Societal risk assessment of terminal and oil refinery unit

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Abstract. This paper presents the societal risk assessment of oil refinery in one of the oil companies in East Java. The oil company operates a terminal for loading and unloading of variety petrochemical products. The products are categorized as flammable which could be hazardous. To prevent unlikely event of hazards such as fire, risk assessment is needed to know the level of risk and propose any mitigation if the risk is unacceptable. The risk assessment is done for all the processes that occurs such as loading and unloading of products and the chemical process in the oil refinery. The system is categorized into 8 nodes based on their function. Firstly, Hazard and Operability (HAZOP) is carried out using BS IEC 61882 standard to identify the deviation of the system, the causes and how to prevent it. The frequency analysis of failure of component is done by using Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) which based on the DNV failure guidance and Oil and Gas Producers (OGP) data as input. In order to know the level of consequence, fire modelling is carried out to simulate how the jet fire and pool fire could impact into the social around the oil refinery in form of heat intensity. The fire modelling for the pool fire and jet fire results the pool radius and flame length respectively, based on the heat intensity of 4 kW/m\textsuperscript{2}, 12.5 kW / m\textsuperscript{2}, and 37.5 kW / m\textsuperscript{2}. Risk is represented using F-N curve with UK-HSE standard. There is unacceptable risk that incurred for jet fire in pipeline and its components from the feedstock tank into pre-cut column, scenario 200 mm hole diameter. Mitigation is done using LOPA to bring the risk to the acceptable region by adding a gas detector which has changed the frequency of system failure from 1.44E-03 to 2.88E-06.

Keywords: Oil refinery, risk assessment, HAZOP, FTA, ETA, fire modelling, LOPA.

1. Introduction
Petroleum or crude oil consists of complex compound of hydrocarbon, found in immense underground reservoirs in liquid, solid, or gaseous form. Petroleum through long chemical engineering process in refinery before it turned into finished product. This paper discusses safety issues in one of the oil companies in East Java which operates large-scale refineries with a capacity of 100 MBCD (Million Barrels per Calendar Day) or 100,000 barrels of condensate per day. The oil products produced in this company include fuels, aromatic products (benzene, toluene, ortho xylene and paraxylene), and LPG (Liquefied Petroleum Gas) and all fluid transfer process is carried out using pipes. Refinery operates 24 hours per day with ± 80 workers per shift and this shift is divided into 2 each day. All processes involving hydrocarbons in the Refinery Unit can cause the occurrence of a potential hazard. Therefore, the risk
level in process of fluid transfer which carried out using pipelines needs to be identified and assess the level of risk to avoid safety and damage issues to company and surrounding. One of the risk assessment methods that can be applied to evaluate the safety of personnel and surrounding environment in the refinery area is the Societal Risk Assessment. Societal risk can be described as the relation between frequency an incident occurred, and number of people are exposed to risk in specific population. Social risk assesses the probability of more than one personnel being injured simultaneously in an incident and societal risk is used to calculate the damage caused by major, various fatality risk to maintain level in acceptable region or in ALARP (As Low As Reasonable Practicable)

2. Methodology
Risk assessment in this paper was carried out in four main phases. In the first phase, identifying all the possible hazards from the operation of the system based on BS IEC 61882. In the second phase, by Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) methods, the frequencies of event were calculated and assess the consequences of oil leakage and the radius of heat intensity that possibly appeared. The assessment of the consequences of this study was carried out using fire modelling approach to determine the consequences of an accident. In the third phase, the risk level is represented against the risk acceptance criteria using F-N curve and UK HSE standard. In the fourth phase, if the level of risk of third phase laid in unacceptable region, a mitigation process is necessary. The workflow of methodology is shown in Figure 1.

As mention above, the F-N curve with UK HSE standard applied for risk evaluation as a representation of the results of the relationship between F and N. Whereby, F is the value of the frequency obtained from the results of the frequency analysis in events per year, represented in y-axis and N is the number of fatalities of the event or consequence, represented in x-axis. The combination of the F value and the N value is plotted to determine whether the risk is acceptable or not.

![Figure 1. Flowchart of Risk Assessment.](image)

![Figure 2. UK HSE Risk Acceptance Criteria.](image)
Risk acceptance of UK HSE standard grouped into 3 regions i.e. broadly acceptable, ALARP, and intolerable/unacceptable area as expressed in Figure 2. The upper bound of risk acceptance has been set at 1.0E-03 per year for non-public or workers. If the risk level exceeds this limit, then the risk level categorized in unacceptable/intolerable area [9].

3. Risk Analysis and Results

3.1 Hazard Identification

Hazard identification is the initial process of societal risk assessment, it used to identify potential hazards that may occur during operation [1]. Hazard and Operability (HAZOP) is a method that commonly used to analyse the specific hazard potential of a system. HAZOP aims to knowing the cause of the potential hazard occurred and generate the type of consequence analysis that must be taken [13]. The processing of crude oil into a finished product is carried out in a large refinery area with a complex system inside. Therefore, the area of refinery needs to be segregated into several parts, this segregation will help create relevant scenario based on the refinery system. The segregated area of refinery unit also can be called as nodes. The node and area segregation are shown in Figure. 3 and defined in Table. 1. On this case there are 8 nodes, the determination of this nodes based on the specific function of each location and the phase of hydrocarbon handled in the system.

![Figure 3. Node Identification.](image)

| Nodes | Information |
|-------|-------------|
| Node 1 | This node is focused on storing condensate in a feedstock before the transferring system for processing. |
| Node 2 | This node includes the pipeline and its components starting from the feedstock tank to transfer condensate into pre-cut column. |
| Node 3 | This node is focused on the pipeline transfer from the pre-cut column to the condensate splitter. |
| Node 4 | This node is focused on the analysis of components in the pipeline from the condensate splitter to the distillate column. |
| Node 5 | This node is about process of transferring oil from distillate column to diesel stripper |
| Node 6 | Node 6 focused on the transfer pipeline that is transferring diesel oil to diesel storage tank. Diesel oil that has been warmed up many times in the previous stage will be cooled before entering the storage tank. |
| Node 7 | This node is focused on filling and storing diesel oil in diesel storage tank. |
| Node 8 | The transfer process using pipes from the diesel storage tank to the vessel |

3.2 Frequency Analysis

In this paper, the Frequency emphasize on two principal frequencies. First, analysis frequency of the oil release and estimated using Fault Tree Analysis (FTA). Second, the Event Frequency and estimated using Event Tree Analysis (ETA).
3.2.1 Fault Tree Analysis

The FTA is used to obtain the initiating event at each node based on the failure frequency of each component at each node. FTA calculating the failure frequency within the case boundaries on Piping and Instrumentation Diagram, such as control valves, safety valves, instrument connections, pumps, feedstock tank, etc [1]. The failure frequency for different hole sizes are calculated based on failure frequency data adopted from DNV Failure Frequency Guidance and International Association of Oil and Gas Producers (IOGP) datasheet. The result of frequency failure for each node with different leakage diameter presented in Table 2.

| Node | Top Event | Failure Frequency |
|------|-----------|-------------------|
| 1    | Oil Release | 4.3E-4 1.3E-4 4.2E-5 1.04E-5 1.76E-5 |
| 2    | Oil Release | 6.8E-5 6.7E-6 6.7E-7 1.69E-8 7.9E-9 |
| 3    | Oil Release | 5.6E-3 1.72E-3 5.2E-4 7.6E-5 2.13E-4 |
| 4    | Oil Release | 5.2E-3 1.7E-3 5.3E-4 7.6E-5 5.9E-5 |
| 5    | Oil Release | 5.2E-3 1.7E-3 5.3E-4 7.6E-5 5.9E-5 |
| 6    | Oil Release | 6.1E-3 1.8E-3 6.3E-4 1.1E-4 9.6E-5 |
| 7    | Oil Release | 3.2E-3 2.9E-3 2.8E-3 2.8E-3 2.8E-3 |
| 8    | Oil Release | 4.1E-3 1.2E-3 3.7E-4 7.4E-5 1E-4 |

3.2.2 Event Tree Analysis

Event Tree Analysis (ETA) is a method used to identify and evaluate possible outcomes if an initiating event occurs due to equipment failure or human error [2]. The purpose of the ETA is to determine whether the initial event will develop into a serious accident or the incident is sufficiently controlled by the safety systems and procedures implemented by the design. The initial event in this case is an oil release. The release of oil can cause a pool fire if there is an ignition from the ignition source. The calculation of oil release is formulated as follows:

\[ Q_L = 2.1 \times 10^{-4} \times d^2 \times \sqrt{\rho_L \times P_L} \]  

(1)

Where:
- \( d \) = hole diameter (mm)
- \( \rho_L \) = liquid density (kg/m³)
- \( P_L \) = initial pressure of liquid (bar gauge)

The fluid density of the condensate is 828.1 kg/m³ and the initial pressure is 9.3 bar. The results of the calculation of the oil release are presented in Table 3.

| No. | Hole Diameter (mm) | Density of Condensate (kg/m³) | PL (bar) | Mass of Oil Release at Higher Range of Hole (kg/s) |
|-----|-------------------|-------------------------------|----------|-----------------------------------------------|
| 1   | 3                 | 828.1                         | 9.3      | 1.66E+01                                      |
| 2   | 10                | 828.1                         | 9.3      | 1.23E+00                                      |
| 3   | 50                | 828.1                         | 9.3      | 3.07E+01                                      |
| 4   | 150               | 828.1                         | 9.3      | 2.76E+02                                      |
| 5   | 200               | 828.1                         | 9.3      | 4.91E+02                                      |

After calculating the ignition probability using equation 1, then determine the frequency for each consequence scenario using the ETA method. The input of ignition probability and probability ignition for immediate and delayed is obtained from OGP (International Association of Oil and Gas Producers). The ignition probability in OGP depends on the type of facility and the amount of gas released per unit time. The result of calculations for each node is shown in Table 4.
Table 4. The result of Event Tree Analysis.

| Node | Hole Diameter (mm) | Pool Fire | Evaporation | Nothing Happened |
|------|--------------------|-----------|-------------|------------------|
| 1    | 50                 | 2.87E-06  | 3.55E-07   | 3.88E-05         |
|      | 150                | 4.98E-06  | 6.16E-07   | 4.80E-06         |
|      | >150               | 1.01E-05  | 1.25E-06   | 6.24E-06         |
|      | 50                 | 4.58E-08  | 5.66E-09   | 6.19E-07         |
| 2    | 150                | 8.10E-09  | 1.00E-09   | 7.80E-09         |
|      | >150               | 4.54E-09  | 5.61E-10   | 2.80E-09         |
|      | 50                 | 3.55E-05  | 4.39E-06   | 4.80E-04         |
| 3    | 150                | 3.59E-05  | 4.44E-06   | 3.46E-05         |
|      | >150               | 1.22E-04  | 1.51E-05   | 7.55E-05         |
|      | 50                 | 3.62E-05  | 4.48E-06   | 4.89E-04         |
| 4    | 150                | 3.64E-05  | 4.50E-06   | 3.51E-05         |
|      | >150               | 3.39E-05  | 4.19E-06   | 2.09E-05         |
|      | 50                 | 3.62E-05  | 4.48E-06   | 4.89E-04         |
| 5    | 150                | 3.64E-05  | 4.50E-06   | 3.51E-05         |
|      | >150               | 3.39E-05  | 4.19E-06   | 2.09E-05         |
|      | 50                 | 3.10E-05  | 3.83E-06   | 5.95E-04         |
| 6    | 150                | 4.87E-05  | 6.02E-06   | 5.53E-05         |
|      | >150               | 4.93E-05  | 6.09E-06   | 4.06E-05         |
|      | 50                 | 1.38E-04  | 1.70E-05   | 2.65E-03         |
| 7    | 150                | 1.24E-03  | 1.53E-04   | 1.53E-04         |
|      | >150               | 1.44E-03  | 1.78E-04   | 1.78E-04         |
|      | 50                 | 1.82E-05  | 2.25E-06   | 3.50E-04         |
| 8    | 150                | 3.28E-05  | 4.05E-06   | 3.72E-05         |
|      | >150               | 5.14E-05  | 6.35E-06   | 4.23E-05         |

3.3 Consequence Analysis

Consequence analysis is carried out to determine the effect of the scenario contained in the ETA calculation. In this study, a consequence analysis is implemented to specify the impact of fire on the facilities and personnel in the location of the incident.

3.3.1 Pool Fire

Pool fire occurs when a hydrocarbon liquid that accidentally release accumulates on an area and ignites [2]. The pool will spread until it is constrained by physical impediments such as reach an equilibrium size. When first ignited, the fire spreads quickly over the hydrocarbon pool and continues to consume the fluid at a characteristic burning rate. The flame height will be at variance with the pool diameter and the flame may be inclined by any cross wind. Data on affected areas and the number of personnel on site are required for consequence modelling. Table 4 shown the list of affected areas and the number of personnel.

Table 5. Receiver area and the number of workers.

| Receiver | Location | Corresponding Node | Number of Workers |
|----------|----------|---------------------|-------------------|
| 1        | Feedstock tank 1 | 1 | 2 |
| 2        | Feedstock tank 2 | 1 | 2 |
| 3        | Storage tank area 1 | 2 | 8 |
| 4        | Central control building | 3 | 25 |
| 5        | Pre-cut column | 3 | 2 |
| 6        | Condensate splitter | 4 | 2 |
| 7        | Power control room | 4 | 2 |
| 8        | Distillate column | 5 | 2 |
| 9        | Diesel splitter | 6 | 2 |
| 10       | Diesel splitter to diesel storage tank | 6 | 4 |
| 11       | Diesel storage tank | 7 | 2 |
| 12       | Storage tank area 2 | 7 | 6 |
| 13       | Berth | 8 | 4 |
| 14       | Marine control building | 8 | 8 |
The simulation result of pool fire modelling is shown in Figure 4 and the calculation result for pool fire consequence analysis using fire modelling approach is presented on Table 6.

![Pool Fire Modelling](image)

**Figure 4.** Pool fire modelling for node 2 with leakage diameter of >150 mm.

**Table 6.** The result of pool fire modelling using fire modelling approach.

| No. | Receiver                  | Leak Bore Diameter (mm) | Corresponding Node | Number of People | Pool Diameter (m) | Heat Intensity Radius 4 kW/m² | Heat Intensity Radius 12.5 kW/m² | Heat Intensity Radius 37.5 kW/m² |
|-----|---------------------------|-------------------------|--------------------|------------------|-------------------|-------------------------------|----------------------------------|----------------------------------|
| 1   | Feedstock Tank 1         | 50                      | 1                  | 2                | 16.87             | 64.82                         | 42.35                            | -                                |
|     |                           | 150                     |                    |                  | 52.39             | 109.49                        | 50.04                            | -                                |
|     |                           | 200                     |                    |                  | 70.42             | 132.53                        | 59.46                            | -                                |
|     |                           | 50                      |                    |                  | 16.87             | 64.82                         | 42.35                            | -                                |
| 2   | Feedstock Tank 2         | 150                     | 1                  | 2                | 52.39             | 109.49                        | 50.04                            | -                                |
|     |                           | 200                     |                    |                  | 70.42             | 132.53                        | 59.46                            | -                                |
|     |                           | 50                      |                    |                  | 52.39             | 109.49                        | 50.04                            | -                                |
| 3   | Storage Tank Area 1      | 150                     | 1                  | 8                | 70.42             | 132.53                        | 59.46                            | -                                |
|     |                           | 200                     |                    |                  | 70.42             | 132.53                        | 59.46                            | -                                |
| 4   | Central Control Building | 150                     | 2                  | 50               | 6.60              | 33.98                         | 25.29                            | 12.14                            |
|     |                           | 200                     |                    |                  | 6.61              | 33.50                         | 24.81                            | 11.64                            |
|     |                           | 50                      |                    |                  | 5.41              | 32.11                         | 24.46                            | 13.39                            |
| 5   | Precut Column            | 150                     | 2                  | 2                | 6.60              | 33.98                         | 25.29                            | 12.14                            |
|     |                           | 200                     |                    |                  | 6.61              | 33.50                         | 24.81                            | 11.64                            |
| 6   | Condensate splitter      | 150                     | 4                  | 2                | 6.56              | 33.88                         | 25.24                            | 12.26                            |
|     |                           | 200                     |                    |                  | 6.57              | 33.41                         | 24.76                            | 11.77                            |
|     |                           | 50                      |                    |                  | 5.36              | 31.98                         | 24.37                            | 13.40                            |
| 7   | Power room control       | 150                     | 4                  | 2                | 6.56              | 33.88                         | 25.24                            | 12.26                            |
|     |                           | 200                     |                    |                  | 6.57              | 33.41                         | 24.76                            | 11.77                            |
|     |                           | 50                      |                    |                  | 5.33              | 31.88                         | 24.30                            | 13.52                            |
| 8   | Distillate column        | 150                     | 5                  | 2                | 6.48              | 33.71                         | 25.13                            | 12.20                            |
|     |                           | 200                     |                    |                  | 6.49              | 33.25                         | 24.66                            | 11.74                            |

3.4 Risk Evaluation
Risk evaluation is concerned to determine the level of risk that produced by refinery operation based on the frequency and consequence analysis. In this paper, risk evaluation using F-N curve and UK HSE standard. The risk evaluation for pool fire with leakage diameter of 200 mm is shown in Figure 5. Based
on the result of risk evaluation of pool fire scenario, the risk level of pool fire is categorized in unacceptable area because exceeds the upper bound of risk acceptance (1.0E-03 per year). Therefore, mitigation process is necessary to obtain the risk level in the ALARP area.

4. Mitigation
Mitigation is an action that applied when the risk level of risk evaluation categorized as an unacceptable category. Mitigation process commonly suggested in order to reduce risk from hydrocarbon fires at refinery. Mitigation method used in this research is LOPA (Layer of Protection Analysis) method. The main purpose of using LOPA is to identify preventive measures against potential consequences of certain risks by adding an Independent Protection Layer (IPL) as a step to reduce the failure frequency in order to maintain the level risk remain in ALARP area. Mitigation is performed by installing gas detector and CO₂ system as an IPL to the system. The worksheet of LOPA and risk evaluation after applied mitigation process is shown in Figure 6.

![Figure 5. F-N curve for pool fire with leakage diameter of 200 mm.](image1)

![Figure 6. (a) LOPA Worksheet; (b) Risk evaluation after mitigated.](image2)
5. Conclusion
Societal risk assessment has been carried out on refinery operation to quantify the risk level of personnel caused by process hydrocarbon hazard events. The first step of risk assessment is identifying all the possible hazards from the operation of the system based on BS IEC 61882 then the frequencies of event were calculated and assess the consequences of oil leakage and the radius of heat intensity that possibly appeared. The risk level is represented against the risk acceptance criteria using F-N curve and UK HSE standard. Based on result of risk evaluation, the risk level of pool fire consequence is in unacceptable region. Hence, mitigation process was carried out. From mitigation process presented in chapter 4, shows that pool fire scenario is lower than acceptable limit of 1.0E-03. Therefore, we can conclude that the risk level of refinery within ALARP (As Low As Reasonable Practicable) region.

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