Malaysian Journal of Chemical Engineering & Technology 5(2) (2022) 132–147

Malaysian Journal of Chemical Engineering & Technology

Journal Homepage: http://myjms.mohe.gov.my/index.php/mjcet

e-ISSN: 2682-8588

Economic loss risk assessment for pressure variation on methanol production

[a] Mohd Aizad Ahmad *, [a] Zulkifli Abdul Rashid, [a] Mohd Fazril Irfan Ahmad Fuad, [b] Iqbal Jamaludin, [c] Arman Abdullah, [a] Azil Bahari Alias

[a] INPRES, School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia.
[b] Kulliyyah Allied Health Sciences, International Islamic University Malaysia, Kuantan, Pahang, Malaysia.
[c] Fakulti Teknologi Kejuruteraan Kimia, Universiti Malaysia Pahang, Gambang, Pahang, Malaysia.

*Corresponding email: mohdaizad@uitm.edu.my

Abstract

The purpose of this paper is to assess the economic loss risk by combining economic loss and frequencies of events per year on methanol production due to piping and reactor incidents. This study assessed the amount of economic loss caused by fatalities-injuries, equipment damage, business disruption, and emergency services of toxicity, thermal radiation, and overpressure events on various pressure reactor conditions for a proposed methanol plant in Manjung, Perak, Malaysia. These case studies compare 7 plants comprising the Conventional Plant using a pressure of 76 bar and reactor size of 42 m^3 and 6 modified plants using downsize reactor of 7.6 m^3 and having pressure conditions of 76, 100, 200, 300, 400, and 500 bar, respectively. The methanol reactor has hazardous chemicals of hydrogen, carbon dioxide, carbon monoxide, and methanol. The number of fatalities-injuries and equipment damage loss was estimated using consequence analysis multiplied by the monetary value of people and equipment. Business disruption loss is calculated using plant outage time and Industry Value Added per employee while emergency service loss is two percent of overall loss. Results proved that the Conventional Plant has a total economic loss risk of RM 766.5k annually while all modified plants have safety improvements between 64% to 89% compared to the Conventional Plant.

Article Info

https://doi.org/10.24191/mjcet.v5i2.19543

Article history:

Received date: 7 September 2022
Accepted date: 28 October 2022
Published date: 31 October 2022

Keywords:

Equipment damage
Fatalities-injuries
Incidents
Piping
Reactor

1.0 Introduction

According to Barbarossa et al., (2014), the increasing amount of carbon dioxide being released into the environment has raised concern in every community such as the industrial community, people, and government. Carbon dioxide is the main cause of the greenhouse gas (GHG) effect and thus contributes to global warming. Based on statistics, around one-third of worldwide anthropogenic carbon dioxide emission comes from industrial activity (Berghout et al., 2013) because they release a significant amount of carbon dioxide to the environment without any technology applied to reduce the emission. The increasing amount of carbon dioxide in the atmosphere will only contribute to climate change. The fossil fuel power generation sector is one of the bigger contributors to carbon dioxide emissions. This situation is likely to continue for another decade because of the increasing dependence on fossil fuels in the power industry. Carbon capture utilization (CCU) is recognised as a new business benefit for carbon dioxide since captured carbon dioxide can be utilised as the main feedstock for other chemical production. The chemical products involved are carbonates, formic acid, methanol, and fuels such as kerosene and methane.

As emphasised by Olah (2005), methanol as a fuel is a crucial potential, as it can be used as normal fuel for mobile transportation, and can be selected as raw material to produce olefin, which can synthesise hydrocarbons. Production of methanol as liquid fuel is also studied in other transportation modes such as maritime (Brynolf et al., 2014) and aviation (Atsonios et al., 2015), while there is also potential production of hydrogen from methanol for vehicles (Nielsen et al., 2013). A methanol economy could provide more production of methanol, as suggested in the USA and

China (Faberi et al., 2014). However, methanol production using the conventional method, which is from coal or natural gas will contribute to more emissions of GHG and increase water consumption (Yao et al., 2018). Thus, methanol production using carbon dioxide as raw material is the way forward, as methanol can be produced from two pathways; the first is carbon dioxide directly reacting with H_2 to produce methanol whereas the second path is converting carbon dioxide into carbon monoxide, then the carbon monoxide would react with hydrogen and synthesised methanol (Van-Dal & Bouallou, 2012). There are also alternative methods using electrochemical, which are the reduction of carbon dioxide in a fuel cell (Albo et al., 2015; Agarwal et al., 2011; Yamamoto et al., 2002) and photo-electrochemical cell using solar energy (Ampelli et al., 2011).

Their researchers established lab-scale experiments on producing higher conversion of carbon dioxide and higher selectivity of CCU-methanol from carbon dioxide hydrogenation using high-pressure conditions (Bansode, 2014; Bansode & Urakawa, 2014; Gaikwad et al., 2016; Gaikwad, 2018). These are the groups of researchers from the Institute of Chemical Research of Catalonia (ICIQ) that study methanol production on a lab scale. They emphasise the effect of different pressure, temperatures, molar ratio, and Gas Hourly Space Velocities (GHSV) on carbon dioxide conversion and methanol selectivity. Their results achieved a high carbon dioxide conversion of 89.9% and high selectivity of 87.61% of methanol using a pressure of 442 bar, a temperature of 288 °C, the molar ratio of 1:3, and a lower GHSV of 625 h-1. A low GHSV means a higher volume of the reactor is needed (Gaikwad et al., 2016). Another study has produced an energy consumption analysis of a simulated large-scale green methanol production plant using high pressure (Tidona et al., 2013) and suggested that the most energy consumed for this high-pressure process comes from the electrolysis of water to produce hydrogen, not from the compression of the reactants. This statement is backed up by the calculation of energy consumption in their study of a 1 million tons (Mt) per year methanol production plant. A study of how high-pressure condition affects energy consumption showed that pressure at 400 to 1000 bars only contributes 3-5% carbon dioxide compression and 16-26% hydrogen compression of total power requirement (Tidona et al., 2013).

With researchers have achieved breakthrough results in producing more methanol at a higher pressure and eliminating recycle stream as proven by the researcher of ICIQ (Bansode, 2014; Bansode & Urakawa, 2014; Gaikwad et al., 2016; Gaikwad, 2018), the modification of process condition of CCU-methanol production plant in large-scale using high pressure attracts author to assess this plant in term of economic loss risk analysis as no researcher has ever published their work on this particular issue. Recent developments in 2016 at the lab scale of synthesis methanol using high-pressure to increase methanol production draw attention to its safety if it is implemented at large-scale production although there are claims that this condition is safer because reactor volume is reduced (Gaikwad et al., 2016; Gaikwad, 2018). However, there are arguments on safe distance for people and equipment to the effect of toxicity, thermal radiation, and explosion when the high-pressure condition of 442 bar or higher is applied to this plant. There are also questions on the effect of various pressures, with high-temperature reactor combinations on the economic loss risk (Heikkilä, 1999).

Methods to assess the economic impact of an accident in a nuclear reactor were proposed by (Higgins et al., 2008). Authors have pointed out the methodology to determine the monetary value of total accident cost derived from business disruption cost (direct and indirect effect), tourism consumption cost, recovery after accident cost, and health cost involving people. As a result, the more accurate economic impact of the accident using the proposed method can be determined and used as a guideline by authorities.

A comprehensive economic impact assessment of accidents in major chemical hazard facilities is then reported by Health, Safety and Environment (HSE), a United Kingdom (UK) agency (Aldrige et al., 2015). HSE UK proposed a methodology to quantitatively determine the monetary value of total accident cost derived from population cost (fatalities and injuries), evacuation cost, building damage cost, business disruption cost (direct and indirect effect), and emergency services. This proposed method can determine accurately the economic impact of chemical facility accidents and is a useful guideline for authorities.

The 61508 Association has published articles where it discussed guidelines to perform As Low As Reasonably Practicable (ALARP) in process industries (Association, 2019). The report established a framework of cost for risk reduction measures and Safety Integrity Level (SIL) for targeted ALARP for every scenario according to the exposed group in a process plant industry. Therefore, the cost for risk reduction measure and SIL determined can be used for risk reduction budget/allocations per year, as proven by calculations in the proposed framework.

2.0 Methodology

Quantitative Risk Assessment (QRA) has been performed, where the results from consequence and frequency analysis are used as the input to conduct an economic loss risk assessment. This study assessed the amount of economic loss caused by fatalities-injuries, equipment damage, business disruption, and emergency services of toxicity, thermal radiation, and overpressure events on various pressure reactor conditions for a proposed methanol plant in Manjung, Perak, Malaysia. These case studies compare 7 plants comprising the Conventional Plant by (Pérez-Fortes et al., 2016) using the pressure of 76 bar and reactor size of 42 m^3; and 6 modified plants using downsize reactor of 7.6 m^3 and having a pressure condition of 76, 100, 200, 300, 400 and 500 bar, respectively. The methanol reactor has hazardous chemicals of hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO), and methanol (MeOH).

The number of fatalities-injuries and equipment damage loss was estimated using consequence analysis multiplied by the monetary value of people and equipment. Business disruption loss is calculated using plant outage time and Industry Value Added (VA) per employee while emergency service loss is two percent of overall loss. The comparison between every plant has been made for further discussion. Finally, all the plants have been assessed in terms of economic loss risk for all possible scenarios including Vapour Cloud Explosion (VCE), jet fire, and toxicity for both reactor and piping systems. The methodology to conduct an economic loss risk assessment is depicted in Fig. 1.

2.1 *Economic loss method*

To assess whether the cost of implementing measures to reduce risk is justified or not, HSE UK has regulated the Major Hazard Industry (MHI), plant owners to apply cost-benefit analysis for testing. MHI plant owners must take necessary actions and measurements of reducing risk where it can be assessed on how risk is reduced to a level that is as low as reasonably practicable (ALARP). Individual risk levels using HSE-UK criteria categorie three regions which are intolerable region, tolerable if ALARP, and broadly acceptable. The intolerable region constitutes a must risk reduction applied regardless of cost, while tolerable if the ALARP region requires the duty holder to reduce the risk where reasonably practicable as if the cost is not in gross disproportion to the benefits achieved. Broadly acceptable region stipulates that no need for further risk reduction, but to only maintain good practice and not necessarily detailed working to demonstrate ALARP (HSE, 2017), (HSE, 2019). In the ALARP principle, the cost of a measure must be grossly disproportionate for that measure to be considered not to be implemented. The value of the gross disproportionate factor has been discussed, while no exact value is quantified. ALARP framework guidelines (Association, 2019) have suggested a gross disproportion factor of 5 to be used for Cost Benefit Analysis (CBA) in ALARP assessment.

To quantify the cost of reduction measures, one must look at the benefits avoided as reduction measure is implemented for that plant. The benefit of avoiding an accident which can be described as economic loss is derived from the modelling of economic impacts of an accident at major hazard sites, proposed by the expert in HSE UK (Aldrige et al., 2015). In this accident model, the source of total economic loss is identified as the sum of (i) cost of injuries and fatalities, (ii) cost of business disruption loss, (iii) cost of equipment damage, and (iv) emergency services cost. The data is evaluated based on the year 2018. Conversion data of the non-other year of 2018 would be used as Malaysia's Gross Domestic Product (GDP) deflator of that year with the year 2018 value.

2.1.1 *Economic loss due to fatalities and injuries*

The cost of fatalities in Malaysia is Ringgit Malaysia (RM) or Malaysia Ringgit (MYR) 2.3 million while the injuries cost is 10% of the cost of fatalities which is RM 0.23 million, based on 2017 data (Bernama, 2018). The cost of fatalities data is determined based on the statement of the Director-General of Jabatan Pengangkutan Jalan (JPJ) for fatalities due to road accidents (Bernama, 2018). The cost of injuries is set as 10% of the cost of fatalities based on the setting by JPJ in another document referred to by the author (Yusoff et al., 2011), (Yusof et al., 2013). The cost of fatalities and injuries refers to road accidents and is assumed applicable to the workers in the chemical plant in Malaysia as the value of non-financial human for fatal at the workplace is similar to fatal due to road accidents in the report by Health and Safety Executive and Department for Transport values for the prevention of road accidents in the United Kingdom (UK) (Aldrige et al., 2015). The GDP deflator of Malaysia in 2017 and 2018 is 104.5 and 105, respectively. The 2018 value is based on the 2017 value, which has been inflated using GDP deflators, as published by the Trading Economics website (Malaysia GDP Deflator 2000-2020 Data, 2020). Table 1 shows the cost of fatalities and injuries in Malaysia for 2018.

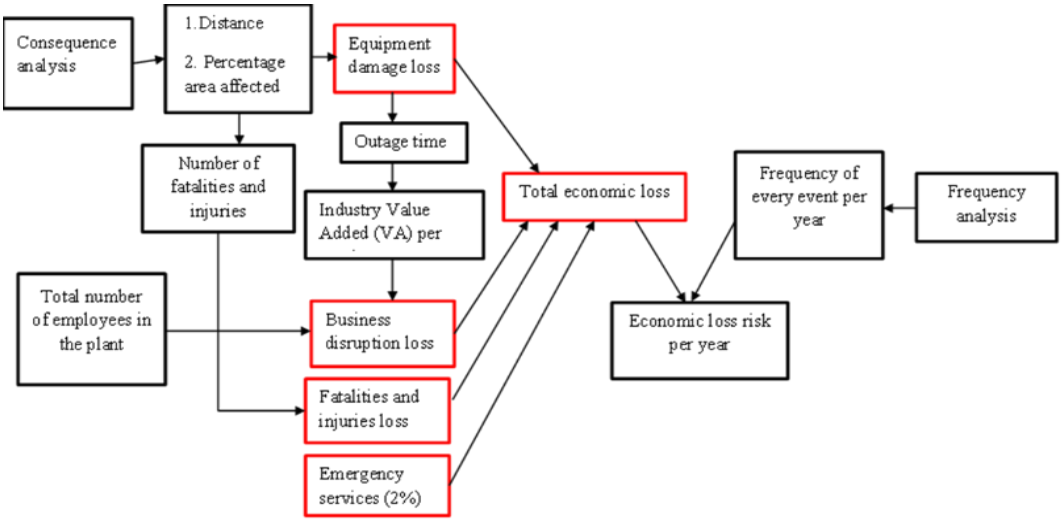

Fig. 1: Methodology for economic loss risk assessment

The benefits of avoided injuries and fatalities derive from the affected area of the orange zone and red zone estimated in consequence analysis, as listed in Table 2. For incident outcome cases of vapor cloud explosion (VCE) and jet fire, the orange zone constitutes a probability of 1 for injuries and 1 for fatalities in the red zone. However, for incident outcome cases of toxicity, only the red zone is considered fatality with the probability of 1 outdoor, while people indoors with red zone have 0.5 fatalities, and the remaining people indoors are considered to have serious injuries. Examples of outdoor locations are the processed plant area and utility area while indoors are the control room, office, and workshop/maintenance/laboratory. Orange zone is not considered serious injuries for toxicity because people exposed to this incident are plant operators which have a low vulnerability to the chemicals. Injuries for the calculation of benefit avoided are assumed to be serious injuries, while minor injuries are not applicable.

Red zone criteria for VCE incidents must fall into overpressure of 0.6 bar and more, while the orange zone is between 0.24 to 0.6 bar. 0.6 bar can cause fatalities and destruction of buildings while 0.24 bar is likely to cause serious injury. Jet fire incidents can potentially cause death in 60 seconds for the red zone which must have thermal radiation of 10 kW/m² and more, while the orange zone which has thermal radiation between 5 kW/m² to 10 kW/m² could cause 2nd-degree burns (serious injuries) within 60 seconds. Red zone criteria for the toxicity of carbon monoxide must have an Acute Exposure Guideline Levels -3 (AEGL-3), which has a concentration of 330 ppm and more, while for methanol toxicity, its red zone and level of its AEGL-3 is a concentration of 7200 ppm and more. For carbon dioxide toxicity concentration, red zone criteria must have an Immediately Dangerous to Life or Health (IDLH) of 40,000 ppm and more. The value of AEGL-3 constitutes a concentration of chemicals exposure to an individual for 60 minutes which could cause death while IDLH imposes a maximum concentration to which an individual could be exposed without permanent health effects (Jones et al., 2013). Table 2 shows the probability of fatalities and injuries according to incident outcome cases and zones.

2.1.2 Economic loss due to business disruption

Business disruption loss is estimated by evaluating the potential loss of industry Value-Added (VA) and then relating it to employment. Business disruption loss can be categorised into direct effect and indirect effect. Loss directly affected industries are calculated by loss of potential VA per year and per worker in this industry. In this case study, the methanol plant is considered as the manufacturing industry, thus data of VA for the manufacturing sector is used. In 2017, the Malaysian manufacturing industry recorded a VA of RM 294 billion with 2,214,883 employees in this sector, thus VA per employee per year is RM 132,738.4 (Kei, 2018).

The direct effect of business disruption loss is assumed to be lost during the period of this business closed and the employees need to be evacuated. For methanol plants, the period of business closed is assumed to be equal to the period of outage or shutdown in terms of the day needed, and the number of outage days is determined by the cost of equipment damage that needs to be repaired. Therefore, the potential direct effect of business disruption loss is determined by how many days of outage plants are per 365 days in a year and the number of employees involved in this particular methanol plant.

Meanwhile, business loss indirectly affected by the methanol plant is using a multiplier based on Input-Output for the UK according to the industries listed. According to the table presented by HSE-UK (Aldrige et al., 2015), the manufacturing industry for the chemicals sector has a multiplier effect of 2.82 for indirect loss, thus giving a total of business disruption the sum of direct business disruption loss and indirect business disruption loss.

As the data for VA per employee is for 2017, the GDP deflator for 2017 and 2018 is used to inflate the VA in 2018. The GDP deflator of Malaysia in 2017 and 2018 is 104.5 and 105, respectively. Table 3 tabulates the total business disruption loss per year and day for every employee in the manufacturing plant in 2018.

2.1.3 Economic loss due to equipment damage

Method to quantify equipment damage cost in methanol plant is using area affected for red zone and orange zone, then taking imposed area to the value of the damage for three areas in the plant –(i) H_2 and CO_2 compression section, (ii) methanol formation section and (iii) methanol purification section. The value of damaged equipment installed for every section of the methanol plant is calculated based on the value of repair or replacement cost data used by Orbit onshore in 2005, as cited by the authors (Jones et al., 2013), (Bardy et al., 2008). The cost of repair or replacement for every piece of equipment is listed in Table 4, and the total number of the equipment with cost per unit per every section for the Conventional Plant is identified and tabulated in Table 5.

Every plant has a different repair cost for every section, as this repair cost depends on the capacity production of the plant. The method calculation according to the production capacity uses cost curve methods, adapted from the book author by (Towler & Sinnott, 2021). The cost curve method is given by Eq. (1).

$$C_2 = C_1\left(\frac{S_2}{S_1}\right) \tag{1}$$

where C_2 is the repair cost of the plant with a capacity of S_2 and C_1 is the repair cost of the plant with a capacity of S_1.

Repair cost for Conventional Plant is used as the base calculation for modified plants. At H2 and CO_2 compression section, totaling repair cost of USD 1.76 million is needed if the whole section is damaged. Meanwhile, at the MeOH formation and MeOH purification section, USD 935,000 and USD 620,000 need to be used respectively for the repair of the total damage to equipment.

Table 6 summarises the total repair cost for every section in the plant and for all plants studied using price in USD, in the year 2005. H_2 and CO_2 compression section cover area of 67,962 ft², while MeOH formation and purification section utilise 75,168 ft² and 58,362 ft², respectively.

Table 1: Cost of fatalities and injuries in Malaysia (price in RM, the year 2018)

Type of Accident	Accident Cost (RM)
Workplace fatal accidents	2,311,005
Serious injuries	231,100

Table 2: Probability of fatalities and injuries for incident outcome cases and zone

Type of Incident Outcome Cases	Probability (Red Zone)	Probability (Orange Zone)
VCE– fatalities	1	0
VCE– injuries	0	1
Jet fire - fatalities	1	0
Jet fire - injuries	0	1
Toxicity - fatalities	Outdoor people - 1; Indoor people – 0.5	0
Toxicity - injuries	Indoor people – 0.5	0

Table 3: Total business disruption loss per employee in 2018

Direct Business Disruption Loss Per Employee Per Year	Indirect Business Disruption Loss Per Employee Per Year	Total Business Disruption Loss Per Employee Per Year
2017	2017	2017
RM 132738.4	2.82 x RM 132738.4	RM 132738.4 + (2.82 x RM 132738.4)
2018	2018	2018
RM 132738.4 x (105/104.5)	(2.82 x RM 132738.4) x (105/104.5)	(RM 132738.4 + (2.82 x RM 132738.4)) x (105/104.5)
	Total business disruption loss per employee per year in 2018	RM509,486.82
	Total business disruption loss per employee per day in 2018	RM1395.85

Table 4: Repair or replace cost (USD, price 2005) for a variety of equipment types

Equipment Type	Repair or Replace Cost (USD)
Compressors	250,000
Reactors	80,000
Tanks	80,000
Heater	60,000
Large Pipes	50,000
Exchangers	50,000
Vessels	40,000
Medium pipes	20,000
Other/Generals	20,000
Column	10,000
Filters	10,000
Small pipes	5,000
Pumps	5,000

Table 5: Number of equipment and repair costs for every section in the Conventional Plant

Equipment Type	Unit	Cost Per Unit (USD)	Repair or Replace Cost (USD)
CO_2 and H_2 compression section			
Compressors	5	250,000	1,250,000
Exchangers	5	50,000	250,000
Medium Pipes	13	20,000	260,000
Total			1,760,000
Methanol formation section			
Compressors	1	250,000	250,000
Heaters	1	60,000	60,000
Exchangers	3	50,000	150,000
Reactor	1	80,000	80,000
Vessels	2	40,000	80,000
Medium Pipes	14	20,000	280,000
Small Pipes	3	5,000	15,000
Others	1	20,000	20,000
Total			935,000
Methanol purification section			
Compressors	1	250,000	250,000
Small Pipes	2	5,000	10,000
Exchangers	3	50,000	150,000
Column	1	10,000	10,000
Vessels	1	40,000	40,000
Medium Pipes	8	20,000	160,000
Total			620,000

Calculation of the total cost of equipment damage is based on the intersection area of the red zone and orange zone to every section of the plant (Cavanagh & Linn, 2006), (Bardy et al., 2008). Therefore, the total cost of repair for equipment damage is given by Eq. (2).

$$F_{repair,o} = v_{repair,h} * C_{repair} * a_{h,o} \tag{2}$$

where $F_{repair,o}$ is the repair cost for the incident outcome case, o, $v_{repair,h}$ is the repair vulnerability for hazard zone h for each incident outcome cases, $C_{repair,}$ is the repair cost for the entire area, and $a_{h,o}$ is fraction of the area covered by hazard zone h.

Repair vulnerability is based on the American Petroleum Institute (2016) which defines hazard caused by thermal radiation at 12.5 kW/m² as 50% equipment damage while 37.5 kW/m² as 100% equipment damage. In terms of hazards caused by overpressure, 4.35 psi contributes to 50% of equipment damage while 7.25 psi is 100% of equipment damage (Bardy et al., 2008). Table 7 summarises repair vulnerability for incident outcome cases and zone, involving jet fire and VCE in red and orange zone, respectively. For jet fire, the red zone has thermal radiation of 10 kW/m², which has 43% repair vulnerability while the orange zone, which ranges between 5 to 10 kW/m² has 28 % repair vulnerability using the calculation of the log-log relationship between repair vulnerability and thermal radiation as in Eq. (3) (Aldrige et al., 2015). For the VCE incident outcome, the red zone has the level overpressure of 8 psi, which has 100% repair vulnerability while the orange zone, which ranges between 3.5 psi to 8 psi has 37 % repair vulnerability using the calculation of the log-log relationship between repair vulnerability and overpressure as described in Eq. (3).

$$\frac{\log 100 - \log 50}{\log 100 - \log v_{repair,h}} = \frac{\log 7.25 - \log 4.35}{\log 7.25 - \log 3.5} \qquad (3)$$

The repair cost for the incident outcome case, $F_{repair,o}$ which is in the USD price of 2005, is then deflated to the price of 2018 using the CEPCI index value of 2005 and 2018. CEPCI index value for equipment in September 2005 is 541.2, while the CEPCI index value for equipment in August 2018 is 749.8 as retrieved on 9 August 2019 (Chemical Engineering, n.d.). Then, the $F_{repair,o}$ is converted from the price of USD in 2018 to Ringgit Malaysia (MYR) using the average conversion for the whole year 2018, which is MYR 4.04 for USD 1 (OFX, n.d.).

Equipment damage causes the plant to be shut down or outage for several days. Input from outage time will be used for the calculation of total business disruption loss especially VA loss per employee per day.

Method to calculate outage time in terms of the day uses API correlation (American Petroleum Institute, 2016) as in Eq. (4), using property damage value in 2005 (Cavanagh & Linn, 2006).

$$Outage\ time = 10^{\left(\left(\left(\log_{10}\left(\frac{Property\ damage\ value}{10^6}\right)\right)*0.58532\right)+1.24194\right)} \qquad (4)$$

For toxic events, which do not have any equipment damage, equipment damage loss is replaced by repair cost due to leakage or hole in reactor vessel or piping system. Every toxic which is MeOH toxic, CO_2 toxic, and CO toxic event is assumed to have a one-hole leak, therefore, the cost of repair is based on this one-hole leak. The cost of repair per one-hole confirmed defect is 1000 pound sterling based on Non-Destructive Test (NDT) data (Wall et al., 1998). This value is then deflated by comparing the GDP deflator of 1998 and 2005, which are 70.9 and 80.78, respectively (United Kingdom GDP Deflator 1955-2020 Data, 2020).

Therefore, the cost of repair for the toxic event is 1139 pounds sterling in 2005, converted to US Dollar becomes USD 2074, the same as in 2005 (OFX, n.d.). Thus, the cost of repair for one defected hole in 2005, USD is used to calculate the number of outage times.

Table 6 Total repair cost (USD, 2005) for each section in all plants

Plant	Total Repair Cost (if All Section Damage)		
	H_2 And CO_2 Compression Section (Price In USD, 2005)	Methanol Formation Section (Price In USD, 2005)	Methanol Purification Section (Price In USD, 2005)
Conventional Plant	1,760,000	935,000	620,000
Plant 76.4 bar	1,631,635	201,215	122,586
Plant 100 bar	1,641,442	257,273	160,586
Plant 200 bar	1,673,649	441,383	285,389
Plant 300 bar	1,702,937	608,805	398,881
Plant 400 bar	1,731,528	772,245	509,672
Plant 500 bar	1,733,461	783,294	517,162

Table 7 Repair vulnerability for incident outcome cases and zone [36]

Type of Incident Outcome Cases	Repair Vulnerability (Red Zone)	Repair Vulnerability (Orange Zone)
VCE	100% or 1	37 % or 0.37
Jet fire	43 % or 0.43	28 % or 0.28

2.1.4 Economic loss due to emergency services

Emergency services costs involve local authorities and public agencies doing protective measures, clearing debris, infrastructure replacement, extra staff cost, etc. An estimation of emergency cost is proposed by an HSE UK expert (Aldrige et al., 2015) which is a 2% amount of total accident cost. Total accident cost is the combination of fatalities and injuries cost, business disruption loss, equipment damage cost, and emergency services cost itself.

2.2 Frequency using event tree method

A list of hazardous incidents for every plant has been identified according to Purple Book (Stoffen, 2005). This book states that, if a mixture of various dangerous substances has its physical, chemical, and toxic properties, it should be treated in the same way as pure substances. Therefore, as suggested by Purple Book, the initiating events for continuous and instantaneous release involved hazardous chemicals in the mixture of CO_2-H_2-MeOH-CO-H_2O are pure chemicals of CO_2, H_2, MeOH, and CO. Thus, when a release occurred from reactor leakage, the mixture is treated as a separated event containing pure substance in the mixture which is the release of CO_2, H_2, MeOH and CO, respectively. Chosen representatives' size of leakages for the reactor and pipeline involves continuous and instantaneous release scenarios. For continuous-release, sizes of leakages are 10 mm and 25 mm, dedicated to incidents A and B, respectively, while for instantaneous release from the reactor, 160 mm hole is chosen, representing incident C, whereas, for the piping system, leakage size of 5 mm and pipe rupture of 150 mm are categorised as incident D and incident E, respectively.

Likelihood of frequencies analysis involved frequency of leak occurred at vessel and pipe, probability of the incident outcome, probability of wind direction, and probability of day and night condition. For pipe leakage, the frequency of leak also involves all equipment along the pipeline such as compressors, coolers, heaters, and others. Leak frequency for vessels and pipes is based on the Risk Assessment Data Directory published by the International Association of Oil and Gas Producers (OGP) (Norsok et al., 2010). The probability of incident outcomes is based on guidelines from Purple Book (Stoffen, 2005) where the probability is according to the hazardous characteristic of the chemical whether it belongs to toxic characteristic only chemical or has both toxic and flammable characteristics. As presented in Fig. 2, CO and CO_2 are considered toxic only chemicals, whereas the eventual scenario is only a toxicity scenario, which has a probability of 1. For H_2 and MeOH, both chemicals have both flammable and toxic characteristics, so the event tree is divided into H_2 and MeOH flammable; and H_2 and MeOH toxic.

H_2 and MeOH flammable follow the probability criteria of case I as illustrated in Fig. 3, while H_2 and MeOH toxic have incident outcome probability as shown in Fig. 4. Continuous sources below 10 kg/s or instantaneous sources below 1000 kg belong to the case I category, whereas continuous sources released between 10–100 kg/s and instantaneous releases subjected to 1000 to 10,000 kg are referred to as case II. For case I, the immediate ignition probability is 0.2 and no immediate ignition is 0.8, however, for case II, the probability of immediate ignition and no immediate ignition is 0.5 for both H_2 and MeOH. Therefore, another two-event tree is developed to describe possible incident outcome cases, as depicted in Fig. 5 and Fig. 6.

3.0 Results and discussion

3.1 Economic loss risk per year

Economic loss risk per year is calculated based on economic loss in Ringgit Malaysia (RM) multiplied by frequencies per year to indicate the level of risk for the Conventional Plant and 6 modified plants. Economic loss risk is identified according to the scenario that happened in the plants including VCE, jet fire, CO toxic, CO_2 toxic, and MeOH toxic for both reactor and piping systems. Economic loss risk indicates money per year that would be lost as all incidents listed happened in the plants, where higher economic loss risk can be given priority for risk preventive and mitigation measurement. Economic loss risk is compared among conventional plants and modified plants in terms of risk factors and safety improvement. A risk factor is a ratio between the economic loss risks of the modified plant to the conventional plant, while safety improvement is the difference between the risk value of the conventional plant to the modified plant divided by the conventional plant's risk value.

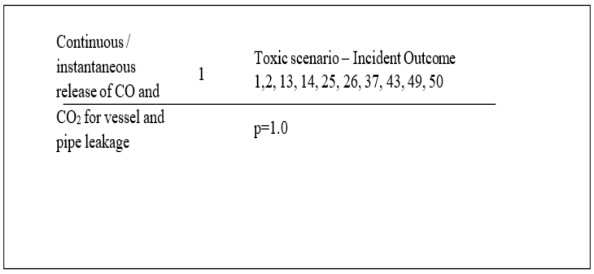

Fig. 2: Event tree of CO and CO_2 toxic release

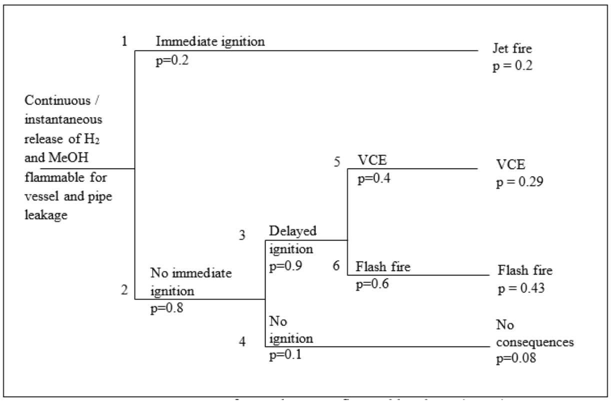

Fig. 3: Event tree of H_2 and MeOH flammable release (case I)

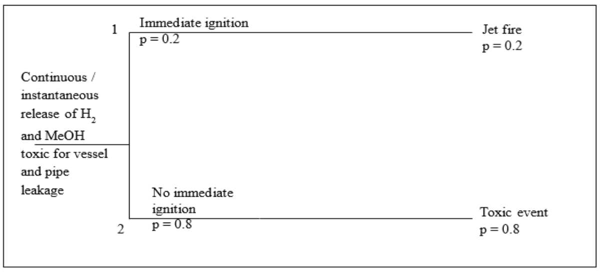

Fig. 4: Event tree of H_2 and MeOH toxic release (case I)

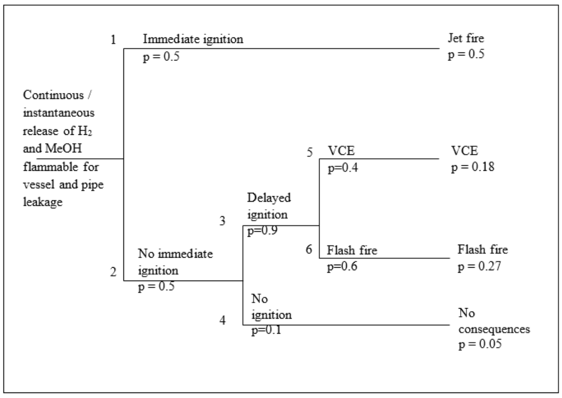

Fig. 5: Event tree of H_2 and MeOH flammable release (case II)

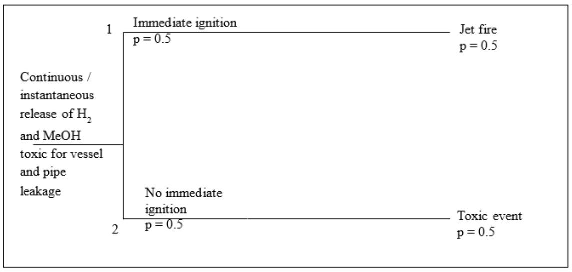

Fig. 6: Event tree of H_2 and MeOH toxic release (case II)

3.1.1 VCE scenario in a reactor

Economic loss risk per year is derived to compare conventional plants with 6 modified plants. It is observed that as the plant operates from 76 bar to 300 bar, the safety improvement decreases from 62% to 12%, but as pressure operates from 300 bar to 500 bar, the safety is improved to 80 %. The highest safety improvement for the VCE scenario in the reactor mostly contributes to the reduced amount of H_2 present and also there is no red zone threat for 25 mm leakage and 160 mm leakage at a higher pressure of 400 bar to 500 bar, as H_2 concentration dissipates quickly in the environment. Table 8 lists the economic loss (RM), frequency per year, risk per year (RM per year), risk factors, and safety improvement.

3.1.2 Jet fire scenario in a reactor

Jet fire scenario, which is contributed by MeOH and H_2 jet fire, has a minor impact on conventional plants compared to modified plants especially Plant 200 bar to Plant 500 bar. Table 9 shows a comparison of safety improvements from conventional plants to other modified plants. It is proved that as pressure increases from 200 bar to 500 bar, the safety improvement is negative as the economic loss risk is higher for Plant 200 bar to Plant 500 bar compared to the conventional plant.

The conventional plant only has an economic loss risk of about RM 951 per year, while Plant 400 bar risk has about RM 13,500 per year. It is also indicated that the jet fire scenario has increased with the presence of more methanol mass, as pressure is up from 200 bar to 500 bar.

3.1.3 A toxic scenario in a reactor

Economic loss risk for toxicity scenario in reactor contributed by released of MeOH, CO, and CO_2. CO and CO_2 have reduced hugely as pressure up to 500 bar from 76 bar, compared to the conventional plant, while MeOH toxicity has minor red zone threat although its amount increased. As shown in Table 10, the plant which operates at 400 and 500 bar has a safety improvement of about 89 to 93%, compared to a safety improvement of about 68% and below for plants operated between 76 bar to 300 bar. The main contributor to the huge reduction of economic loss risk is the largely reduced amount of CO mass present at Plant 400 bar and 500 bar.

3.1.4 VCE scenario in a piping system

Economic loss risk for VCE scenario at the piping system, as tabulated in Table 11 shows that Plant 500 bar has the highest risk among modified plants, which is RM 243, 877, with a risk factor 1.21 of for the Conventional Plant, while Plant 76 bar is only 0.08 risk factor of the Conventional Plant. It is also observed that as the plant operates from 76 bar to 500 bar, safety improvement decreased from 92% to 18% and experienced negative safety improvement, about 18% to 21% at operating pressure of 400 bar and 500 bar, respectively. The factor contributing to higher economic loss risk for Plant 400 bar and 500 bar is because of higher frequency of failure due to added compressors and heaters, plus more red zone footprint area is generated due to more mass and volume belonging to H_2 in the pipeline system.

3.1.5 Jet fire scenario in a piping system

The highest economic loss risk for the modified plant which is Plant 500 bar, has only 1% safety improvement compared to the Conventional Plant, due to higher frequency failure in Plant 500 bar, as presented in Table 12. Plant 76 bar illustrates the highest safety improvement for the jet fire scenario in the piping system, which is 89% and has a risk factor of 0.11. However, as the plant operates from lower to higher pressure until 500 bar, there is an increase in economic loss risk per year in a risk factor from 0.11 to 0.99. For this jet fire scenario in the piping system, the factor contributing to higher economic loss risk for Plant 400 bar and 500 bar is the same as the VCE scenario, where there is more H_2 mass present which can lead to bigger jet fire events and higher frequency of failure due to added compressors and heaters.

3.1.6 A toxic scenario in a piping system

Economic loss risk for the toxic scenario in the piping system has only happened in the conventional plant because it has carbon monoxide (CO) through its recycling stream, aside from carbon dioxide. However, although carbon dioxide also has a substantial quantity in Conventional Plant and modified plants, these amounts do not produce a red zone threat footprint, for all plants. Thus, the economic loss risk for the toxic scenario in the piping system only considers CO toxicity. Economic loss risk for CO toxic scenario in Conventional Plant is RM 368,738 per year, as presented in Table 13.

3.1.7 Total economic loss risk

Total economic loss risk is counted for every plant which comprises of economic loss risk for each scenario which is VCE, jet fire, the toxic scenario at the reactor; and VCE, jet fire, and toxic scenario at the piping system. All resulting economic loss risks for each scenario are summed up to get the total economic loss risk for all plants. Table 14 shows the total economic loss risk for each plant, with risk factors and safety improvement.

As presented in Table 14, the highest safety improvement among modified plants is Plant 76 bar, with 89%. Table 14 also list Plant 400 and 500 bar to achieve 64% safety improvement, although these plants need to operate at a higher pressure of 400 bar and 500 bar, respectively. Although the modified plants operate at a higher pressure of 400 and 500 bar, the safety is improved by 64% compared to the Conventional Plant, which operates at lower pressure of 76 bar.

Meanwhile, Fig. 7 shows how the economic loss risk factor changes as the operating pressure of the reactor are changed from 76 bar to 500 bar. The economic loss risk factor is the highest at pressure 400 bar and 500 bar with 0.36, as pressure increases from 76 bar to 500 bar. These results indicate that the higher the operating pressure of the reactor, the riskier the plant can be, however, compare with Conventional Plant, Plant 400 and 500 bar are still inherently safer because these modified plants produce safety improvement of 64% as they operated using downsize reactor of 7.6 m³.

Table 8 Economic loss risk for VCE scenario - reactor

Plant	Economic Loss (RM)	Frequency Per Year	Economic Loss Risk (RM/Year)	Risk Factor	Safety Improvement
Conventional Plant	6.32E+08	9.33E-05	58,928		
Plant 76 bar	2.39E+08	9.33E-05	22,271	0.38	62%
Plant 100 bar	3.38E+08	9.33E-05	31,559	0.54	46%
Plant 200 bar	4.74E+08	9.33E-05	44,199	0.75	25%
Plant 300 bar	5.59E+08	9.33E-05	52,140	0.88	12%
Plant 400 bar	2.12E+08	5.76E-05	12,233	0.21	79%
Plant 500 bar	2.03E+08	5.76E-05	11,880	0.20	80%

Table 9 Economic loss risk for jet fire scenario - reactor

Plant	Economic Loss (RM)	Frequency Per Year	Economic Loss Risk (RM/Year)	Risk Factor	Safety Improvement
Conventional Plant	1.61E+07	5.92E-05	951		
Plant 76 bar	1.77E+06	5.92E-05	105	0.11	89%
Plant 100 bar	2.50E+06	5.92E-05	148	0.16	84%
Plant 200 bar	9.11E+06	1.79E-04	1,632	1.72	-72%
Plant 300 bar	2.28E+07	1.79E-04	4,081	4.29	-329%
Plant 400 bar	5.31E+07	2.54E-04	13,471	14.17	-1317%
Plant 500 bar	5.91E+07	2.14E-04	12,647	13.30	-1227%

Table 10 Economic loss risk for toxic scenario - reactor

Plant	Economic Loss (RM)	Frequency Per Year	Economic Loss Risk (RM/Year)	Risk Factor	Safety Improvement
Conventional Plant	4.98E+08	3.58E-04	136,473		
Plant 76 bar	1.35E+08	3.24E-04	43,790	0.32	68%
Plant 100 bar	1.75E+08	3.63E-04	44,419	0.33	67%
Plant 200 bar	2.45E+08	3.82E-04	54,683	0.40	60%
Plant 300 bar	2.16E+08	4.23E-04	45,678	0.33	67%
Plant 400 bar	7.88E+07	3.98E-04	15,146	0.11	89%
Plant 500 bar	9.58E+07	4.28E-04	9,210	0.07	93%

Table 11 Economic loss risk for VCE scenario - piping

Plant	Economic Loss (RM)	Frequency Per Year	Economic Loss Risk (RM/Year)	Risk Factor	Safety Improvement
Conventional Plant	2.29E+08	8.78E-04	201,325		
Plant 76 bar	3.95E+07	3.91E-04	15,451	0.08	92%
Plant 100 bar	8.30E+07	7.71E-04	64,021	0.32	68%
Plant 200 bar	1.05E+08	7.73E-04	80,821	0.40	60%
Plant 300 bar	1.43E+08	1.16E-03	165,592	0.82	18%
Plant 400 bar	2.06E+08	1.16E-03	238,358	1.18	-18%
Plant 500 bar	2.11E+08	1.16E-03	243,877	1.21	-21%

Table 12 Economic loss risk for jet fire scenario - piping

Plant	Economic Loss (RM)	Frequency Per Year	Economic Loss Risk (RM/Year)	Risk Factor	Safety Improvement
Conventional Plant	2.04E+06	6.73E-05	137		
Plant 76 bar	5.65E+05	2.61E-05	15	0.11	89%
Plant 100 bar	6.47E+05	5.56E-05	36	0.26	74%
Plant 200 bar	9.20E+05	5.60E-05	52	0.38	62%
Plant 300 bar	1.23E+06	8.69E-05	107	0.78	22%
Plant 400 bar	1.54E+06	8.69E-05	134	0.98	2%
Plant 500 bar	1.57E+06	8.69E-05	136	0.99	1%

Table 13 Economic loss risk for toxic scenario - piping

Plant	Economic Loss (RM)	Frequency Per Year	Economic Loss Risk (RM/Year)
Conventional Plant	1.68E+08	2.19E-03	368,738

Table 14 Total economic loss risk

Plant	Economic Loss (RM)	Frequency Per Year	Economic Loss Risk (RM/Year)	Risk Factor	Safety Improvement
Conventional Plant	1.54E+09	3.65E-03	766,553		
Plant 76 bar	4.16E+08	8.94E-04	81,631	0.11	89%
Plant 100 bar	5.99E+08	1.34E-03	140,183	0.18	82%
Plant 200 bar	8.33E+08	1.48E-03	181,387	0.24	76%
Plant 300 bar	9.42E+08	1.94E-03	267,598	0.35	65%
Plant 400 bar	5.52E+08	1.95E-03	279,342	0.36	64%
Plant 500 bar	5.70E+08	1.94E-03	277,534	0.36	64%

3.2 Comparison of economic loss risk and methanol production

As presented in Table 15 and depicted in Fig. 8, the highest safety improvement among modified plants is Plant 76 bar, with 89%. However, Plant 76 bar also has the lowest methanol production, which is 13% of the Conventional Plant, as shown in Table 15 and Figure 8. This situation means that to improve safety by about 89%, it needs to lower the methanol production to as low as 13% of the Conventional Plant production ratewhere Plant 76 bar modifies its reactor volume and eliminates recycle stream. The results in Table 15 also highlight Plant 400 and 500 bar achieving significant 64% safety improvement, although these plants need to operate at higher pressure. These results inform that, although the modified plants operate at a higher pressure of 400 and 500 bar, it only needs to sacrifice the production rate by about 20% to 22%, compared to other modified plants, which need to cut the production rate from 42% to 87% to improve their safety by 65% to 89%.

Fig. 9 shows the percentage of safety improvement achieved for the same methanol production as the Conventional Plant and the percentage of methanol production at risk is the same as the Conventional Plant. Plant 500 bar produces the most safety improvement at 55%, followed by Plant 400 bar with 53%. Plant 76 bar and Plant 100 bar only produce safety improvement of 19% and 1%, respectively, whereas Plant 200 and Plant 300 bar observed safety improvement of 38% and 39%, respectively. All plants have successfully improved the safety when compared to Conventional Plant.

If the modified plants which need to be designed have the same risk as the Conventional Plant, then Plant 500 bar has the most improvement in methanol production per year as it produces 220% methanol production, which is 2.2 times of Conventional Plant production capacity, followed by Plant 400 bar with 215%. Plant 76 and Plant 100 bar only have methanol production of 1.24 and 1.01 times of Conventional Plant, whereas Plant 200 and Plant 300 bar have methanol production of 160% and 165%. In the summary, all modified plants have achieved safety improvement between 1% to 55% when methanol production is similar to Conventional Plant and produced 1.01 to 2.2 times of Conventional Plant methanol production per year when the risk is at the same level as the Conventional Plant.

Table 15: Comparison of methanol production rate per year and safety improvement

Plant	Production (kg/ hr)	Production (ton / year)	Methanol Production	Safety Improvement
Conventional Plant	55,078	440,624	100%	0%
Plant 76 bar	7,262	58,094	13%	89%
Plant 100 bar	10,177	81,417	18%	82%
Plant 200 bar	20,883	167,061	38%	76%
Plant 300 bar	31,735	253,882	58%	65%
Plant 400 bar	43,112	344,899	78%	64%
Plant 500 bar	43,906	351,246	80%	64%

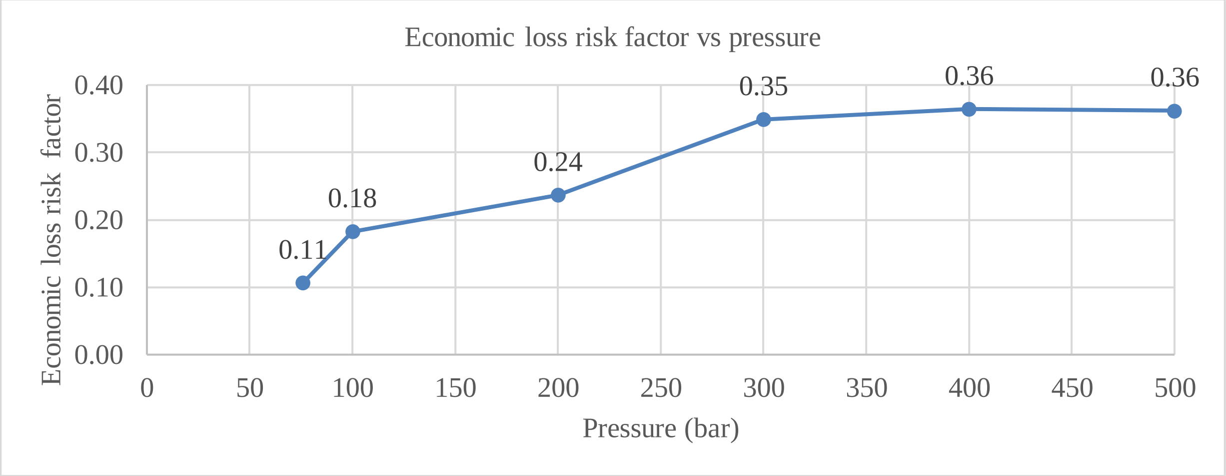

Fig. 7: Economic loss risk factor for pressure variation of methanol production

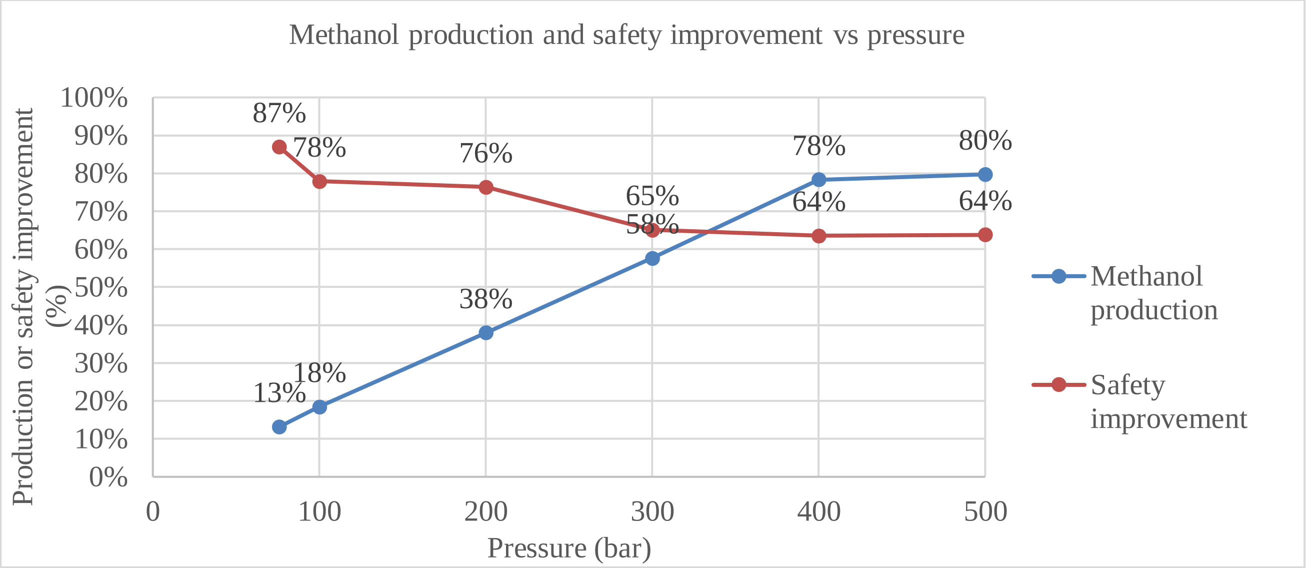

Fig. 8: Methanol production and safety improvement for pressure variation

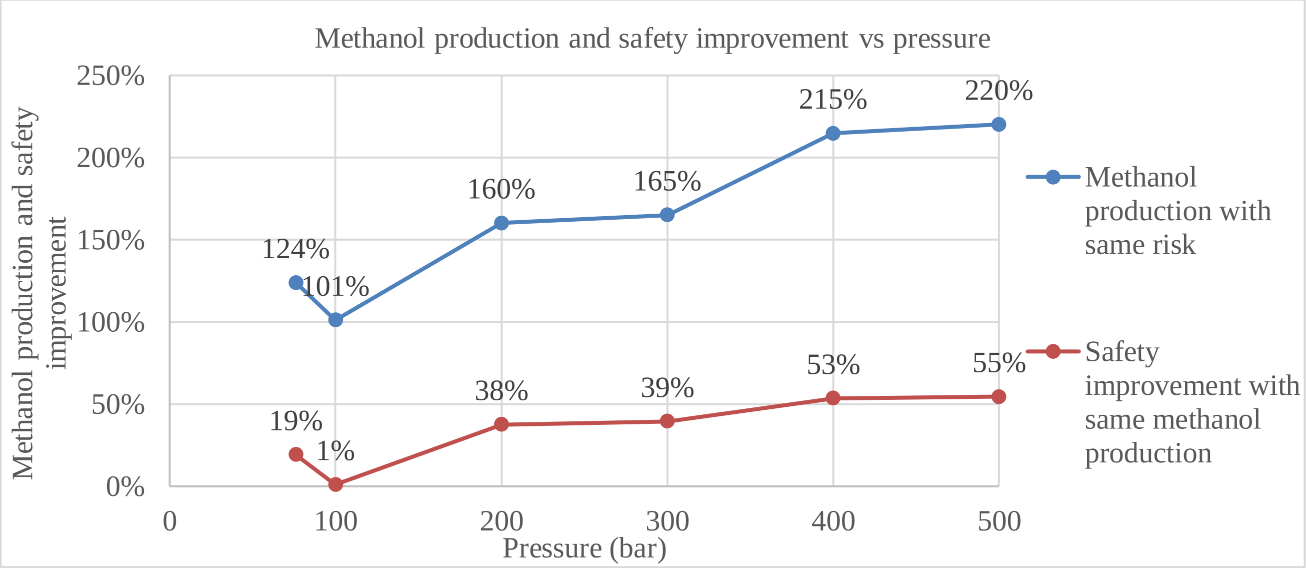

Fig. 9: Methanol production and safety improvement for same risk and production

4.0 Conclusions

Economic loss risk assessment was performed on pressure variation for methanol production due to various incidents in the reactor and piping system. Safety improvement of modified plants achieved a value between 64% to 89%. Thus, modified plants, which eliminate recycling streams and use downsize reactors attained inherently safer conditions although operated at higher pressure up to 500 bar, compared to Conventional Plant. Extended research performing economic loss risk assessment on higher H_2:CO_2 molar ratio such as 7:1 and 10:1 at high pressure could be recommended in future studies.

Acknowledgement

The authors would like to acknowledge Universiti Malaysia Pahang (UMP), International Islamic University Malaysia (IIUM), and School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM) for the UMP-IIUM-UITM SUSTAINABLE RESEARCH COLLABORATION 2020 (UMP.05/26.11/4/1/01(2)) grant, for all the funding and support given in establishing this project.

.

References

Agarwal, A. S., Zhai, Y., Hill, D., & Sridhar, N. (2011). The electrochemical reduction of carbon dioxide to formate/formic acid: engineering and economic feasibility. *ChemSusChem*, *4*(9), 1301–1310. https://doi.org/10.1002/cssc.201100220

Albo, J., Alvarez-Guerra, M., Castaño, P., & Irabien, A. (2015). Towards the electrochemical conversion of carbon dioxide into methanol. *Green Chemistry*, *17*(4), 2304–2324. https://doi.org/10.1039/C4GC02453B

Aldrige, T., Cruse, H., Munday, M., & Roche, N. (2015). *Modelling the economic impacts of an accident at major hazard sites (RR1055)*. 114. http://www.hse.gov.uk/research/rrpdf/rr1055.pdf

American Petroleum Institute. (2016). API Recommended Practice 581 - Risk-based Inspection Methodology. *American Petroleum Institute (API), April*, 632.

Ampelli, C., Passalacqua, R., Genovese, C., Perathoner, S., & Centi, G. (2011). A novel photoelectrochemical approach for the chemical recycling of carbon dioxide to fuels. *Chemical Engineering Transactions*, *25*, 683–688. https://doi.org/10.3303/CET1125114

Association, T. 61508. (2019). *ALARP Framework Guidance on achievement of ALARP in the Process Industries*. https://www.61508.org/images/downloads/ALARP_Guidance_V1_Published_13.03.2019.pdf

Atsonios, K., Kougioumtzis, M.-A., Panopoulos, K. D., & Kakaras, E. (2015). Alternative thermochemical routes for aviation biofuels via alcohols synthesis: Process modeling, techno-economic assessment and comparison. *Applied Energy*, *138*, 346–366. https://doi.org/10.1016/j.apenergy.2014.10.056

Bansode, A. B. (2014). *Exploiting high pressure advantages in catalytic hydrogenation of carbon dioxide to methanol*. [Doctoral Thesis, Universitat Rovira i Virgili]

Bansode, A., & Urakawa, A. (2014). Towards full one-pass conversion of carbon dioxide to methanol and methanol-derived products. *Journal of Catalysis*, *309*, 66–70. https://doi.org/10.1016/j.jcat.2013.09.005

Barbarossa, V., Vanga, G., Viscardi, R., & Gattia, D. M. (2014). CO2 as carbon source for fuel synthesis. *Energy Procedia*, *45*, 1325–1329. https://doi.org/10.1016/j.egypro.2014.01.138

Bardy, M., Oliveira, L. F., & Cavanagh, N. (2008). Managing business risks from major chemical process accidents. *Institution of Chemical Engineers Symposium Series*, *154*, 1046.

Berghout, N., van den Broek, M., & Faaij, A. (2013). Techno-economic performance and challenges of applying CO2 capture in the industry: A case study of five industrial plants. *International Journal of Greenhouse Gas Control*, *17*, 259–279. https://doi.org/10.1016/j.ijggc.2013.04.022

Bernama. (2018). *Cost of fatalities in Malaysia*. The Sun Daily. https://www.thesundaily.my/archive/lives-lost-road-accidents-each-worth-rm23m-XUARCH528974

Brynolf, S., Fridell, E., & Andersson, K. (2014). Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of Cleaner Production*, *74*, 86–95. https://doi.org/10.1016/j.jclepro.2014.03.052

Cavanagh, N., & Linn, J. (2006). Process Business Risk A methodology for assessing and mitigating the financial impact of process plant accidents. *ASSE-MEC Seventh Professional Development Conference and Exhibition, Bahrain*.

Chemical Engineering. (n.d.). The Chemical Engineering Plant Cost Index. Retrieved August 9, 2019, from https://www.chemengonline.com/pci-home

Faberi, S., Paolucci, L., & Jiménez, I. (2014). *Methanol: A Future Transport Fuel Based on Hydrogen and Carbon Dioxide?* https://trimis.ec.europa.eu/project/methanol-future-transport-fuel-based-hydrogen-and-carbon-dioxide

Gaikwad, R. (2018). *Carbon dioxide to methanol: stoichiometric catalytic hydrogenation under high pressure conditions*. [Doctoral Thesis, Universitat Rovira i Virgili]

Gaikwad, R., Bansode, A., & Urakawa, A. (2016). High-pressure advantages in stoichiometric hydrogenation of carbon dioxide to methanol. *Journal of Catalysis*, *343*, 127–132. https://doi.org/10.1016/j.jcat.2016.02.005

Heikkilä, A.-M. (1999). *Inherent safety in process plant design* (384) [Doctoral Thesis, Technical Research Centre of Finland]

Higgins, N. A., Jones, C., Munday, M., Balmforth, H., Holmes, W., Pfuderer, S., Mountford, L., Harvey, M., & Charnock, T. (2008). *COCO-2: a model to assess the economic impact of an accident*. Health Protection Agency.

HSE, U. K. (2017). *HSE principles for cost benefit analysis (CBA) in support of ALARP decisions*.

HSE, U. K. (2019). *"Cost Benefit Analysis (CBA) Checklist."* pp. 1–5.

Jones, R., Lehr, W., Simecek-Beatty, D., & Reynolds, M. (2013). *ALOHA®(Areal Locations of Hazardous Atmospheres) 5.4. 4: Technical Documentation*.

Kei, H. M. (2018). Department of Statistics Malaysia Press Release. *Dep. Stat. Malays. Putrajaya*, 5–9.

Malaysia GDP Deflator 2000-2020 Data. (2020). *Trading Economics*.

Nielsen, M., Alberico, E., Baumann, W., Drexler, H.-J., Junge, H., Gladiali, S., & Beller, M. (2013). Low-temperature aqueous-phase methanol dehydrogenation to hydrogen and carbon dioxide. *Nature*, *495*(7439), 85–89. https://doi.org/10.1038/nature11891

Norsok, T., Federation, T., Industry, N., Federation, T., & Industry, N. (2010). *NORSOK STANDARD Risk and emergency preparedness assessment*. *October*, 1–107.

OFX. (n.d.). *Yearly Average Rates*. Retrieved 2021. https://www.ofx.com/en-au/forex-news/historical-exchange-rates/yearly-average-rates/#main

Olah, G. A. (2005). Beyond oil and gas: the methanol economy. *Angewandte Chemie International Edition*, *44*(18), 2636–2639. https://doi.org/10.1002/anie.200462121

Olah, G. A., Goeppert, A., & Prakash, G. K. S. (2018). *Beyond oil and gas: the methanol economy, third, updated and enlarged edition*. John Wiley & Sons (US).

Pérez-Fortes, M., Schöneberger, J. C., Boulamanti, A., & Tzimas, E. (2016). Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. *Applied Energy*, *161*, 718–732. https://doi.org/10.1016/j.apenergy.2015.07.067

Stoffen, P. G. (2005). Guidelines for quantitative risk assessment. *Ministerie van Volkshuisvesting Ruimtelijke Ordening En Milieu. CPR 18E*. https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS3/PGS3-1999-v0.1-quantitative-risk-assessment.pdf

Tidona, B., Koppold, C., Bansode, A., Urakawa, A., & von Rohr, P. R. (2013). CO2 hydrogenation to methanol at pressures up to 950 bar. *The Journal of Supercritical Fluids*, *78*, 70–77. https://doi.org/10.1016/j.supflu.2013.03.027

Towler, G., & Sinnott, R. (2021). *Chemical engineering design: principles, practice and economics of plant and process design*. Butterworth-Heinemann.

United Kingdom GDP Deflator 1955-2020 Data. (2020). *Trading Economics*.

Van-Dal, E. S., & Bouallou, C. (2012). CO2 abatement through a methanol production process. *Chem Engineering Transactions*, *29*, 463–468. 10.3303/CET1229078

Wall, M., Wedgwood, F. A., & Martens, W. (1998). Economic assessment of inspection - The inspection value method. *NDT.net*, *3*(12).

Yamamoto, T., Tryk, D. A., Fujishima, A., & Ohata, H. (2002). Production of syngas plus oxygen from CO2 in a gas-diffusion electrode-based electrolytic cell. *Electrochimica Acta*, *47*(20), 3327–3334. https://doi.org/10.1016/S0013-4686(02)00253-0

Yao, Y., Chang, Y., Huang, R., Zhang, L., & Masanet, E. (2018). Environmental implications of the methanol economy in China: well-to-wheel comparison of energy and environmental emissions for different methanol fuel production pathways. *Journal of Cleaner Production*, *172*, 1381–1390. https://doi.org/10.1016/j.jclepro.2017.10.232

Yusof, M. F. M., Nor, N. G. M., & Mohamad, N. A. (2013). Malaysian value of statistical life for fatal injury in road accident: A conjoint analysis approach. *Journal of Society for Transportation and Traffic Studies*, *2*(2), 30–40.

Yusoff, M. F. M., Mohamad, N. A., & Nor, N. G. M. (2011). Malaysian value of fatal and non fatal injury due to road accident: The willingness to pay using conjoint analysis study. *Proceedings of the Eastern Asia Society for Transportation Studies Vol. 8 (The 9th International Conference of Eastern Asia Society for Transportation Studies, 2011)*, 33. https://doi.org/10.11175/eastpro.2011.0.33.0