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ORIGINAL ARTICLE

Quantitative Risk Assessment of Hydrotreated Vegetable Oil at an Oil and Gas Company

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ABSTRACT

Introduction: An oil and gas refinery processes flammable liquids so it is prone to various hazards, such as leaks that may lead to pool fires if a heat source is present. A quantitative risk assessment (QRA) was conducted to identify risk, evaluate potential consequences, and implement mitigation measures. **Methods:** The Hazard Operability (HAZOP) study determined the hazardous spots, and the probability of each equipment failure was determined using fault tree analysis (FTA). Event Tree Analysis (ETA) calculated the probability of every possible consequence caused by leaks. Individual risk per annum and potential loss of life were used to measure the risk level of the system. **Results:** Based on HAZOP, every operating equipment can potentially cause a pool fire. In FTA, scenarios were developed based on different leakage hole sizes, ranging from 1-3 mm, 3-10 mm, 10-50 mm, 150 mm, and >150 mm. The results indicated that leakage could occur across all operating equipment. Similarly, the ETA applied the same bore size scenarios. Pool fire modeling scenarios resulted in three heat flux zones: the red zone (10 kW/m²), the orange zone (5 kW/m²), and the yellow zone (2 kW/m²). Smaller leak holes resulted in a higher probability but a smaller pool fire radius. The initial risk of the export facility was unacceptable. Therefore, two mitigation scenarios were proposed to minimize the risks: adding safeguards and reducing worker hours. **Conclusion:** The final results showed that for every piece of equipment, the overall risk of the export facility became acceptable after mitigation.

Keywords: hydrotreated vegetable oil, oil and gas company, pool fire, quantitative risk assessment, risk analysis

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INTRODUCTION

The oil and gas industry is one of the sources of the economy that has an essential role in providing energy sources for the global community (Lu *et al*., 2019). But behind this vital role, this industry is also associated with several dangerous risks that can impact the environment, the operators who work in it, and the surrounding community (Hou *et al*., 2022). Many cases have involved accidents in the process facilities (Tananta and Ramadhani, 2024). The number of accidents in the oil and gas industry varies yearly. For example, in the United States, a country with active oil and gas operations, there were 14 explosion (combustion/fire) incidents in one year, the highest number of incidents. These accident examples from the National Institute for Occupational Safety and Health demonstrate the dangers and risks from 2017 to 2018 (The National Institute for Occupational Safety and Health (NIOSH), 2020), emphasizing the critical need for risk assessment. There are various consequences of accidents in the oil and gas industry, such as explosions, fires, fluid leaks, and others. A particular concern is the cause of these accidents, such as flammable fluid leaks. Many risk analysis methods are used to identify and estimate risks. Several previous journals have examined quantitative risk assessment (QRA), such as Hernández-Báez *et al*. (2023), who explored modeling the consequences of jet and pool fires from hydrogen-filled pipes, seeking social and individual risks. Subsequently, Hou *et al*. (2022) explain quantitative risk assessment with the aim of an accident caused by a double pool fire while using a dual pool fire synergy (DPFS) model for calculating the thermal radiation. Yuan *et al*. (2021) discussed the impact of damage from diesel

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oil pool fires and Joubert, Steyn and Pretorius (2021) proposed a risk assessment framework based on the Hazard Operability Study (HAZOP) for dismantling large industrial machine structures. Hosseini, Givehchi and Maknoon (2020) used the fuzzy fault tree analysis (FTA) and event tree analysis (ETA) to propose a cost-based fire risk assessment framework in the natural gas industry

Risk assessment is an essential tool for thoroughly assessing a particular area's safety, financial viability, and environmental integrity and methodically examining the potential hazards of fatalities for persons operating within its boundaries. Taking a quantitative approach, this strategy uses numerical data to delve deeply into the ramifications of prospective accidents, providing a granular grasp of their potential outcomes. These evaluations, which involve thorough calculations and analysis, not only help to detect risks but also pave the way for continual review, if necessary, implementing targeted mitigation steps to enhance safety and resilience (Ostrom (2019).

In this paper, several issues were observed. Two storage tanks store and process flammable fluids named hydrotreated vegetable oil (HVO). Several pieces of equipment are operating in the existing system, such as two storage tanks that lead to transfer pumps A and B through pipes. This system is prone to leakages if one of the equipment fails. If this flammable liquid leak finds a heat source, a pool fire can occur at any time. Therefore, a quantitative risk assessment (QRA) is necessary to identify all potential hazards and consequences if any undesired events occur in the system. QRA uses a data-driven approach and objective risk measurement (Ostrom, 2019). QRA also helps organizations formulate policies and procedures to be able to manage the risks and plan mitigation actions. Additionally, it fosters enhanced comprehension among stakeholders, enabling them to address risks effectively and act accordingly (Landoll, 2021).

The main objective of this research is to thoroughly understand potential failure modes and their effects within the scope of a jetty loading area handling hydrotreated vegetable oil (HVO) at an oil and gas company. A quantitative risk assessment framework is selected. Initially, HAZOP is used to identify scenarios and potential hazards; the FTA is then used to find the probability of each potential cause of failure. Furthermore, ETA is used to find all possible consequence scenarios, and the radius of fire is determined using a pool fire scenario. Finally, the use of individual risk to determine the risk of each affected individual, as well as the use of potential loss of life to determine the level of probability of death of each individual, is also essential.

METHOD

Figure 1 shows an illustration of the conceptual model in this research. In the initial stage, hazard and operability (HAZOP) is used to identify potential causes of failure or hazards in the system. Furthermore, two frequency modeling methods were used, namely the fault tree analysis to find the probability of each piece of equipment that can potentially cause a pool fire. Then event tree analysis was used to find the probability of the pool fire consequence scenario. After that, the type of pool fire consequence was created by calculating and analyzing the heat flux and threat zone. In the final stage of QRA, the individual risk and potential loss of life methods were used to identify impacts on humans. Then, mitigation was carried out by measuring the risk category, emphasizing the risk value in the discussion of this research.

Hazard and Operability Study (HAZOP)

Hazard and operability (HAZOP) is a qualitative method used to identify various potential causes

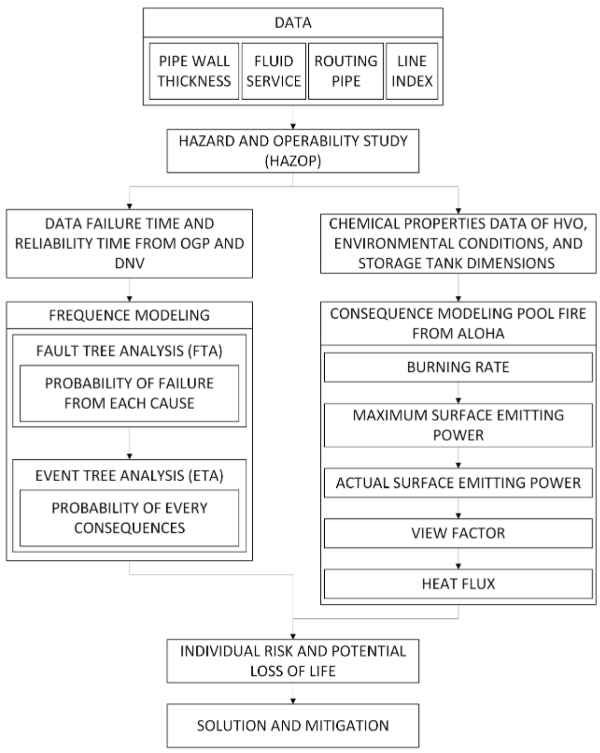


Figure 1. Conceptual Model

of failure or hazards of the observed system (Marhavilas *et al*., 2020). In this method, it is necessary to identify and analyze deviations or potential hazard scenarios in the equipment working in the system (Galalizadeh *et al*., 2020). After that, the results of the scenario can be searched for the probability of failure using the fault tree analysis method.

Fault Tree Analysis (FTA)

The first frequency modeling is fault tree analysis (FTA), analyzes and generates all potential failure events (Al Banna and Ramadhani, 2023). FTA has three main components: the first is called the top event or failure event, the basic event which is the individual factors that, when combined, will create a top event, and the final component, namely the gate that connects the events (in the form of an OR/AND gate) (Gachlou, Roozbahani and Banihabib, 2019). FTA is used to determine the probability of equipment failure from the deviation scenarios developed in HAZOP. The probability of the top event in this method is used to analyze and calculate the consequence scenario in the ETA phase.

Event Tree Analysis (ETA)

Event tree analysis (ETA) is a systematic approach used in risk assessment and decision-making to analyze the potential outcomes of various events or scenarios, particularly in complex systems or processes (Momeni *et al*., 2021). This method involves creating a visual representation resembling a tree structure, depicting events as nodes and possible outcomes as branches stemming from those nodes. Each branch represents events that can occur, leading to different outcomes. The ETA calculation is performed by multiplying each of its pathways to determine whether operational safeguards are successful (Kabir and Papadopoulos, 2019). This step uses ETA to make consequence scenarios based on the processed fluid, safeguards, etc. Each of the top event probabilities in FTA are used for initiating event's probabilities in ETA diagrams.

Pool Fire Modelling

Pool fires typically occur in fuel and diesel oil jets, where hydrocarbons (heavier than hexane), glycol, oil, and hydraulic fluids become involved fuels (Ridwan and Ramadhani, 2024). This type of consequence modeling is used based on the fluid type, which is a flammable liquid. In heat flux calculations, the flame shape is assumed to be cylindrical. Here are the steps to determine the heat flux value.

Burning Rate Calculation

This calculation uses the Burgess-Strasser-Grumer method because it provides good results for general hydrocarbon burning rate calculations and liquid fuel, and the parameters calculated in the formula are included in the data.

$$\mathfrak{m}' = \rho_L c_1 \frac{\Delta Hc}{\Delta Hv + Cp(Tb - Ta)} \quad (1)$$

where m′ is burning rate (kg/m^{2}s), ΔHc is combustion heat (J/kg), ΔHv is evaporation heat (J/kg), Cρ is specific heat capacity of the fuel (J/kgK), ρl (kg/m^3) is fluid density at the boiling temperature, *Tb* & *Ta* boiling point of the fuel and ambient temperature (K), and $c_1 = 1.27 \times 10^{-6}$m/s..

Calculation of Maximum Surface Emitting Power

The maximum surface emitting power (SEPmax) is calculated for the radiative power from the flame's surface if no soot or smoke is present.

$$SEPmax = Fs \frac{1}{\left(1 + \frac{L}{D}\right)} \mathfrak{m}' \Delta Hc \quad (2)$$

where Fs is radiation fraction (-) indicating the fraction of combustion energy emitted from the flame temperature, L is average flame length (m), and D is pool diameter (m).

Calculation of Actual Surface Emitting Power

Actual surface emitting power (SEPact) is calculated for the radiative power from the flame's surface if soot or smoke is present.

SEPact=SEPmax (1-s)+SEPsoot s

SEPsoot is surface emitting power from soot/smoke (kW/m^2) and s is the fraction of surface covered by soot (-).

View Factor Calculation

The view factor calculation, Fview (-) **(3)** is a small portion of emitted radiation that reaches the receptor per unit area. This receptor can be a person or material. The flame shape is considered as an inclined cylinder. Fview is calculated as a function of the perpendicular contribution Fv and the horizontal contribution Fh.

$$Fview = \sqrt{F_v^2 + F_h^2} \quad (4)$$

Fview is the view factor, Fh is the horizontal contribution, and Fv is the perpendicular contribution.

Heatflux Calculation

Heatflux, q' (kW/m^2), at a certain distance from the center of the fire, is calculated as:

$$q' = SEP_{act} F_v \tau_a \quad (5)$$

With τa(-) as atmospheric transmissivity with the formula:

$$\tau_a = c_4 [P_w (X - R)]^{-0.09} \quad (6)$$

where q' is heat-flux (kW/m^2), τa is atmospheric transmissivity, c4 is equal to 2.02 (unit (Pa$^{0.09}$m$^{0..09}$)), and Pw is partial pressure of water vapor in the air (Pa).

Individual Risk

Individual risk (IR) aims to measure the level of risk faced by specific individuals in environments potentially at high risk, such as workers, inhabitants of areas surrounding high-risk facilities, or the general public near potential hazard sources. It determines whether the individual risk level is within acceptable limits based on specific safety standards (Tzenova, 2018). Individual risk per annum (IRPA) is a risk measure indicating the likelihood of an individual dying within one year due to exposure to hazards or specific activities. The formula for calculating IRPA is the sum of LSIR or location specific individual risk, multiplied by the attendance factor in that area, as shown in equation 8.

IRPA = ∑LSIR x Presence Factor (7)

LSIR = ∑F x P (8)

In calculating LSIR, the probability of fatality due to the event at the location or P is obtained from calculating thermal radiation dose, probability of injury or death, and overall effect on the receivers within the consequence modeling radius. Equation 9 represents the formula for thermal radiation dose. A probability is needed to calculate the probability of injury or death, which requires using the probit function. This calculation can be seen in equations 11 and 12.

$$D = t_{eff} (q')^{4/3} \quad (9)$$

$$t_{eff} = t_r + \frac{(x_o - r)}{u} \quad (10)$$

$$P = F_k \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{Pr - 5}{\sqrt{2}}\right)\right] \quad (11)$$

$$Pr = c_1 + c_2 \ln D \quad (12)$$

where q' is heat flux from consequence modeling, teff is person's exposure time from heat flux, tr is the reaction time of an individual (assumed 5 seconds), xo is the distance between the flame surface and the position of heat flux intensity (<1 kW/m^2), r is the distance between a person and the flame surface, u is escape velocity (assumed 4 m/s).

Potential Loss of Life

Potential loss of life (PLL) is a parameter calculated to measure each individual's likelihood of loss of life from a specific consequence under certain conditions. PLL represents the risk experienced by individuals involved in the incident location over a specific period (Vidmar and Perkovič, 2018). To find PLL, a formula is needed that multiplies the number or sum of IRPA by people on building (POB) or the number of people in the building/location being observed. Equation 13 is the PLL formula which mentioned above:

PLL = ∑IRPA x POB (13)

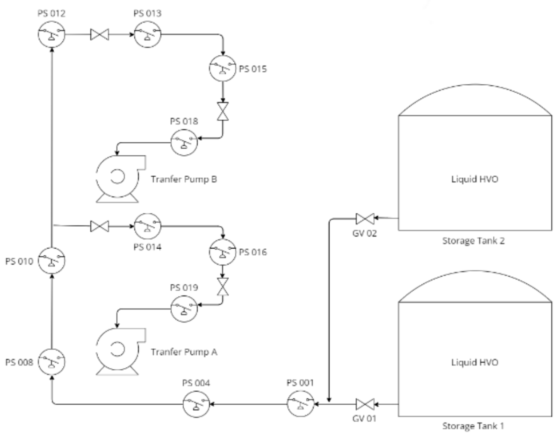
In calculating IRPA and PLL, the results must be in a risk category called as low as reasonably practicable (ALARP). If the IRPA and PLL numbers show above 1E-4, then the category is called unacceptable risk. If the results show 1E-4 to 1E-6, then it is included in the ALARP (risk must be reduced if 'reasonably practicable') category. Furthermore, if the result value shows 1E-6 to 1E-7, then it is called acceptable risk. Finally, if the result number shows below 1E-7, it is called negligible risk (Langdalen, Abrahamsen and Selvik, 2020). This paper uses Google Bard, Grammarly, and ChatGPT to translate some information from Indonesian to English at the drafting stage of the writing process.

RESULTS

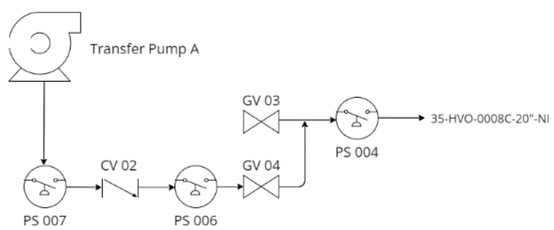
Before using HAZOP, it is necessary to have an overview of the working process cycle and the equipment used in the initial stages. The author uses a PFD or process flow diagram to describe this cycle.

Hazard Operability Study (HAZOP)

The system is divided into two nodes to determine the HAZOP method in this research. This selection is based on the different operating pressures in the first and second nodes. Figure 2 shows the classification of nodes 1 and 2 in the system. The division is based on the different operating temperatures between node 1 and node 2. In Figure 2 (a), the process of distributing HVO fluid from storage tanks 1 and 2 is separated to transfer pumps A and B. The cycle above has an operating pressure of 0.9-1 barg with an operating temperature of 38°-39°C. Figure 2 (b) depicts the process at node 2 from transfer pump A to the process cycle



(a)



(b)

Figure 2. Process Flow Diagram for: a) Node 1 and b) Node 2

35-HVO-0008C-20"-NI. The cycle above has an operating pressure of 17-18 barg with an operating temperature of 38°-39°C.

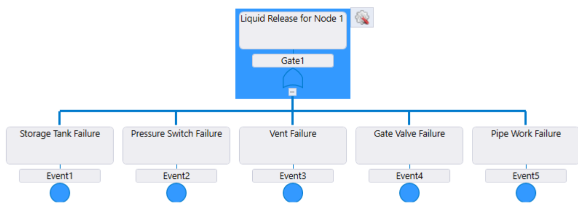
Fault tree analysis (FTA) determines the probability of each cause of a pool fire occurrence. Therefore, which event or value has the most significant impact on causing the liquid release can be identified. In frequency modeling, this study involves scenarios with various hole sizes. These hole scenarios include leaks of 1-3 mm, 3-10 mm, 10-50 mm, 50-150 mm, and >150 mm.

Figure 3 shows the fault tree analysis diagram of the liquid release in nodes 1 and 2. FTA diagrams are designed with the top event being liquid release for node 1 and node 2, and then followed by all the corresponding equipment and instrumentations in each node. The failure scenario considered in the development of the FTA diagram is that a failure of any of this equipment will lead to a liquid release scenario. Thus, the logic "OR" explains the relationship between the top event and all basic events.

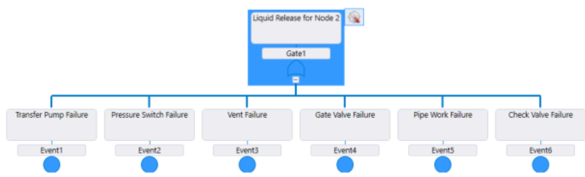
Event Tree Analysis (ETA)

Event tree analysis is then used to determine the probability of each outcome resulting from the initiating event, a liquid release. The liquid release, in the form of HVO fluid, is created because the ultimate consequence desired is a pool fire.

Based on Figure 4, the pool fire results because, after the liquid release event from the FTA diagram at node 1, it is followed by an immediate ignition event accompanied by the failure of the fire water system function. If the fire water system works in the path, then the outcome of that path becomes



(a)



(b)

Figure 3. Fault Tree Analysis (FTA) Diagram for Liquid Release at a) Node 1 and b) Node 2

a pool of leaked HVO fluid combined with water from the FWS, resulting in an HVO + H2O pool. Delayed pool fire means a burning that occurs from the leakage but experiences a delay, or the ignition source does not directly come when the leakage occurs. In the outcome, which is unignited fluid release, after the leakage occurs, it is not followed by events such as combustion or failure of other equipment, so the leakage does not cause any failure. In node 2, the Event Tree Analysis (ETA) diagram has similarities because the same safeguards are implemented. The only difference is the numerical value of the initiating events. Table 1 represents a recapitulation of the calculations for all ETA diagrams.

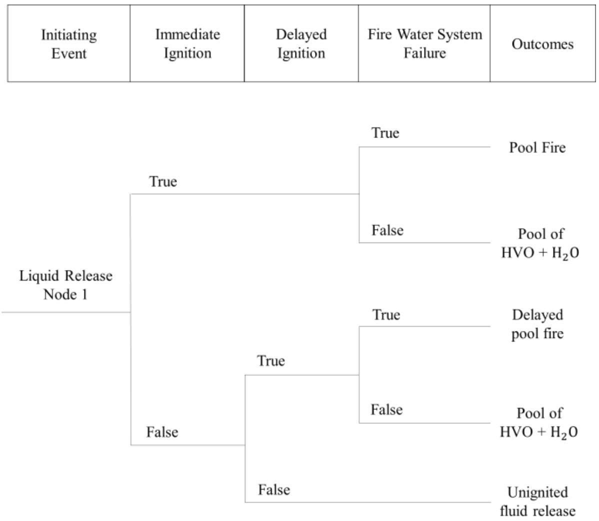


Figure 4. ETA Diagram for Node 1

Consequence Modeling (Pool Fire)

Consequence modeling is used in this research with pool fire as the output. This type of fire has a specific radius caused by the diameter and quantity of liquid exposed to the heat source. Pool fire is chosen as the consequence modeling because the fluid under investigation, in this case, is liquid HVO. In this stage, pool fire calculations are designed using ALOHA (Areal Locations of Hazardous Atmospheres) software. Like frequency modeling, the scenarios used in this stage are bore size scenarios or hole diameters. These scenarios include 1-3 mm, 3-10 mm, 10-50 mm, and >150 mm for each diameter. Figure 5 depicts the radius

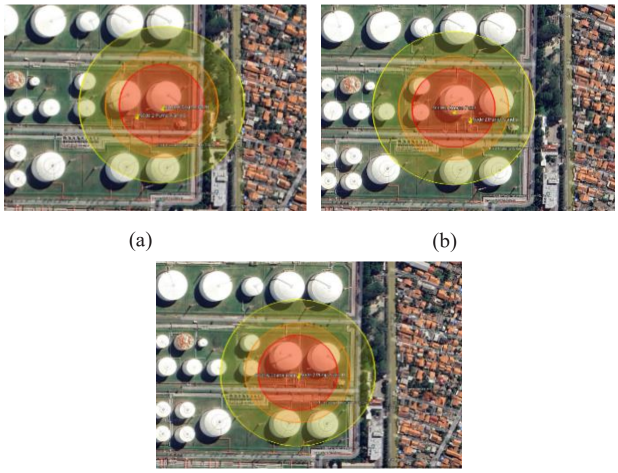


Figure 5. The Radius of the Pool Fire for a 50 mm Leakage at: a) Storage Tank 1 at Node 1, b) Storage Tank 2 at Node 1, and c) Pump Area at Node 2

Table 1. The results of calculating the frequency of each Outcome on the ETA Diagram

Node	Bore Size (mm)	Scenario Frequency (outcomes)				
			Pool of HVO + H2O	Delayed pool fire	Pool of HVO + H2O	Unignited fluid release
1	1-3	1.169E-7	1.168E-4	3.893E-7	3.889E-4	1.294E-1
	3-10	6.202E-7	6.195E-4	3.857E-7	3.853E-4	1.282E-1
	10-50	3.769E-7	3.766E-4	3.861E-7	3.858E-4	1.283E-1
	50-150	9.030E-6	9.021E-3	3.599E-7	3.596E-4	1.196E-1
	>150	9.030E-6	9.021E-3	3.599E-7	3.596E-4	1.196E-1
2	1-3	3.755E-7	3.751E-4	4.011E-7	4.007E-4	1.333E-1
	3-10	1.413E-6	1.411E-3	3.881E-7	3.877E-4	1.289E-1
	10-50	7.886E-6	7.878E-3	3.654E-7	3.650E-4	1.214E-1
	50-150	9.037E-6	9.028E-3	3.602E-7	3.598E-4	1.197E-1
	>150	9.044E-6	9.035E-3	3.605E-7	3.601E-4	1.198E-1

of a pool fire as simulated through the ALOHA software, subsequently plotted onto Google Earth with a scenario diameter of 50 mm. The result of the pool fire modeling radius is based on the assumption of a wind speed scenario of 5 m/s, with the wind direction originating from the south (as the south direction represents the sea), clear weather with some clouds during the day, an air temperature of 33°C, and a relative humidity of 75%.

Individual Risk Per Annum (IRPA)

The calculation of IRPA is obtained by multiplying the total LSIR by the number of working hours per day or 24 hours, multiplied by 365, which is the total number of days in a year.

Potential Loss of Life (PLL)

The purpose of PLL calculation is to measure the level of risk to a group of people affected by hazards without explicitly identifying or detailing whether a particular worker is more exposed than another worker. Table 2 shows the IRPA and PLL calculation results based on worker location, worker category, and POB for node 1 and node 2, where the risk category for each worker category is determined.

Table 2. Calculation Results of IRPA and PLL for Node 1 and Node 2

Worker Location	Worker Category	POB	IRPA	PLL	Risk Category
		Node 1			
Warehouse	Head of Warehouse	1	3.8425E-4	3.8425E-4	ALARP
	Warehouse Manager	1	3.8425E-4	3.8425E-4	ALARP
	Warehouse Supervisor	1	3.8425E-4	3.8425E-4	ALARP
	Heavy Equipment Operator Technician	2	7.6849E-4	1.5369E-3	Unacceptable
	Checker	2	7.6849E-4	1.5369E-3	Unacceptable
	Receiving and Storage Operations	2	7.6849E-4	1.5369E-3	Unacceptable
	Warehouse Maintenance	2	7.6849E-4	1.5369E-3	Unacceptable
	Warehouse Security	2	1.1527E-3	2.3054E-3	Unacceptable
Tankage and Storage Area	Process Technician	3	7.6849E-4	2.3055E-3	Unacceptable
	Safety Inspector	1	3.8425E-4	3.8425E-4	ALARP
	Area Supervisor	1	3.8425E-4	3.8425E-4	ALARP
	Tank Crew	2	3.8425E-4	7.6855E-4	ALARP
	Instrumentation and Control Technician	2	7.6849E-4	1.5369E-3	Unacceptable
	Terminal Operator	3	7.6849E-4	2.3055E-3	Unacceptable
Residential Area	Local Resident	4	1.1527E-3	4.6108E-3	Unacceptable
Node 2					
Warehouse	Head of Warehouse	1	5.4077E-4	5.4077E-4	ALARP
	Warehouse Manager	1	5.4077E-4	5.4077E-4	ALARP
	Warehouse Supervisor	1	5.4077E-4	5.4077E-4	ALARP
	Heavy Equipment Operator Technician	2	1.0815E-3	2.1630E-3	Unacceptable
	Checker	2	1.0815E-3	2.1630E-3	Unacceptable
	Receiving and Storage Operations	2	1.0815E-3	2.1630E-3	Unacceptable
	Warehouse Maintenance	2	1.0815E-3	2.1630E-3	Unacceptable
	Warehouse Security	2	1.6223E-3	3.2446E-3	Unacceptable
Tankage and Storage Area	Process Technician	3	1.0815E-3	3.2445E-3	Unacceptable
	Safety Inspector	1	5.4077E-4	5.4077E-4	ALARP
	Area Supervisor	1	5.4077E-4	5.4077E-4	ALARP
	Tank Crew	2	5.4077E-4	1.0815E-3	Unacceptable
	Instrumentation and Control Technician	2	1.0815E-3	2.1630E-3	Unacceptable
	Terminal Operator	3	1.0815E-3	3.2445E-3	Unacceptable
Residential Area	Local Resident	4	1.6223E-3	6.4892E-3	Unacceptable

The first mitigation measure involves adding safeguards such as heat detectors, a foam supply system, and blast (Svalova, 2018). The heat detector detects heat sources in specific areas so that ignition does not occur in the event of a liquid release like HVO. Figure 5 The radius of the pool fire for a 50 mm leakage at: a) storage tank 1 at node 1, b) storage tank 2 at node 1, and c) pump area at node 2.

Ignition does not occur because the heat source has been detected and safeguarded beforehand. The second safeguard is the foam supply system, which provides backup firefighting foam if the fire water system cannot be activated. The third safeguard involves adding blast walls, which contain fires if both the fire water system and heat detectors fail to function during ignition (Roy and Matsagar, 2021).

DISCUSSION

Hazard and Operability Study (HAZOP)

In the process involving system nodes 1 and 2, hydrotreated vegetable oil (HVO) a fluid prone to combustion in the presence of a heat source, is contained. HVO, has a flash point ranging from 130°C to 160°C and an ignition temperature of 250°C. However, if the heat exposure does not

Table 3. The Calculation Results of IRPA and PLL After the First Mitigation at Node 1 and Node 2

Worker Location	Worker Category	POB	IRPA	PLL	Risk Category
		Node 1			
Warehouse	Head of Warehouse	1	1.9214E-8	1.9214E-8	Acceptable
	Warehouse Manager	1	1.9214E-8	1.9214E-8	Acceptable
	Warehouse Supervisor	1	1.9214E-8	1.9214E-8	Acceptable
	Heavy Equipment Operator Technician	2	3.8427E-8	7.6854E-8	Acceptable
	Checker	2	3.8427E-8	7.6854E-8	Acceptable
	Receiving and Storage Operations	2	3.8427E-8	7.6854E-8	Acceptable
	Warehouse Maintenance	2	3.8427E-8	7.6854E-8	Acceptable
	Warehouse Security	2	5.7641E-8	1.1528E-7	Acceptable
Tankage and Storage Area	Process Technician	3	3.8427E-8	1.1528E-7	Acceptable
	Safety Inspector	1	1.9214E-8	1.9214E-8	Acceptable
	Area Supervisor	1	1.9214E-8	1.9214E-8	Acceptable
	Tank Crew	2	1.9214E-8	3.8427E-8	Acceptable
	Instrumentation and Control Technician	2	3.8427E-8	7.6854E-8	Acceptable
	Terminal Operator	3	3.8427E-8	1.1528E-7	Acceptable
Residential Area	Local Resident	4	5.7641E-8	2.3056E-7	Acceptable
Node 2					
Warehouse	Head of Warehouse	1	2.7039E-8	2.7039E-8	Acceptable
	Warehouse Manager	1	2.7039E-8	2.7039E-8	Acceptable
	Warehouse Supervisor	1	2.7039E-8	2.7039E-8	Acceptable
	Heavy Equipment Operator Technician	2	5.4078E-8	1.0816E-7	Acceptable
	Checker	2	5.4078E-8	1.0816E-7	Acceptable
	Receiving and Storage Operations	2	5.4078E-8	1.0816E-7	Acceptable
	Warehouse Maintenance	2	5.4078E-8	1.0816E-7	Acceptable
	Warehouse Security	2	8.1118E-8	1.6224E-7	Acceptable
Tankage and Storage Area	Process Technician	3	5.4078E-8	1.6223E-7	Acceptable
	Safety Inspector	1	2.7039E-8	2.7039E-8	Acceptable
	Area Supervisor	1	2.7039E-8	2.7039E-8	Acceptable
	Tank Crew	2	2.7039E-8	2.7039E-8	Acceptable
	Instrumentation and Control Technician	2	5.4078E-8	1.0816E-7	Acceptable
	Terminal Operator	3	5.4078E-8	1.6223E-7	Acceptable
Residential Area	Local Resident	4	8.1118E-8	3.2447E-7	Acceptable

reach this ignition temperature, a pool fire will not ignite (Li *et al*., 2021). Meanwhile, pressure does not significantly affect the ignition of a fire in an HVO pool (National Fire Protection Association, 2021). The HAZOP method in this study shows that pool fire can occur at any of the various deviations identified (Nehal *et al*., 2024). In this case, node 1 and node 2 have potential sources of failure that can cause pool fires, where the main source comes from all working equipment (Shafie and Mohammad, 2023).

Fault Tree Analysis (FTA)

The first frequency method is FTA, where the probability of a top event occurring is obtained from calculating each failure probability for each piece of equipment working on the system. In the analysis process, there were two FTA diagrams identified due to differences in equipment working at node 1 node 2 (Markulik *et al*., 2021). Next, leak size scenarios are used, including 1-3 mm, 3-10 mm, 10-50 mm, 50-150 mm, and >150 mm (Baskoro, Artana and Dinariyana, 2021). This method also determines the leak's location, which is determined based on each potential failure or probability of each equipment being calculated. This consideration is done because leaks can occur in the observed cycle at node 1 or node 2. The top event probabilities from these FTAs served as the initiating events in the event tree analysis (ETA). The initiating events from the FTA, based on different bore sizes, were used in the ETA diagrams (Hosseini, Givehchi and Maknoon, 2020).

Event Tree Analysis (ETA)

Each outcome's probability varied according to the bore size, leading to different risk profiles (Chu and Chang, 2017). In Figure 4, the pool fire scenario occurs due to the liquid release followed by immediate ignition, compounded by the failure of the fire water system. If the fire water system operates effectively in this sequence, the outcome would be the accumulation of leaked HVO fluid mixed with water from the fire water system, resulting in an HVO + H2O pool. A delayed pool fire indicates combustion occurring from the leakage, but with a delay, the ignition source does not immediately ignite the leaking fluid. The final outcome, unignited fluid release, occurs when the leakage does not lead to ignition or other equipment failures, thus not causing any subsequent failure or hazard (Singh, Kumar and Pusti, 2022). The worst-case outcome in the ETA was a pool fire, while the safest was an unignited fluid release (Mares, Nagy and Radu, 2020).

Consequence Modelling (Pool Fire)

The pool fire consequence modeling showed varying radii depending on the bore type or leak size (Yang *et al*., 2020). Smaller bore sizes made heat flux levels less likely to be lethal within 60 seconds, indicating a lower hazard to the surrounding area (Shi *et al*., 2019). This finding aligns with Hosseini, Givehchi and Maknoon's (2020) research. They stated that if the leakage is below 5 mm or, in this case, 3 mm bore size, there will be no fatality or significant damage if a heat source follows the leakage within a certain period. Radiant heat (kW/ m^2) manifests varying effects based on intensity (Changphuek, Chetiyanukornkul and Boongla, 2024). At an intensity of 2 kW/m^2, an individual will experience pain within 60 seconds, indicated by a yellow-shaded area. At 5 kW/m^2, exposure for 60 seconds can result in second-degree burns, marked by an orange-shaded area. Conversely, at 10 kW/m^2, exposure for 60 seconds can be potentially lethal, denoted by a red-shaded area (Tang, Chang and Wang, 2020).

Individual Risk Per Annum (IRPA) & Potential Loss of Life (PLL)

In IRPA and PLL calculation, not all worker categories at nodes 1 and 2 have results within the ALARP zone, which is the minimal risk criteria. Some categories exhibit unacceptable risk, with values exceeding 1E-3. In the PLL results for node 1, six worker categories fall within the ALARP risk level: warehouse head, warehouse manager, warehouse supervisor, safety inspector, area supervisor, and tank crew. The remaining categories have unacceptable risk levels. In a research conducted by Budiarta, Handani and Dinariyana (2020), risk assessment was carried out using the risk mapping (f-N) curve. The results of the risk assessment after the addition of safeguards in the LOPA mitigation, as well as the ALARP and acceptable risk values were obtained from the safeguards gas detector, pressure alarm, and temperature alarm because the fluid being processed is gas. Table 3 shows the calculated IRPA, PLL, and risk category after implementing additional safeguards in the system. In the PLL results for node 2, five worker categories fall within the ALARP risk level: warehouse head, warehouse manager, warehouse supervisor, safety inspector, and area supervisor. The other categories also have unacceptable risk levels. Neither node 1 nor node 2 has worker categories with results in the green or acceptable risk zone. Therefore, mitigation measures are necessary to address these risk levels. In the first mitigation phase, the deployment of each safeguard can be tailored to different placements (Landoll, 2021). For example, in the case of the foam supply system, which serves as a backup for the fire water system in case of its failure, it is therefore positioned nearby or within the vicinity of the fire water system area. Blast walls can be situated in the gaps between each work location. For instance, blast walls can shield or separate each tankage area, delineate working equipment from office or building sections housing numerous personnel, such as warehouses or head offices, and isolate the HVO processing facility from residential areas (Jung and Lee, 2019).

The final safeguard is the heat detector, designed to detect heat sources and trigger an alarm. These devices can be deployed at each node by placing two at each storage tank with a maximum distance of 9 meters between them and two transfer pump areas, A and B, with a maximum distance of 4.6 meters (National Fire Protection Association, 2021).

CONCLUSION

Quantitative risk assessment plays a crucial role in effectively assessing the risk level of the system under study. In this research, risk assessment includes identifying issues or hazards, modeling the frequency of system and equipment failures, modeling consequences such as pool fire, and determining individual risks and potential loss of life. In the hazard identification results, HAZOP can identify various deviations and hazards that may arise in the HVO export facility. This is followed by frequency modeling using fault tree analysis (FTA), which successfully models failure scenarios of each working equipment to determine the probability of HVO liquid leakage per scenario of bore size. Furthermore, event tree analysis (ETA), modeled from the probability results of the top event from FTA, diagrams various outcomes from the safest, if all, safeguards work to the worst-case scenario of a pool fire. The probability of each outcome has also been successfully calculated. The consequence modeling determines each bore size scenario's radius and heat flux. The results of this quantitative risk assessment (QRA) are calculated using the individual risk per annum method and calculating potential loss of ;life, which proves that the HVO export facility in this study is not yet classified as an acceptable risk overall. Therefore, the authors conducted mitigation measures such as adding safeguards and reducing working hours for workers. The results show that all risk criteria for each node were successfully reduced to meet acceptable risk criteria.

CONFLICT OF INTEREST

In this study, no financial interests or personal relationships could have influenced the authors' work.

AUTHOR CONTRIBUTION

M.I.T.R.T: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing – original draft, Validation, Writing – review & editing. A.R.R: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

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