rate [failure/hour]	P (n=1) Probability	Probability Category	Consequence Category
Centrifugal pump	1	Fail to stop on demand	1.55E-06	0.01340243	D	IV
Lift non-return valve	2	All modes	1.46E-06	0.01263428	D	II
Swing check valve	3	All modes	1.46E-06	0.01263428	D	II
Globe valve	4	External leakage-Process medium	1.94E-06	0.01671740	D	II
	5	Structural deficiency	3.90E-07	0.00340677	C	II
	6	Valve leakage in close position	9.70E-07	0.00843012	C	II
Butterfly valve	7	Structural deficiency	3.90E-07	0.00340677	C	II
	8	External leakage-Process medium	4.31E-06	0.03637678	D	II
	9	Valve leakage in close position	7.40E-07	0.00644423	C	II
Cargo tank (primary barrier)	10	Catastrophic	5.70E-12	0.00000005	A	IV
	11	Minor failure	1.14E-10	0.00000100	A	II
Secondary and relief pipelines (400 mm)	12	Crack of 4 mm in pipelines between 300 and 499 mm	9.13E-09	0.00008000	B	II
	13	Rupture 1/3 pipeline diameter in pipelines between 300 and 499 mm	2.28E-09	0.00002000	B	IV
	14	Guillotine in pipelines between 300 and 499 mm	7.99E-10	0.00000700	B	IV
Liquid header line (600 mm)	15	Crack of 4 mm pipelines between 500 and 1000 mm	7.99E-09	0.00007000	B	II
	16	Rupture 1/3 pipeline diameter in pipelines between 500 and 1000 mm	1.14E-09	0.00001000	B	IV
	17	Guillotine in pipelines between 500 and 1000 mm	4.56E-10	0.00000400	B	IV
Butterfly valve activated by the ESD	18	Fail to close on demand	5.42E-05	0.29550184	D	IV
	19	Structural deficiency	5.16E-06	0.04322743	D	II
	20	External leakage-Process medium	6.47E-05	0.32155361	D	II
Relief Valve	21	Structural deficiency	8.50E-07	0.00739505	C	II
	22	External leakage-Process medium	3.00E-06	0.02561267	D	II
	23	Valve leakage in close position	2.62E-06	0.02244309	D	II
Manifold	24	All modes	2.27E-05	0.16283750	D	II

Table 6 - Risk Matrix

			Consequence			
			Negligible	Marginal	Critical	Catastrophic
			I	II	III	IV
Frequency	Frequent	E	M	M	C	C
	Probable	D	NC	M(2;3;4;8; 19;20;22;23; 24)	C	C (1;18)
	Less Probable	C	NC	M(5;6;7;9; 21)	M	C
	Remote	B	NC	NC(12;15)	M	M(13;14;16; 17)
	Extremely remote	A	NC	NC(11)	NC	M (10)

The failure of the tank primary barrier is not so critical because it has the secondary barrier which function is to collect the LNG in case of primary barrier failure. Table 6 shows the risk of each one of the failure modes presented on Table 5 (observing their numeration). The analysis indicates 3 failure modes that are considered NC, the majority (19 failure modes) are considered M and finally 2 failure modes correspond to Critical category which are number 1 and number 18 (‘fail to stop on demand’ of the pump and ‘fail to close on demand’ of the butterfly valves activated by the ESD respectively).

3.6. Recommendations

The maintenance procedures and the operational recommendations can be used as contingency measures aiming at reducing the probability of failures of the components listed in the Cause-Consequence diagram.

The ESD system presents the lowest reliability among the safety barriers once it presents a great number of components that must be working to keep system functionality. It is mainly constituted by sensors that are considered electronic devices as for reliability analysis. The pieces of equipment, such as valves, that are controlled by ESD also have actuators that are usually hydraulic powered. As for reliability analysis the duration of the useful life of electronic components is very long and the failure rate is considered constant. The maintenance activities associated with sensors are typically corrective aiming at restoring the functionality of the device after the loss of function or performance. The hydraulic actuators reliability can be modeled as aging components with monotonically increasing failure rate during operational life. For those components preventive inspection and maintenance can reduce reliability deterioration. To check the sensors and actuators operational condition, at the beginning of loading/unloading operation, the ESD system is tested, including the actuation of valves and cargo pumps of LNG carrier and terminal. Also, after the cool down operation, the valves are actuated in order to verify any detrimental effect of the cargo low temperature on the valves performance. Nevertheless, due to its random failure nature, the sensors can fail during loading/unloading operations, without presenting previous performance deterioration. Those failures can affect ESD system reliability as proposed in the failure scenario presented in the cause-consequence diagram.

For the valves controlled by ESD the maintenance recommendations are preventive inspection and time based substitution of components subjected to wear. A periodically tested and repaired component can have its failure rate modeled as constant, provided that the maintenance activities cause no deterioration of the valve. Nevertheless, there is still a chance that a valve can fail during loading/unloading operations.

For structural components such as piping system and cargo tank primary barrier the Linear Elastic Fracture Mechanics concepts can be used to calculate the number of load cycles to cause the propagation of a crack until it becomes a through thickness crack, causing LNG leakage [13]. The crack propagation in pipelines is associated with the cyclic loads induced by temperature change during cooling down operations. In the primary barrier the main load is the weight of the cargo. Structural inspection during ship life and pressure test of piping system before loading/unloading operations will reduce the probability of structural failure. Special care must be taken during the execution or repair welds aiming at not introducing more defects in the structural part.

4. CONCLUSIONS

The proposed method of risk analysis allows understanding the events that cause the LNG leakage and the consequences of those events during cargo handling operations. The method helps to determine the critical components, which failures lead to a high level risk.

The use of Bayesian Networks to help the quantitative analysis of the Cause-Consequence Diagram proved to be efficient. BNs are very appropriate to represent complex dependencies between components. Unlikely FTA, however, BN does not allow an easy study of the system just by analyzing its configuration, been necessary to know the Conditional Probability Table from each node.

Although the paper identified some failure scenarios that could cause critical consequences in case of LNG leakage, it also stressed the safety measures adopted by LNG transportation industry to prevent an accident. The sophisticated safety systems include gas detection and low temperature monitoring, heat and fire detection and cargo-related emergency shutdown devices. All processes involved in LNG handling are certified by classification societies to ensure international standard of safety.

Nevertheless, the paper also shows the possibility of improving operational safety based on developing a reliability database specific for equipment used in LNG carriers and terminals. That database would support precise reliability estimate that would improve risk analysis and design of this type of ship. It would also support the improvement of maintenance procedures developed for this type of ships.

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