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Abstract

In a complex processing facility, there is likelihood of occurrence of cascading scenarios, i.e. hydrocarbon release, fire, explosion and dispersion of combustion products. The consequence of such scenarios, when combined, can be more severe than their individual impact. Hence, actual impact can be only represented by integration of above mentioned events. A novel methodology is proposed to model an evolving accident scenario during an incidental release of LNG in a complex processing facility. The methodology is applied to a case study considering transitional scenarios namely spill, pool formation and evaporation of LNG, dispersion of natural gas, and the consequent fire, explosion and dispersion of combustion products using Computational Fluid Dynamics (CFD). Probit functions are employed to analyze individual impacts and a ranking method is used to combine various impacts to identify risk during the transitional events. The results confirmed that in a large and complex facility, an LNG fire can transit to a vapor cloud explosion if the necessary conditions are met, i.e. the flammable range, ignition source with enough energy and congestion/confinement level. Therefore, the integrated consequences are more severe than those associated with the individual ones, and need to be properly assessed. This study would provide an insight for an effective analysis of potential consequences of an LNG spill in any LNG processing facility and it can be useful for the safety measured design of process facilities.

Keywords	LNG spill, accident transition, integrated consequence, CFD
Taxonomy	Explosion, Fire, Hazard
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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
The required data are available within the manuscript.

Dear Editor,

Kindly find attached, our revised manuscript entitled "Modelling an integrated impact of fire, explosion and combustion products during transitional events caused by an accidental release of LNG" for the possible publication in the "Journal of Process Safety and Environmental Protection". This is original work of authors and unpublished. I am corresponding author and all authors are agreed to submit this MS to this journal. There is no conflict of interest.

Best regards,

Dr Rouzbeh Abbassi
Senior Lecturer,
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Responses to Editor's and Reviewer's Comments

Editor

Comment 1. Your paper should become acceptable for publication pending suitable minor revision and modification of the article in light of the appended reviewer comments.

Response 1. Thank you very much for your time and consideration. The comments provided by the reviewer have been considered and the manuscript has been revised accordingly.

Reviewer 1:

Comment 1: The reviewer must apologize for not being able to ask a question in such a manner that the authors understand the point the reviewer is trying to make. Apologies for that. What the reviewer wants to point out that the pressure increase developed during the dispersion is 1 mbar. Do the authors believe that a difference of 1 mbar in initial pressure will have a substantial effect on the final pressure? Using simple equations like the ideal gas law will help you assess the effect on the final pressure, knowing the adiabatic flame temperature.

Response 1: Thank you very much for your time and providing a precise review of this manuscript. In this study, authors do not believe that 1 mbar initial pressure will have a substantial effect on the final pressure. Nevertheless, the main purpose of illustrating the maximum pressure developed in the layout during the leak and the dispersion is to assess the potential location of a Vapour Cloud Explosion (VCE). To clarify this for the future reviewers, the following sentences have been added in the updated manuscript.

*The variation of air pressure in the layout in the presence of the dispersed vapour can be a useful information for assessing the potential location of a VCE. During gas dispersion, gas concentration in the air can create different initial pressure, which is one of the parameters on which the strength of explosion depends (Kundu et al., 2016). In this study, the maximum pressure developed during the dispersion of LNG vapour is 0.001 barg (illustrated in **Error! Reference source not found.**). The 1 mbar initial pressure may not have a substantial effect on the strength of a VCE.*

Comment 2: The authors did not answer the question of the reviewer in the original version of the manuscript. **Original comment**: Suppose there is a change in wind direction, it is raining, there is snow, the leak is small than assumed by the authors, the companies use water mist systems for dispersion, time, the company has installed sniffers (generally the case), et cetera,

how does this affect the outcome of your analysis? Are the authors aware that there are quite some parameters at stake?

Response 2: Thank you. Authors acknowledge that a change in weather conditions such as wind direction, snow, rains and source terms may affect the outcome of an analysis. Because responses to gas leak and its dispersion are strongly dependent on the operating parameters and one set of parameters may not represent all scenarios. Thus, a combination of strategies needs to be applied by considering prevalent operating conditions. For illustration purpose, the authors have presented only a specific case in this study. Once operating conditions such as wind speed, wind direction, snow, rain or other parameter changes, the response need to be evaluated accordingly considering different scenarios. Through this study, the authors wish to convey that use of systematic approach help to envisage a range of scenarios and thus required responses can be obtained accordingly. For clarification, the authors have added following sentences in 'Conclusion' section of the revised version of the manuscript.

A change in weather conditions and source terms may affect the outcome of an analysis related to gas leak and dispersion. Responses to gas leak and its dispersion are strongly dependent on these parameters and one set of parameters may not represent all cases. For illustration purpose, this study has presented only a specific case. Once operating conditions such as wind speed, wind direction, snow, rain or other parameter changes, the response need to be evaluated accordingly. The current study serves to highlight the importance of transitional events modelling and expands the scope of the integrated consequence modelling approach. Despite having complex correlations among various parameters involved in LNG spill and subsequent events, the integrated risk profiles can be effective for designing safety systems to mitigate potential effects and risk associated with thermal radiation, overpressure and combustion products during fire and/or explosion events. Consideration of effects among thermal radiation, overpressure and combustion products in the transitional event modelling, makes the study unique and realistic in safety analysis of an LNG processing facility.

Comment 3: Minor grammatical changes and typos

Response 3: They have been considered and the manuscript has been revised accordingly.

Modelling an integrated impact of fire, explosion and combustion products during transitional events caused by an accidental release of LNG

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Abstract

In a complex processing facility, there is likelihood of occurrence of cascading scenarios, i.e. hydrocarbon release, fire, explosion and dispersion of combustion products. The consequence of such scenarios, when combined, can be more severe than their individual impact. Hence, actual impact can be only represented by integration of above mentioned events. A novel methodology is proposed to model an evolving accident scenario during an incidental release of LNG in a complex processing facility. The methodology is applied to a case study considering transitional scenarios namely spill, pool formation and evaporation of LNG, dispersion of natural gas, and the consequent fire, explosion and dispersion of combustion products using Computational Fluid Dynamics (CFD). Probit functions are employed to analyze individual impacts and a ranking method is used to combine various impacts to identify risk during the transitional events. The results confirmed that in a large and complex facility, an LNG fire can transit to a vapor cloud explosion if the necessary conditions are met, i.e. the flammable range, ignition source with enough energy and congestion/confinement level. Therefore, the integrated consequences are more severe than those associated with the individual ones, and need to be properly assessed. This study would provide an insight for an effective analysis of potential consequences of an LNG spill in any LNG processing facility and it can be useful for the safety measured design of process facilities.

Keywords: LNG spill, accident transition, integrated consequence, CFD

1. Introduction

LNG is considered as a safe and environmentally-friendly fuel. Safe storage, processing, transportation and usage are mandatory requirements for any fuel and LNG continues to reveal a long track record of safety in all these areas (Yeo et al., 2016). However, in a complex processing facility such as a floating liquefied natural gas (FLNG) (Baksh et al., 2016a, b), an incidental release of LNG may not simply lead to an event with only its individual impact. There is likelihood of escalating a minor event into more damaging events. For instance, an accidental release of LNG in a production facility has the potential to pose several hazards such as fire, explosion, brittle fracture, asphyxiation and freeze burn/frostbite. A leakage of LNG may be a single minor event itself. However, due to instantaneous vaporisation, it is likely to cause several events such as a fireball, flash fire, Vapour Cloud Explosion (VCE), and pool fire when the vapour is ignited. Escalation of the mentioned events to a storage facility, may lead to Boiling Liquid Expanding Vapour Explosion (BLEVE). The entire sequence of events and their interactions during an LNG spill event in an FLNG processing facility is illustrated in **Fig. 1**.
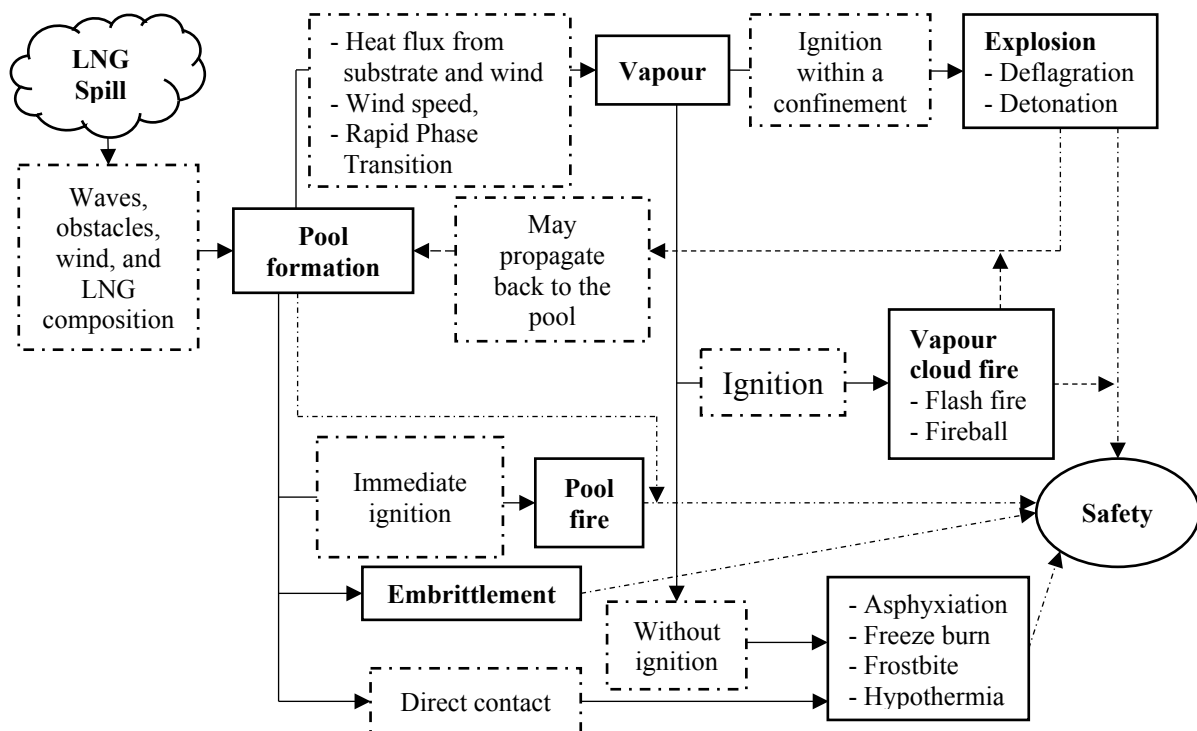

Fig. 1. LNG spill events (adapted from Ikealumba and Wu (2014) with some modifications).

Due to the potential of having several events during an unintended LNG spill, the US Government Accountability Office (GAO) commissioned a study and recommended to improve the state of knowledge surrounding the potential for cascading damage to LNG vessels

in the case of an incidental release of LNG (US Government Accountability Office (GAO), 2007). The study of cascading damage issues has proven difficult primarily because these events require the analysis of the interaction of a series of complex physical phenomena such as LNG flow, heat transfer, fracture and damage. Petti et al. (2013) summarized the outcomes of the studies on cascading damage (Figueroa et al., 2011; Petti and Kalan, 2011; Petti et al., 2011) which explored the cryogenic and fire thermal damage to an LNG ship during a large LNG cargo tank breach.

In these studies (Figueroa et al., 2011; Petti and Kalan, 2011; Petti et al., 2011), impacts (pressure wave, shrapnel or projectile) from the explosion are not considered in the cascading damage analysis. Examples of evolving accident scenarios are reported in (Ouddai et al., 2012; Petrie and Großbritannien, 1988). The Piper Alpha tragedy in 1988 caused 165 deaths due to an explosion after the release of flammable material. In the accident, leakage of gas occurred, and the presence of an ignition source caused multiple events such as a fireball and jet fire, followed by VCEs. The sequence of events led to the total loss of the platform (Pate -Cornell, 1993). In 2004, an LNG accident occurred in the Skikda LNG plant in Algeria resulting in 27 casualties, 56 injuries and $900 million loss. During this multiple explosions occurred due to excessive pressure in an adjacent boiler (Ouddai et al., 2012). The BP's Texas City refinery explosion in 2005 caused 15 deaths and 180 injuries due to hydrocarbon release and subsequent fire and explosion (Manca and Brambilla, 2012). The release resulted in a VCE followed by a pool fire (Broadribb, 2006). In 2010, the Macondo accident in the Gulf of Mexico occurred with a series of events such as blowout, dispersion of released hydrocarbons, explosion and fire (Deepwater Horizon Study Group (DHSG), 2011). The flame propagating from the explosion reached the flammable vapour dispersed over the platform and led to the fire at the source of release at the drilling floor. Major accidents that occurred in process facilities are well explained in (Abdolhamidzadeh et al., 2011; Al-shanini et al., 2014; Khan and Abbasi, 1999). These accidents are mainly associated with fires, explosions and toxic product release. Most past studies regarding fire and explosion accidents were limited to individual fires or explosions or combustion products modelling and did not address evolving accident scenarios (Dadashzadeh et al., 2013a; Dadashzadeh et al., 2014; Gavelli et al., 2011; Kim and Salvesen, 2002). For instance, Dadashzadeh et al. (2013a) modelled the dispersion of flammable gas integrated with explosion consequences of the BP Deepwater Horizon explosion using a Flame Acceleration Simulator (FLACS). Smoke and heat radiation released from the fire also affect human health and offshore structures; however, this impact was not addressed in the consequence analysis. Dadashzadeh et al. (2014) proposed a methodology for toxicity risk

assessment during an LNG fire and revealed that high risks are found at the process facility due to higher concentrations of combustion products and longer exposure time. However, the direct consequence of fire was not considered. Baalisampang et al. (2017a) and Baalisampang et al. (2017b) modelled the impact of a fire in a typical FLNG processing facility. Other potential events, their interactions, and consequences were not included by Baalisampang et al. (2017a). Kim and Salvesen (2002) conducted a study on LNG vapour release, which was addressed as a possible VCE. However, a potential fire scenario was not considered. Another study by Koo et al. (2009) focused on pool fire modelling only and no consideration was given to a VCE or other possible interactions such as a jet fire. But in most cases, fire, explosion and combustion product release occur one after another or simultaneously resulting in integrated consequences (Baalisampang et al., 2018a; Baalisampang et al., 2018b). Reviews of past accidents (Al-shanini et al., 2014; Dadashzadeh et al., 2013a; Manca and Brambilla, 2012) and models (Al-shanini et al., 2014; Baksh et al., 2015; Kim and Salvesen, 2002; Koo et al., 2009) demonstrate a need to evaluate the entire accident sequence to mitigate the impact, to develop appropriate response methods and to prevent accidents by designing safety measures in the system. Combination of various accidental events is important as one event may lead to another and increases the overall consequences. To model entire impacts of a potential accident in a complex processing facility, it is essential to consider transitional event scenarios because in such modelling, entire causes and effects of a series of events are considered. In comparison to onshore processing facilities, offshore facilities are deemed more vulnerable to transitional events due to limited topside space and harsh environmental conditions (Baalisampang et al., 2016). Some offshore accidents involving transitional events are given in **Table 1**.

Table 1
Offshore fire and explosion accidents associated with multiple events

Accident name, year and geographical region	Event sequence	Consequences	References
Piper Alpha, 1988, Europe North Sea	Release ⟶ Explosion ⟶ Fire	165 fatalities, total loss	(Pate - Cornell, 1993)
High Island Pipeline, 1989, US GOM	Collision ⟶ Release ⟶ Explosion ⟶ Fire	11 fatalities, 4 injuries and significant damage	(OPG, 2010b)
Enchova Central, 1984, America South East	Blowout ⟶ Fire ⟶ Explosion	42 Fatalities, 19 injuries and significant damages	(OPG, 2010b)

Lake Maracaibo, 1993, America South East	Explosion $\longrightarrow$ Fire	11 fatalities, significant damage	(OPG, 2010b)
Ubit, 1995, Africa West	Explosion $\longrightarrow$ Fire	10 fatalities, 23 injuries and severe damage	(OPG, 2010b)
Petrobras P-36, 2001, America South East	Explosion $\longrightarrow$ Fire $\longrightarrow$ Capsizing	11 fatalities, total loss	(OPG, 2010b)
Bombay High North, 2005, Asia South	Collision $\longrightarrow$ Release $\longrightarrow$ Fire	12 fatalities, severe damage to the jacket	(OPG, 2010b)
Deepwater Horizon, 2010, GOM	Blowout $\longrightarrow$ Release $\longrightarrow$ Fire $\longrightarrow$ Explosion	11 people died, 17 injuries and total loss	(Deepwater Horizon Study Group (DHSG), 2011)
Black Elk, 2012, GOM	Release $\longrightarrow$ Fire $\longrightarrow$ Explosion	3 people died, pollutant spill	(BSEE, 2013)
SOKAR platform, 2014, Caspian Sea	Explosion $\longrightarrow$ Fire	12 people fell into the sea	(Fattakhova and Barakhnina, 2015)
Abkatun Alfa platform, 2015, GOM	Explosion $\longrightarrow$ Fire	7 people died, 45 injuries	(Offshore Post-Everything offshore energy, 2015)

In fire and explosion accidents, a combined impact assessment is assumed to provide a more accurate consequence than individual one. In fire and explosion accidents, a damage potential (radius) can be increased if the impact of combustion products is considered (Dadashzadeh et al., 2014). During fire and explosion accidents, depending upon the types of burning materials and their combustion products, people are exposed to adverse health effects. For an integrated impact study, Khan and Amyotte (2004) proposed a methodology that incorporated fire, explosion and toxic release damage indices to evaluate the inherent safety of a facility based on inherent safety guidelines. Dadashzadeh et al. (2013b) proposed a new methodology for modelling an integrated consequence of fire and explosion using the Fire Dynamics Simulator (FDS) and FLACS and concluded that the risk of combined consequences is higher than each individual risk. But potential risk from combustion products during fire and/or explosion was not considered in the study. Niazi et al. (2018) proposed an integrated consequence modelling approach for fire and combustion products using risk based and grid-

based approaches and claimed that the risk posed by thermal radiation is confined only to the lower deck. But the risk of exposure to combustion products was present~~found~~ in ~~the~~ a larger area~~portion~~ than that of the radiation, due to ~~under~~ the influence of wind. Unlike previous studies (Dadashzadeh et al., 2013b; Khan and Amyotte, 2004; Niazi et al., 2018), the current study proposes a risk-based approach to model an integrated impact of fire, explosion and combustion products during an accidental release of LNG in a typical FLNG processing facility.

2. Methodology

This study proposes a methodology that models an integrated impact of evolving accident scenarios such as release, pool fire, explosion events and dispersion of combustion products as illustrated in **Fig. 2**. Currently, several Quantitative Risk Assessment (QRA) softwares tools such as IMESAFR (Tatom et al., 2011), Riskcurves (GexCon, 2018b), EFFECTS (GexCon, 2018a), Riskan (Lewis, 2005), HAMS-GPS (HAMSAGARS) and Phast and Safeti (DNV-GL, 2018) are available for accident modelling. They are simpler and faster than most CFD tools. A majority of QRA software tools lacks the capability of considering complex effects of geometry and equipment in the simulation and cannot model evolving accident scenarios. But th~~is~~e study~~current approach~~ considers the effect of complex geometry and/or equipment and models cascading events and their impacts using the following five steps.

In step 1, LNG release scenario, pool formation, vaporisation and dispersion of LNG vapour are modelled using FLACS. These phenomena are simulated with careful consideration of plausible scenarios.
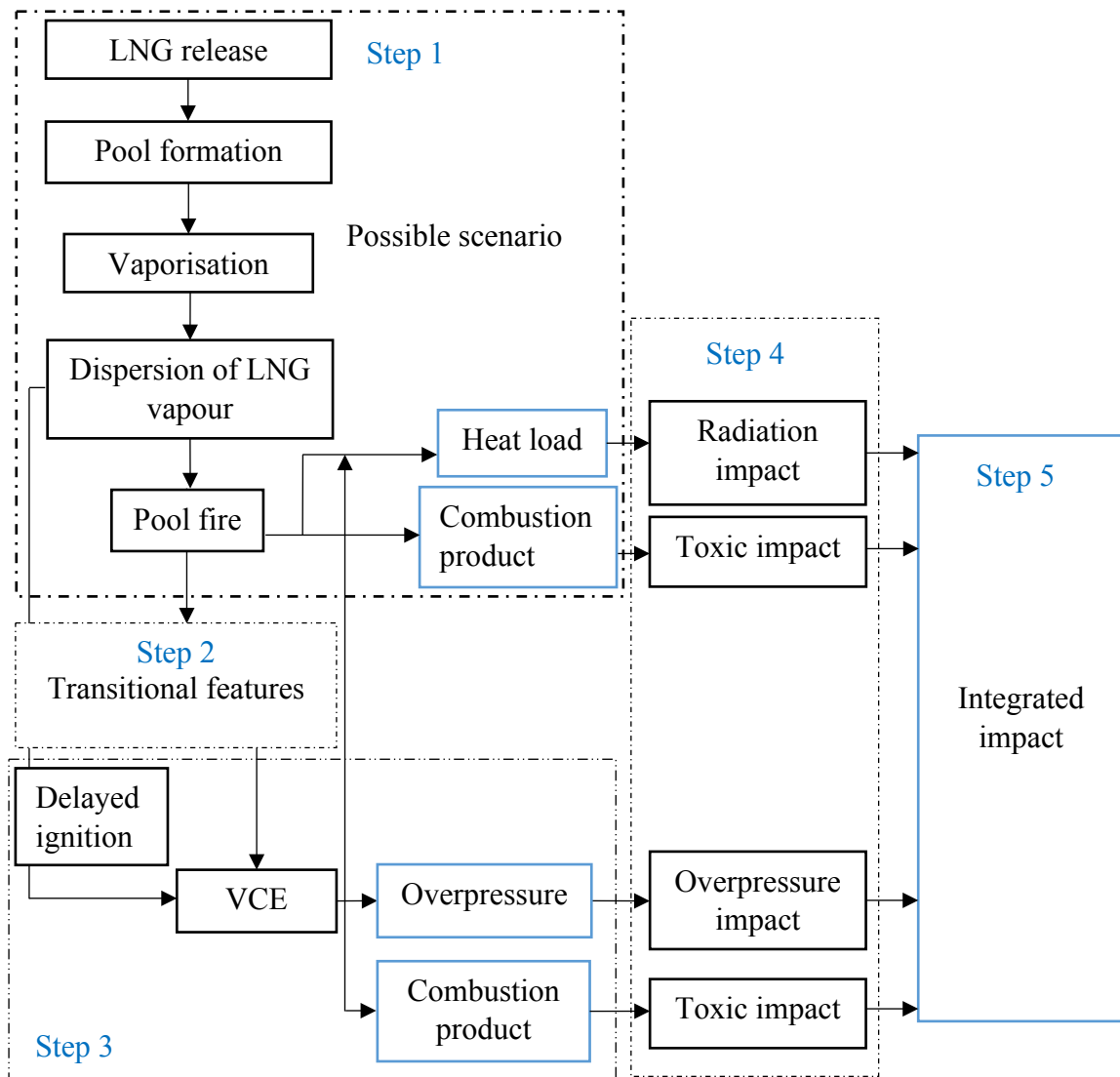
Fig. 2. Proposed methodology for modelling an integrated impact of transitional events to human during an LNG spill.

In step 2, the potential transitional phenomena are considered by attending to a series of events such as dispersion of LNG vapour, pool fire and VCE. ~~In this transitional event, t~~The phenomenological changes to spilled LNG and vaporisation due to a culmination of atmospheric effects and thermal radiation are considered for assessing the occurrence of potential cascading~~transitional~~ events. The thermal load obtained from the pool fire is used as the source of ignition for the VCE. For transitional events to occur, some minimum conditions need to be fulfilled. For instance, a dispersion event can transit to pool fire only if the flammability condition is met. Similarly, a~~n~~ VCE occurs when pertinent conditions such as confinement, turbulence, ignition source, and flammable gas cloud are present (Atkinson et al., 2017; Center for Chemical Process Safety, 1996). These pertinent conditions are considered as stimuli for the transitions (events) (Alzbutas, 2015). ~~Turbulence is required for the flame front~~

~~to accelerate to the speeds required for a VCE which is typically formed by the interaction between the flame front and obstacles (Center for Chemical Process Safety, 1996). General conditions required to cause a particular event are considered as stimuli for the transitions (events) (Alzbutas, 2015).~~ During a release, with the vaporisation and dispersion of LNG in air, only a vapour concentration in the range of 5-15 vol.% will sustain the propagation of a flame upon ignition. The concentration of the vapour above the upper explosion limit may act as feed gas to the fire. ~~The remaining vapour concentration may act as feed gas to the fire.~~ However, if the dispersed vapour~~s~~ ~~concentration~~ accumulate~~outside this range builds overpressure~~ in nearby semi-confined or confined areas, the fire may transform to a~~n~~ VCE upon ignition. This may increase the severity of consequence in total. If the flammable gas release is not ignited immediately, a vapor plume will form which will drift and disperse by the ambient winds and/or natural ventilation. If the vapour is ignited, but does not explode, it will result in a flash fire, in which the gas cloud within the flammable range burns very rapidly. If the vapour is not isolated during this time, the flash fire may burn to yield a jet fire at the source of the release, under the condition that the concentration range is appropriate, and the leak is present.

In step 3, the heat released from the pool fire is modelled as the potential ignition source to ignite the flammable gas accumulated at a position away from the pool fire location such that the fire did not consume the rich vapour cloud from this location. It was assumed that this location did not get direct fire flame and the presence of high thermal radiation from the fire resulted in an autoignition of the vapour or influenced other ignition sources to ignite. During a release of a flammable gas, if the ignition is delayed by 5-10 min, a VCE may be the outcome (Assael and Kakosimos, 2010; Soman and Sundararaj, 2012). For ignition to take place, the vapour cloud must be within the flammable range, while at the same time a source able to supply the required energy must be available (Assael and Kakosimos, 2010). To model a pool fire transiting to a VCE, thermal radiation and other parameters such as temperature and pressure development are extracted from the previous step. There are various models available for gas explosion modelling, like empirical, phenomenological and CFD (Lea and Ledin, 2002). According to Tam and Lee (1998), CFD codes are inherently more flexible than both empirical and phenomenological models and are applicable to all fields. Some commonly used CFD models for explosion simulations are EXSIM, FLACS and AutoReaGas (Lea and Ledin, 2002). FLACS developed by the Global Explosion Consultants (GexCon AS) has been used widely for the modelling of gas dispersion and explosion in onshore or offshore facilities (Hansen et al., 2005). In this study, FLACS is used to model the fire and explosion scenarios.

In step 4, the consequences of fire, explosion and/or combustion product release are analysed individually using probit functions. The heat load obtained from the fire is used to assess the fire impact to assets and people. The probability of human impacts from the heat radiation is calculated by Eq. (2), considering the probit model given in Eq. (1).

Probit function $(Pr) = c_1 + c_2 \ln D,$ (1)

The probability of injury or death $(P) = F_k \frac{1}{2}\left[1 + erf\left(\frac{Pr - 5}{\sqrt{2}}\right)\right],$ (2)

where D is the thermal dose $\left(\frac{kW}{m^2}\right)^{\frac{4}{3}} s$, c_1 and c_2 are probit coefficients, F_k is a clothes correction factor, and erf is the error function. The thermal dose is obtained from the post processing file using inbuilt utilities in FLACS.

Sudden large changes in pressure due to an explosion can lead to dramatic and possibly fatal damage to vital human organs such as lungs and ears. The impact of explosion is assessed based on the calculation of the probability (P) of injury or death employing Eqs. (3)-(8).

Probit function $(Pr) = c_1 + c_2 \ln S,$ (3)

The probability of injury or death $(P) = \frac{1}{2}\left[1 + erf\left(\frac{Pr - 5}{\sqrt{2}}\right)\right],$ (4)

where variable S is defined according to the type of the effect calculated by $S = \left(\frac{4.2}{\overline{P}} + \frac{1.3}{\overline{i}}\right),$

where $\overline{i}$ is the scaled impulse $\left(Pa^{\frac{1}{2}}.s.kg^{-\frac{1}{3}}\right)$, $\overline{P}$ is scaled pressure (-) and c_1 and c_2 are probit coefficients (Assael and Kakosimos, 2010). Explosion effects on humans are usually categorised as:

1. Direct or primary effects

   The overpressure from the explosion can cause injury to sensitive human organs, or death.

2. Indirect effects

   The indirect effects are sub-divided into two categories

   a. Secondary effects refer to injuries or death caused by fragments or debris thrown by explosion's blast,

   b. Tertiary effects that refer to injuries or death caused by whole-body displacement and collision with stationary objects or structures, because of the explosion's blast waves.

The probabilities of impact to lung, eardrum rupture, head impact and whole-body displacement impact are calculated using Eq. (4). However, the Pr are different. In this study, the following probit functions are used for each type of impact (Assael and Kakosimos, 2010).

For lung damage, $Pr = 5 – 5.74 \ln S$ (5)

For eardrum damage, $Pr = – 12.6 + 1.524 \ln P_s$ (6)

For head impact, $Pr = 5 – 8.49 \ln S$ (7)

For whole-body displacement, $Pr = 5 – 2.44 \ln S$ (8)

where P_s is overpressure (Pa). According to Clancey (1972) cited in Crowl and Louvar (2011) 1-99% fatalities can occur when exposed to over 2 bar.

Toxicity of combustion products accounts for a major cause of death and injury from unwanted fires (Hartzell, 1992). The main combustion products are divided into two types: asphyxiant gases, which prevent oxygen uptake by cells, leading to loss of consciousness and death; irritant gases which cause immediate incapacitation affecting eyes and upper respiratory tract long-term damage in the lung (Hull and Stec, 2010). Because of these harmful effects, they can seriously jeopardise evacuation. During an LNG fire or VCE, carbon monoxide (CO) and nitrogen dioxide (NO_2) are the main toxic combustion products (Dadashzadeh et al., 2014).

In the step 5, the integrated impact of fire, explosion and combustion product release is estimated. For integration of fire and VCE effects a grid-based approach is used such that consequence severity can be mapped as an index. To estimate risk of each event, a risk-based approach was further adopted using a severity index and probability of each effect. The severity index for each type of effect (S_i) is estimated using expert judgment. The effects are ranked based on their severity of damages (**Table 2**) and experts' judgment on a scale of 1–10.

Table 2
Severity scores for human effects caused by fire and explosion (Dadashzadeh et al., 2013b)

	Fire			**Explosion**			
Effects	First degree burn	Second degree burn	Death	Lung damage	Eardrum rupture (injury)	Head impact (death)	Whole body displacement (death)
Score (S)	2	5	10	10	5	10	10

The severity index for each effect at any location of the plant is calculated as follows:

$\text{Risk}_i = S_i \times P_{i,}$ (9)

Where, Risk_i denotes the severity index for each effect and i denotes the effects (first degree injury, second degree injury and death for fire; lung damage, eardrum rupture, head impact and

whole-body displacement for explosion). At each grid point, the maximum severity index among the various effects of each accident is considered using Eqs. (10) and (11) for a fire and explosion respectively.

$$\text{Risk}_{f} = \text{maximum } [\text{Risk } _{First\ degree\ burn}, \text{ Risk } _{Second\ degree\ burn}, \text{ Risk } _{Death}] \tag{10}$$

$$\text{Risk}_{e} = \text{maximum } [\text{Risk } _{Lung}, \text{ Risk } _{Eardrum\ damage}, \text{ Risk } _{Head\ impact}, \text{Risk } _{Whole\ body\ displacement}] \tag{11}$$

The total risk of fire and VCE (Risk_{fe}) at any location is estimated using Eq. (12),

$$\text{Risk}_{fe} = \text{Risk}_{f} + \text{Risk}_{e} \tag{12}$$

Using the Risk_{fe} at any location of the layout, risk contour can be obtained considering cumulative effects of a fire and VCE.

The toxicity risk assessment is carried out according to the methodology proposed by Dadashzadeh et al. (2014). A hazard index (HI) was estimated at each grid point of the layout using Eq. (13) (National Research Council, 1998).

$$HI = \frac{Estimated\ concentration\ (mg/m^3)}{Reference\ toxic\ value\ (mg/m^3)} \tag{13}$$

For toxic risk estimation of each contaminant of the combustion product, Eq. (13) can be written as in Eq. (14).

$$\text{Risk}_{combustion\ product} = \frac{Exposure\ concentration}{TLV - STEL} \tag{14}$$

Where TLV-STEL is the Threshold limit value - Short Term Exposure Limit (mg/m^3). By adding the hazard quotients (hazard indices) for the individual emission toxicants, the hazard quotient of all toxicants is obtained as shown in Eq. (15). A risk of a health effect is assumed to exist at those exposure locations where the hazard index exceeds 1.

$$Risk_{Total\ combustion\ product} = Risk_{CO} + Risk_{NO_2} \tag{15}$$

Finally, the integrated risk at any location of the facility is estimated by investigating the Risk_{fe} and the $\text{Risk}_{combustion\ products}$ under any considered scenarios.

3. Application of the integrated methodology: a case study

The proposed methodology is applied to a typical layout consisting of several process equipment as shown in **Fig. 3**. Leak, vaporisation and dispersion are strongly dependent on the operating parameters and may need to consider prevalent operating conditions. In this case study, prevalent operating conditions are considered based on FLACS user's manual (GexCon AS, 2013). In this scenario, 10 kg/s of LNG is released at an LNG processing plant. According to Woodward (2010) the appropriate wind speed for flammable cloud dispersion is usually

close to 2 to 4 m/s and thus, the wind speed is taken as 3 m/s with an ambient temperature of 20°C. A pool of LNG is formed at the release location and vaporization occurs due to the ambient conditions. The vaporized LNG is then dispersed by the wind and a fuel vapour cloud is formed in the process area. At 125 s, an ignition occurs in the process area which leads to a pool fire. After 55 s the fire transits to a VCE in the congested and confined portion of the facility. This time is chosen based on the presence of the maximum thermal radiation in the layout. The heat load released due to the fire enhances the LNG vaporization over the LNG pool and causes a VCE. A transitional scenario is developed considering the inherent characteristics of the LNG spill and various potential events (such as pool formation, spreading, vaporization, and vapour dispersion) are modelled.

Fig. 3. A layout chosen for the transitional events modelling

3.1. Release, pool formation, vaporisation and dispersion modelling

In this scenario, an instantaneous release of LNG is considered which led to a pool formation and formed a flammable vapour plume upon vaporisation. A pool fire is considered with a delayed ignition. The entire layout 85 m × 55 m × 20 m is considered for simulation with a grid resolution of 0.4 m for the x and y directions and 0.3 m in the z direction. A sensitivity analysis was performed using volumetric concentration to select the grid size for a solution independent of the mesh size. Around the leak location, the grid resolution was

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adjusted to 0.2 m while at the locations far from the pool area, grids were stretched according to grid refinement guideline given in GexCon AS (2013). The LNG was assumed to be composed of 85% methane, 10% ethane and 5% propane. According to Pitblado et al. (2005) the maximum credible puncture hole is 250 mm. Thus, a point leak is considered from a 0.05 m^2 hole for 120 s forming a pool. A dynamic pool model (PM3) is chosen which means that the pool spreads with non-uniform pool temperature due to the influence of heat and mass transfer in each control volume (GexCon AS, 2013). A constant evaporation rate of 0.14 kg/(m^2s) is considered based on the OPG (2010a). The considered leak parameters are given in **Table 3**.

Table 3
Leak parameters considered in the release scenario

Leak type	Jet
Leak position	(26.5, 20, 1.2) m
Leak direction	+X
Start time	5 s
Duration	120 s
Outlet	
a. Area	0.05 m^2
b. Mass flow rate	10 kg/s
c. Relative turbulence intensity	0.02 (Low)
d. Turbulence length scale	0.025 m
e. Temperature	-160°C

The initial and boundary conditions assigned for the simulation are provided in **Table 4** and **Table 5** respectively. The Euler boundary condition is a zero pressure condition and demands significant distance in all directions (GexCon AS, 2013).

Table 4
Initial conditions used

Parameters	**Values**
Characteristic velocity	0.1 m/s
Relative turbulence intensity	0.1
Turbulence length scale	0.01 m
Temperature	20 °C

Ambient pressure	100 kPa
Ground roughness	0.001 m
Reference height	2 m
Pasquill stability class	F

Table 5
Boundary conditions

Name	Type
XLO	Wind
XHI	Euler
YLO	Wind
YHI	Euler
ZLO	Euler
ZHI	Euler

All parameters required for post processing are given in **Table 6**.

Table 6
 A list of simulated parameters

Output parameters	Unit
Pressure (P)	barg
Maximum pressure (PMAX)	barg
Velocity vector (VVEC)	m/s
Combustion product mass fraction (PROD)	-
Temperature (T)	K
Mass fraction of carbon monoxide (CO)	-
Radiative heat flux (QRAD)	kW/m^2
Total heat flux (Q)	kW/m^2
Mass fraction of soot (SOOT)	-
Heat dose (QDOSE)	$((kW/m^2)^{4/3})s$

Mass fraction of Nitrogen Dioxide (NO_2)	-
Probability of death (PDEATH)	-
Toxic probit (PROBIT)	-
Toxic concentration (TCONS)	mg/m^3
Toxic dose (TDOSE)	mg/m^3.minute

The vaporised fuel concentrations in the layout are monitored during the dispersion as shown in **Figs. 4** and **5**. The presence of flammable concentrations (0.05 - 0.15) indicates that the fuel has the potential to be ignited in several areas of the layout. This would likely contribute to the occurrence of transitional events or evolving accident scenarios.

Fig. 4. Dispersion of vaporised LNG over the layout (m^3/m^3) at time 125 s

Fig. 5. 3D dispersion of fuel in the layout (m^3/m^3) at 125 s which shows the maximum volume of gas cloud.

3.2. Assessing the possibility of transitional features

A VCE is considered as the final event and to identify transitional features, fire modelling is considered. Based on the dispersion characteristics of the LNG vapour, a pool fire is modelled with a delayed ignition 125 s using the FLACS fire model as demonstrated in **Fig. 6**. In the fire simulation, the Discrete Transfer Method (DTM) model is used because this is the most accurate radiation model (GexCon AS, 2013). Emissivity of 0.85 is used because it is applicable to most steel surfaces. To provide numerical stability, radiation start ramp is considered to be 1 (GexCon AS, 2013). The Eddy Dissipation Concept (EDC) is chosen as the combustion model. The Formation Oxidation model is chosen as the soot model. For typical hydrocarbons, the soot yield is in the order of 1% (GexCon AS, 2013). Radiation, smoke and engulfment are the main hazards of a pool fire (Jagger and O'Sullivan, 2004). The possibility of ignition of the accumulated LNG vapour due to the thermal radiation release from the fire needs to be assessed for transitioning to a VCE.

Fig. 6. 3D pool fire model at 125 s

The main purpose of the transitional event modelling is to analyse if the fire or dispersed vapour can cause a VCE or flash fire in the presence of an existing fire. The most likely location of an VCE can be identified based on the presence of a flammable concentration of LNG vapour, confinement/equipment congestion and ignition source. An autoignition can be a source of ignition of the vapour or heated objects due to the thermal radiation from the fire (Planas-Cuchi et al., 1997; Zheng and Chen, 2011). According to the fuel concentration and its developed pressure during LNG vapour dispersion, a transition of the pool fire to a VCE is modelled. The transition from fire to VCE is considered after 55 s of the start of the fire, that is at 180 s. The small pressure developed during LNG vapour dispersion is demonstrated in **Fig. 7**.

Fig. 7. Pressure developed in in the layout during dispersion of the fuel (barg)

3.3. Toxic potency assessment of combustion products

During LNG (mainly methane) fire, CO, Carbon dioxide, NO_2, unburnt methane and water are produced as combustion products depending on complete or incomplete combustion reaction. In this study, only CO and NO_2 are considered for toxic potency assessment owing to their high toxicity ~~According to~~ (Dadashzadeh et al., 2014). ~~CO and NO_2 are considered as the main combustion products of LNG fire. Thus, CO and NO_2 are used for toxic potency assessment in this study.~~ The different symptoms and health effects of CO and NO_2 are found in Purser et al. (2015) and the National Research Council (1998) respectively. ~~As shown in **Table 7**, the concentration levels of CO can have different health effects.~~

~~**Table 7**~~

~~Health effects at different concentrations of CO (Purser et al., 2015)~~

~~CO in air/ppm~~	~~CO in air/ (mg/m³)~~	~~Inspired /%~~	~~Carboxyhemoglobin (COHb) by ranges (approx.)~~	~~Toxic effects~~
~~1~~	~~1.15~~	~~0.0001~~	~~0~~	~~None. COHb normal range~~
~~3~~	~~3.44~~			~~1-1.5%. Note that inhaled CO adds to the baseline value~~
~~9~~	~~10.31~~		~~2~~	~~Vasodilation, slight reduction in time to exhaustion, possibly minor central nervous system effects~~
~~10~~	~~11.46~~	~~0.001~~		
~~30~~	~~34.37~~		~~5~~	
~~50~~	~~57.28~~			~~Reduced performance of complex tasks~~
~~70~~	~~80.19~~		~~10~~	
~~90~~	~~103.1~~			~~Headache, nausea, impaired judgement, lethargy, dizziness, shortness of breath (not marked early on)~~
~~100~~	~~114.56~~	~~0.01~~	~~20~~	

3.4. Integration of impact analysis

In this current study, an integrated impact analysis is conducted according to the step 5 of the methodology. The risks severity of combustion products was not directly normalised with those of thermal radiation and overpressure. However, an integrated impact analysis is conducted by investigating the risk contours of fire, VCE and combustion products. Similar to Dadashzadeh et al. (2013b), an integrated risk contour is used for assessing the impact of transitional accident scenarios in the facility.

4. Results and discussion

4.1. Results for transition modelling

The released LNG dispersed in the air resulted in a flammable vapour concentration over the plant not only adjacent to the leak location but also away from it. The autoignition temperature of LNG (primarily methane) is 1004°F (813.15K) (Foss et al., 2003). High temperatures and radiation from the fire reach the congested/confined areas, indicating that during the fire, there is a possibility of transitioning the fire into a VCE. The range of radiation and temperature generated during the fire are given in **Figs**. **8** and **9** respectively.

Fig. 8. Temperature distribution over the layout during the pool fire (K) at 180 s

The maximum temperatures and thermal radiation are 2300K and 80 kW/m² respectively. These high temperature and thermal radiation may easily contribute in causing other fires in adjacent areas. The variation of air pressure in the layout in the presence of the dispersed vapour can be a useful information for assessing the potential location of a VCE. During gases dispersion, concentration in the air can create different initial pressure, which is one of the parameters on which the strength of explosion depends (Kundu et al., 2016). In this study, the maximum pressure developed during the dispersion of LNG vapour is 0.001 barg (illustrated in **Fig. 7**). The 1 mbar initial pressure may not have a substantial effect on the strength of a VCE. ~~The pressure developed during the dispersion of LNG vapour is 0.001 barg (illustrated in~~ **Fig. 7**)~~.The maximum pressure developed during the dispersion of the LNG vapour is about 0.001 barg as illustrated in~~ **Fig. 7**~~.~~ The output results obtained from the fire modelling and the dispersion modelling show that the transition to a VCE or a flash fire is possible.

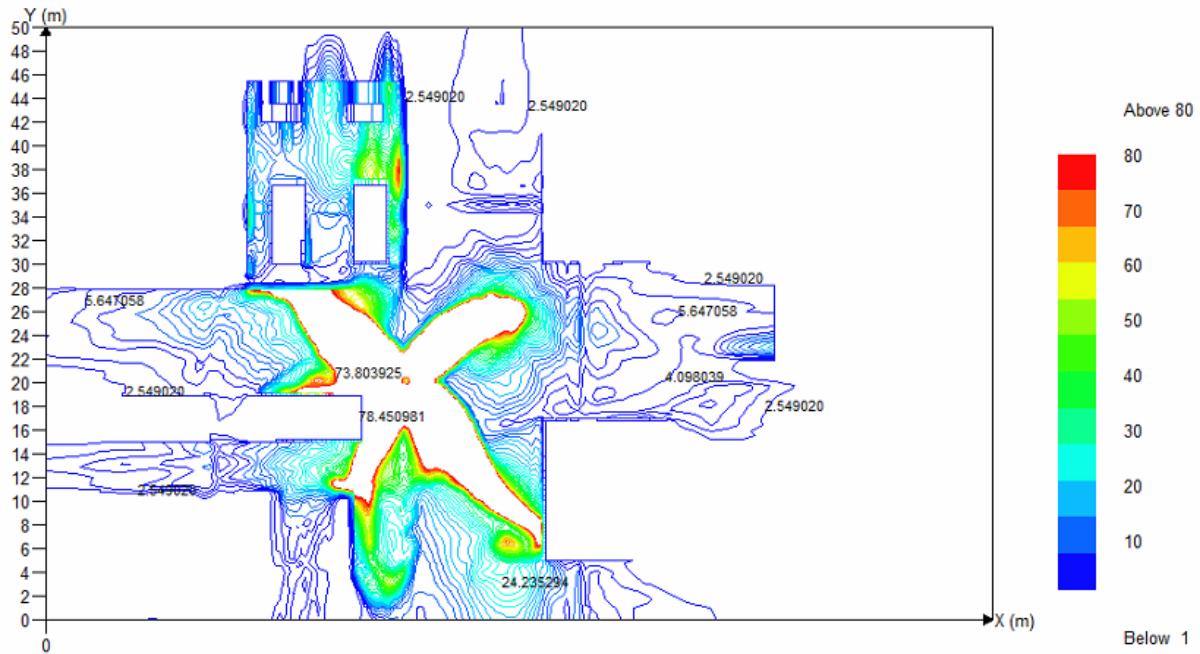**Fig. 9.** Radiation from the fire over the layout (kW/m^2) at 180 s

4.2. Thermal radiation impact

The tenability limit for human beings is approximately 2.5 kW/m^2 (Mannan, 2012). The presence of thermal radiation greater than 2.5 kW/m^2 indicates that the fire can have serious effects to human and adjacent assets. The probability of injuries (first and second-degree burn) and the probability of death at different location of the plant are calculated using the thermal radiation. The maximum damage distance for various effects of fire is given in **Table 7**.

Table 7
Maximum damage distance for various effects of fire

Effects on humans	Heat flux (kW/m^2)	Maximum damage distance (m)
100% lethality in 1 min. 1% lethality in 10 s	37.5	26.2
100% lethality in 1 min. Serious injuries in 10 s	25	33.5
1% lethality in 1 min. First degree burns in 10 s	12	36.7
No lethality. 2nd degree burns probable.	4	39.8

Pain after exposure of 20 s.		
Acceptable limit for prolonged exposure	1.6	43.5

The fire risk index of all grid points was calculated and plotted over the layout as demonstrated in **Fig. 10**. The risk index ($Risk_{fe}$) varies from 1 to the maximum value of 10 at the flame surface.
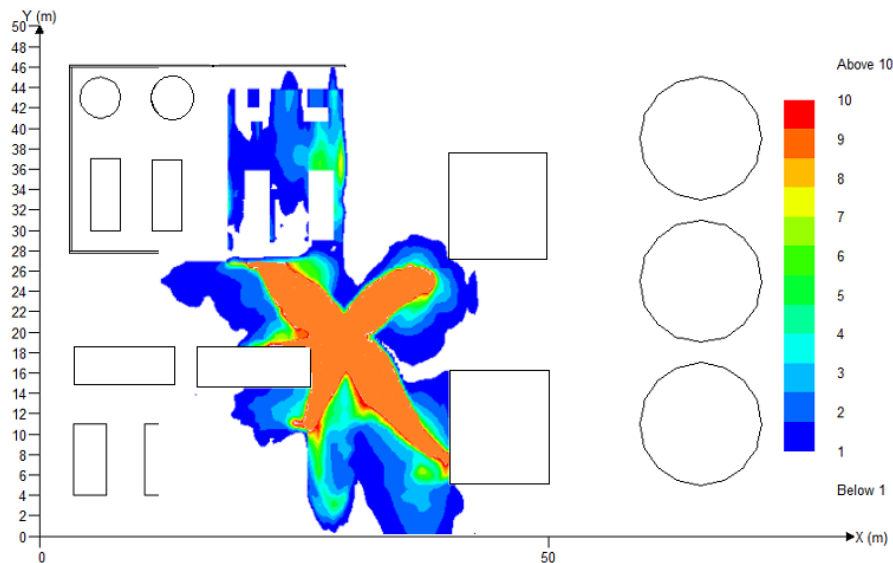

Fig. 10. Fire risk contour in the layout at 180 s

4.3.   VCE impact and risk assessment

The impact of the VCE and its subsequent risk are assessed based on the overpressure developed during the VCE. The explosion overpressure ranges from 0 to 2 barg over the layout and high pressures are found in the areas with a high congestion/confinement level as shown in **Fig. 11**. The developed pressures are limited within a portion of the congested layout. However, the developed pressures can result in damages to assets and humans in those areas of the facility. The damage distance from the VCE ignition point is illustrated in **Table 8**.

Table 8
Damage distance from the VCE ignition point

Effects	Distance from the ignition point (m)
100% fatality	4.60
60% fatality	6.25

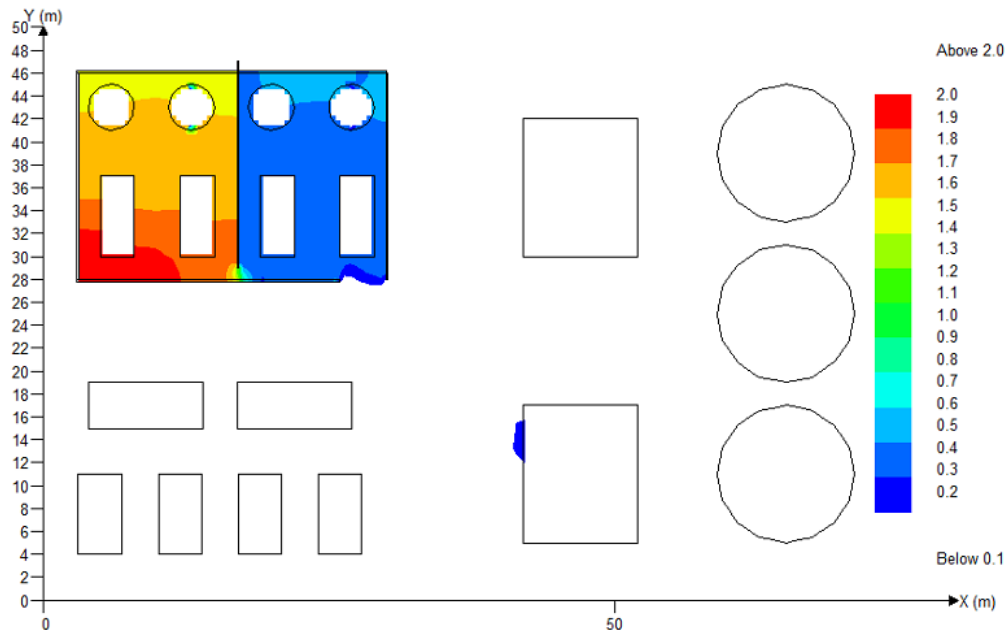|	
Fatal distance limit	7.80
Eardrum damage limit	10.30
Safe distance	15

Fig. 11. VCE pressure over the plant (barg) at 180 s

Using the probit model, the probabilities of injuries or death caused by the overpressure were estimated. Subsequently, the VCE risk index (Risk$_e$) was calculated and plotted over the facility as shown in **Fig. 12**. The values of the VCE risk index vary from 1 to 10. Index 1 corresponds to very low risk and the index 10 shows the maximum risk. A high-risk index is found in the congested/confined areas and vice-versa.

Fig. 12. Explosion risk profile at 180 s

4.4. Combustion product impact

The toxic concentration (mg/m^3) data obtained from the fire and explosion simulations were used for the toxicity assessment. The concentrations of contaminants are high near the fire and explosion locations and confined areas. The toxic concentration of NO_2 is given in **Fig. 13**. In confined areas, the concentration of NO_2 is more than 10^5 mg/m^3. Carbon monoxide is very toxic and a concentration of 1.28% leads to death within 2-3 minutes (Struttmann et al., 1998). The toxic concentration of CO is illustrated in **Fig. 14**. The higher concentrations of NO_2 are present in larger areas of the layout than those of CO. The obtained NO_2 and CO values are relatively high because these concentrations were measured when there was ongoing fire. Risk values are high around the fire and VCE locations due to higher concentrations of contaminants. This is because a risk value directly depends on exposure duration and concentration.
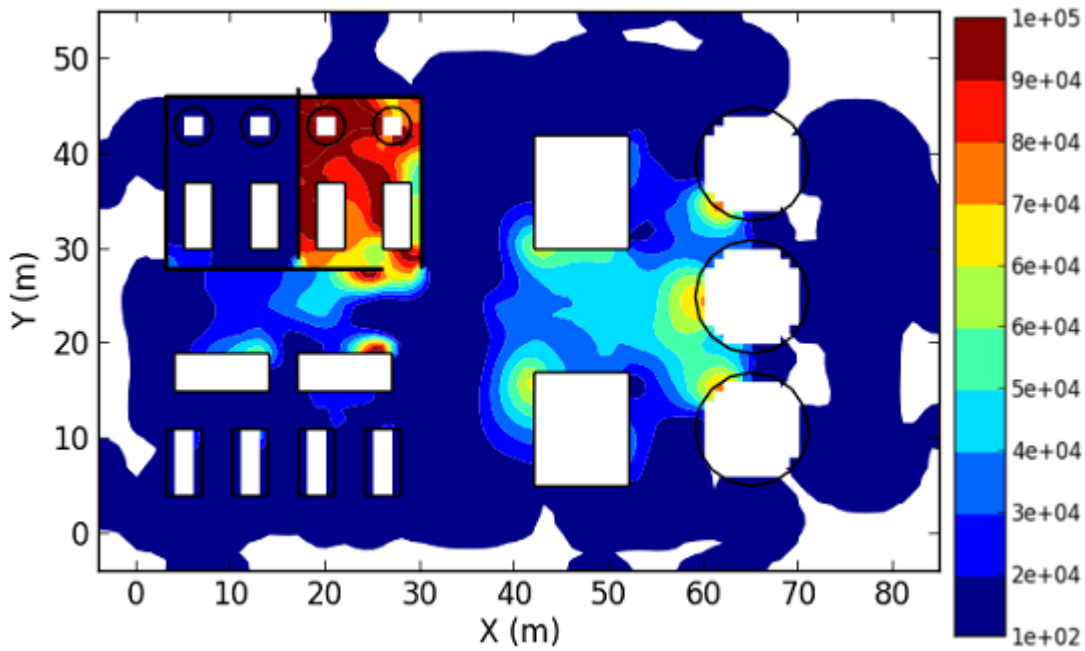
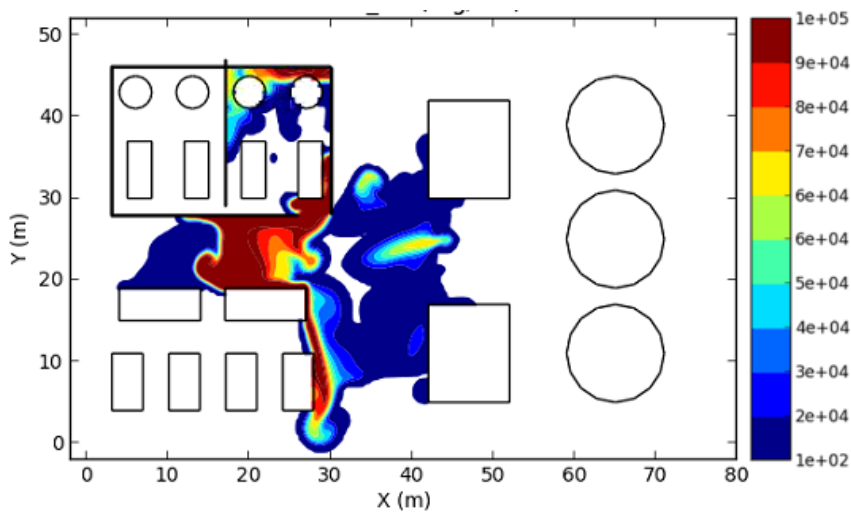**Fig. 13.** Concentration of NO_2 over the layout (mg/m^3) at 180 s

Fig. 14. Toxic concentration of CO (mg/m^3) at 180 s

4.5. Integrated impact during transition of fire to VCE

In most fire and/or explosion events, injury or fatality can be caused by combustion products in addition to radiation or overpressure hazards. **Fig. 15** demonstrates the integrated risk contours in the layout because of thermal radiation and overpressure during the fire and VCE. For simplicity, the range of risk index is normalised between 1 and 10 in the integrated risk profile. High risk indices are available in the fire location and the VCE area due to the inherent nature of those events.
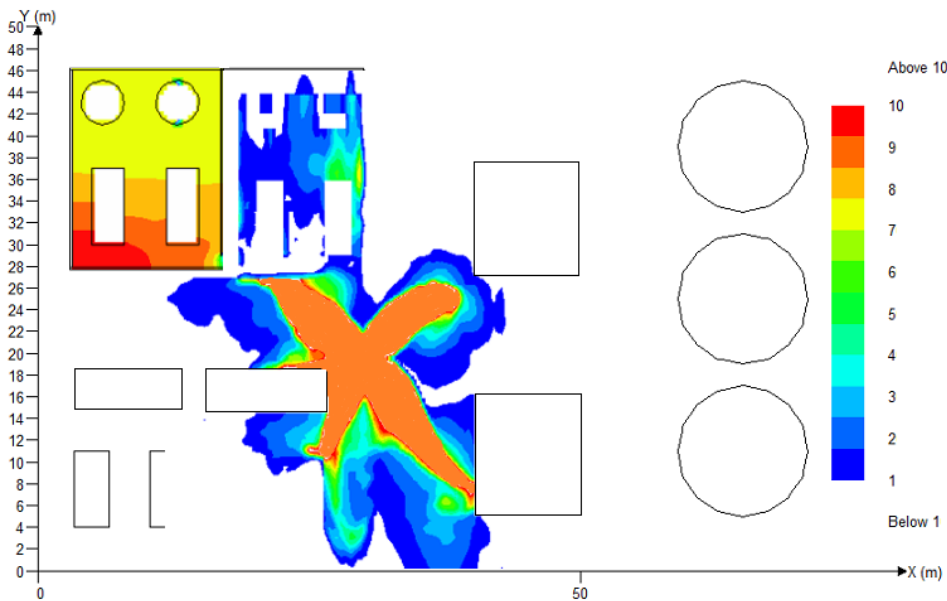
Fig. 15. Integrated risk profile of the fire and the VCE at 180 s

In toxicity risk assessment, an integrated risk of both contaminants is considered as shown in **Fig. 16**. The total combustion product risk shows that significant portions of the facility exceed the acceptable level of risk which is 1. The integrated risk profile of contaminants indicates that the high-risk area is larger than that of the integrated impact of fire and VCE as seen in **Fig. 15** and **Fig. 16**. However, due to the short exposure duration, the severity of the combustion products is lower than that of thermal radiation and overpressure. This shows that the impact of transitional events such as fire and VCE along with combustion products is more severe than an individual phenomenon because more portions of the facility exceeded the acceptable level of risk.

The current approach incorporates an additional feature to the previous integrated consequence studies such as Khan and Amyotte (2004) and Dadashzadeh et al. (2013b). Khan and Amyotte (2004) incorporated fire, explosion and toxic release damage indices, but did not directly assess the consequence. The adopted technique in Khan and Amyotte (2004) cannot be useful for visualizing the area directly affected by fire, explosion and combustion products. The severity of consequence would have been different if the impact of the combustion product was considered by Dadashzadeh et al. (2013b). During a fire and/or explosion, the potential risk from combustion products can be too simple to ignore because toxicity has been a major cause of death and injury from fires (Hartzell, 1992).

This paper illustrated only a specific case study. However, any changes in operating conditions such as wind speed, wind direction, snow, rain or other parameters can be
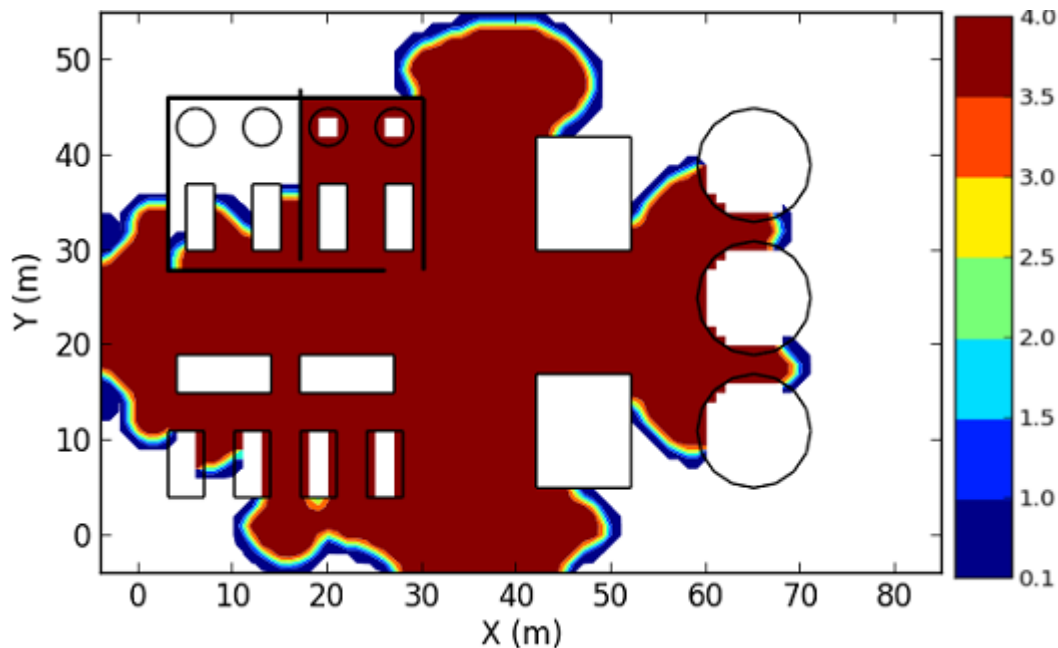
Fig. 16. Integrated risk of combustion products at 180 s

5. Conclusions

In Liquified Natural Gas (LNG) processing facilities, there is a possibility of a fire transitioning into a Vapour Cloud Explosion (VCE) or vice-versa during an accidental release of hydrocarbons as demonstrated in various past fire and explosion accidents. Identification of potential location of transitional events is useful for understanding the occurrence of cascading accident scenarios. A framework has been proposed for modelling transitional events (fire, VCE and combustion product release) and their integrated consequences using Computational Fluid Dynamics (CFD). The proposed framework was applied to a case study considering an accidental LNG release, including vaporisation, a pool fire and a VCE. The impact of each individual event was assessed, and an integrated consequence was modelled using a risk-based approach. The severity of risk during each event in the layout was compared. By analysing the LNG spill, vaporisation, dispersion and subsequent fire in the layout, it is foreseeable that a pool fire can transit to a VCE because of the availability of required suitable conditions such as a flammable vapour concentration, ignition source and congestion/confinement. The risk of the overpressure was limited to confined spaces and was insignificant in other areas. The risk of thermal radiation was present in a larger area in comparison to the VCE. The risk of combustion products was present in a larger area than those of radiation and the overpressure,

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but its severity was lower due to the short exposure duration. It was found that the integrated risk of transitional events was higher than that of the individual risk.

A cChanges in weather conditions and source terms may affect the outcome of an analysis related to gas leak and dispersion. Responses to gas leak and its dispersion are strongly dependent on these parameters and one set of parameters may not represent all cases. For illustration purpose, this study has presented only a specific case. Once operating conditions such as wind speed, wind direction, snow, rain or other parameter changes, the response need to be evaluated accordingly. The current study serves to highlight the importance of transitional events modelling and expands the scope of the integrated consequence modelling approach. Despite having complex correlations among various parameters involved in LNG spill and subsequent events, the integrated risk profiles can be effective for designing safety systems to mitigate potential effects and risks of thermal radiation, overpressure and combustion products during fire and/or explosion events. Consideration of effects among thermal radiation, overpressure and combustion products in the transitional event modelling, makes the study unique and realistic in safety analysis of an LNG processing facility. The proposed methodology would be useful for the safety measure design of processing facilities and an effective emergency preparedness plan.

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Modelling an integrated impact of fire, explosion and combustion products during transitional events caused by an accidental release of LNG

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Abstract

In a complex processing facility, there is likelihood of occurrence of cascading scenarios, i.e. hydrocarbon release, fire, explosion and dispersion of combustion products. The consequence of such scenarios, when combined, can be more severe than their individual impact. Hence, actual impact can be only represented by integration of above mentioned events. A novel methodology is proposed to model an evolving accident scenario during an incidental release of LNG in a complex processing facility. The methodology is applied to a case study considering transitional scenarios namely spill, pool formation and evaporation of LNG, dispersion of natural gas, and the consequent fire, explosion and dispersion of combustion products using Computational Fluid Dynamics (CFD). Probit functions are employed to analyze individual impacts and a ranking method is used to combine various impacts to identify risk during the transitional events. The results confirmed that in a large and complex facility, an LNG fire can transit to a vapor cloud explosion if the necessary conditions are met, i.e. the flammable range, ignition source with enough energy and congestion/confinement level. Therefore, the integrated consequences are more severe than those associated with the individual ones, and need to be properly assessed. This study would provide an insight for an effective analysis of potential consequences of an LNG spill in any LNG processing facility and it can be useful for the safety measured design of process facilities.

Keywords: LNG spill, accident transition, integrated consequence, CFD

1. Introduction

LNG is considered as a safe and environmentally-friendly fuel. Safe storage, processing, transportation and usage are mandatory requirements for any fuel and LNG continues to reveal a long track record of safety in all these areas (Yeo et al., 2016). However, in a complex processing facility such as a floating liquefied natural gas (FLNG) (Baksh et al., 2016a, b), an incidental release of LNG may not simply lead to an event with only its individual impact. There is likelihood of escalating a minor event into more damaging events. For instance, an accidental release of LNG in a production facility has the potential to pose several hazards such as fire, explosion, brittle fracture, asphyxiation and freeze burn/frostbite. A leakage of LNG may be a single minor event itself. However, due to instantaneous vaporisation, it is likely to cause several events such as a fireball, flash fire, Vapour Cloud Explosion (VCE), and pool fire when the vapour is ignited. Escalation of the mentioned events to a storage facility, may lead to Boiling Liquid Expanding Vapour Explosion (BLEVE). The entire sequence of events and their interactions during an LNG spill event in an FLNG processing facility is illustrated in **Fig. 1**.
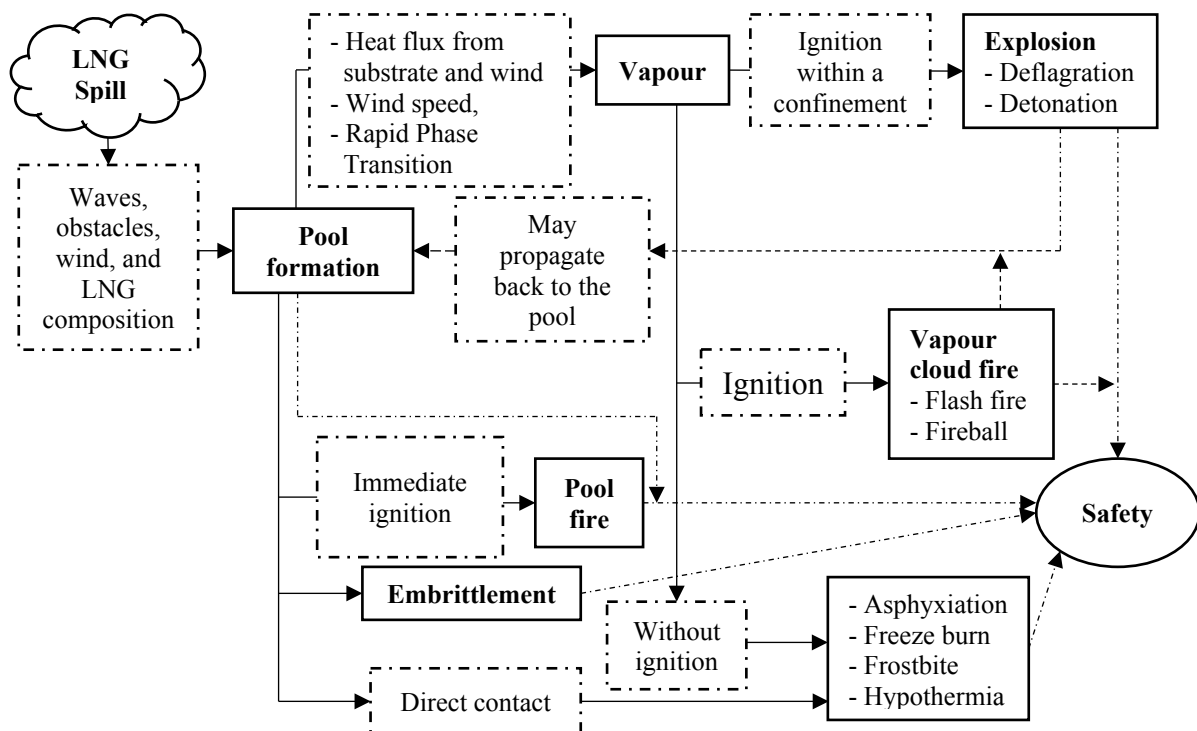

Fig. 1. LNG spill events (adapted from Ikealumba and Wu (2014) with some modifications).

Due to the potential of having several events during an unintended LNG spill, the US Government Accountability Office (GAO) commissioned a study and recommended to improve the state of knowledge surrounding the potential for cascading damage to LNG vessels

in the case of an incidental release of LNG (US Government Accountability Office (GAO), 2007). The study of cascading damage issues has proven difficult primarily because these events require the analysis of the interaction of a series of complex physical phenomena such as LNG flow, heat transfer, fracture and damage. Petti et al. (2013) summarized the outcomes of the studies on cascading damage (Figueroa et al., 2011; Petti and Kalan, 2011; Petti et al., 2011) which explored the cryogenic and fire thermal damage to an LNG ship during a large LNG cargo tank breach.

In these studies (Figueroa et al., 2011; Petti and Kalan, 2011; Petti et al., 2011), impacts (pressure wave, shrapnel or projectile) from the explosion are not considered in the cascading damage analysis. Examples of evolving accident scenarios are reported in (Ouddai et al., 2012; Petrie and Großbritannien, 1988). The Piper Alpha tragedy in 1988 caused 165 deaths due to an explosion after the release of flammable material. In the accident, leakage of gas occurred, and the presence of an ignition source caused multiple events such as a fireball and jet fire, followed by VCEs. The sequence of events led to the total loss of the platform (Pate -Cornell, 1993). In 2004, an LNG accident occurred in the Skikda LNG plant in Algeria resulting in 27 casualties, 56 injuries and $900 million loss. During this multiple explosions occurred due to excessive pressure in an adjacent boiler (Ouddai et al., 2012). The BP's Texas City refinery explosion in 2005 caused 15 deaths and 180 injuries due to hydrocarbon release and subsequent fire and explosion (Manca and Brambilla, 2012). The release resulted in a VCE followed by a pool fire (Broadribb, 2006). In 2010, the Macondo accident in the Gulf of Mexico occurred with a series of events such as blowout, dispersion of released hydrocarbons, explosion and fire (Deepwater Horizon Study Group (DHSG), 2011). The flame propagating from the explosion reached the flammable vapour dispersed over the platform and led to the fire at the source of release at the drilling floor. Major accidents that occurred in process facilities are well explained in (Abdolhamidzadeh et al., 2011; Al-shanini et al., 2014; Khan and Abbasi, 1999). These accidents are mainly associated with fires, explosions and toxic product release. Most past studies regarding fire and explosion accidents were limited to individual fires or explosions or combustion products modelling and did not address evolving accident scenarios (Dadashzadeh et al., 2013a; Dadashzadeh et al., 2014; Gavelli et al., 2011; Kim and Salvesen, 2002). For instance, Dadashzadeh et al. (2013a) modelled the dispersion of flammable gas integrated with explosion consequences of the BP Deepwater Horizon explosion using a Flame Acceleration Simulator (FLACS). Smoke and heat radiation released from the fire also affect human health and offshore structures; however, this impact was not addressed in the consequence analysis. Dadashzadeh et al. (2014) proposed a methodology for toxicity risk

assessment during an LNG fire and revealed that high risks are found at the process facility due to higher concentrations of combustion products and longer exposure time. However, the direct consequence of fire was not considered. Baalisampang et al. (2017a) and Baalisampang et al. (2017b) modelled the impact of a fire in a typical FLNG processing facility. Other potential events, their interactions, and consequences were not included by Baalisampang et al. (2017a). Kim and Salvesen (2002) conducted a study on LNG vapour release, which was addressed as a possible VCE. However, a potential fire scenario was not considered. Another study by Koo et al. (2009) focused on pool fire modelling only and no consideration was given to a VCE or other possible interactions such as a jet fire. But in most cases, fire, explosion and combustion product release occur one after another or simultaneously resulting in integrated consequences (Baalisampang et al., 2018a; Baalisampang et al., 2018b). Reviews of past accidents (Al-shanini et al., 2014; Dadashzadeh et al., 2013a; Manca and Brambilla, 2012) and models (Al-shanini et al., 2014; Baksh et al., 2015; Kim and Salvesen, 2002; Koo et al., 2009) demonstrate a need to evaluate the entire accident sequence to mitigate the impact, to develop appropriate response methods and to prevent accidents by designing safety measures in the system. Combination of various accidental events is important as one event may lead to another and increases the overall consequences. To model entire impacts of a potential accident in a complex processing facility, it is essential to consider transitional event scenarios because in such modelling, entire causes and effects of a series of events are considered. In comparison to onshore processing facilities, offshore facilities are deemed more vulnerable to transitional events due to limited topside space and harsh environmental conditions (Baalisampang et al., 2016). Some offshore accidents involving transitional events are given in **Table 1**.

Table 1
Offshore fire and explosion accidents associated with multiple events

Accident name, year and geographical region	Event sequence	Consequences	References
Piper Alpha, 1988, Europe North Sea	Release ⟶ Explosion ⟶ Fire	165 fatalities, total loss	(Pate - Cornell, 1993)
High Island Pipeline, 1989, US GOM	Collision ⟶ Release ⟶ Explosion ⟶ Fire	11 fatalities, 4 injuries and significant damage	(OPG, 2010b)
Enchova Central, 1984, America South East	Blowout ⟶ Fire ⟶ Explosion	42 Fatalities, 19 injuries and significant damages	(OPG, 2010b)

Lake Maracaibo, 1993, America South East	Explosion $\longrightarrow$ Fire	11 fatalities, significant damage	(OPG, 2010b)
Ubit, 1995, Africa West	Explosion $\longrightarrow$ Fire	10 fatalities, 23 injuries and severe damage	(OPG, 2010b)
Petrobras P-36, 2001, America South East	Explosion $\longrightarrow$ Fire $\longrightarrow$ Capsizing	11 fatalities, total loss	(OPG, 2010b)
Bombay High North, 2005, Asia South	Collision $\longrightarrow$ Release $\longrightarrow$ Fire	12 fatalities, severe damage to the jacket	(OPG, 2010b)
Deepwater Horizon, 2010, GOM	Blowout $\longrightarrow$ Release $\longrightarrow$ Fire $\longrightarrow$ Explosion	11 people died, 17 injuries and total loss	(Deepwater Horizon Study Group (DHSG), 2011)
Black Elk, 2012, GOM	Release $\longrightarrow$ Fire $\longrightarrow$ Explosion	3 people died, pollutant spill	(BSEE, 2013)
SOKAR platform, 2014, Caspian Sea	Explosion $\longrightarrow$ Fire	12 people fell into the sea	(Fattakhova and Barakhnina, 2015)
Abkatun Alfa platform, 2015, GOM	Explosion $\longrightarrow$ Fire	7 people died, 45 injuries	(Offshore Post-Everything offshore energy, 2015)

In fire and explosion accidents, a combined impact assessment is assumed to provide a more accurate consequence than individual one. In fire and explosion accidents, a damage potential (radius) can be increased if the impact of combustion products is considered (Dadashzadeh et al., 2014). During fire and explosion accidents, depending upon the types of burning materials and their combustion products, people are exposed to adverse health effects. For an integrated impact study, Khan and Amyotte (2004) proposed a methodology that incorporated fire, explosion and toxic release damage indices to evaluate the inherent safety of a facility based on inherent safety guidelines. Dadashzadeh et al. (2013b) proposed a new methodology for modelling an integrated consequence of fire and explosion using the Fire Dynamics Simulator (FDS) and FLACS and concluded that the risk of combined consequences is higher than each individual risk. But potential risk from combustion products during fire and/or explosion was not considered in the study. Niazi et al. (2018) proposed an integrated consequence modelling approach for fire and combustion products using risk based and grid-

based approaches and claimed that the risk posed by thermal radiation is confined only to the lower deck. But the risk of exposure to combustion products was present in a larger area than that of the radiation, due to the influence of wind. Unlike previous studies (Dadashzadeh et al., 2013b; Khan and Amyotte, 2004; Niazi et al., 2018), the current study proposes a risk-based approach to model an integrated impact of fire, explosion and combustion products during an accidental release of LNG in a typical FLNG processing facility.

2. Methodology

This study proposes a methodology that models an integrated impact of evolving accident scenarios such as release, pool fire, explosion events and dispersion of combustion products as illustrated in **Fig. 2**. Currently, several Quantitative Risk Assessment (QRA) softwares tools such as IMESAFR (Tatom et al., 2011), Riskcurves (GexCon, 2018b), EFFECTS (GexCon, 2018a), Riskan (Lewis, 2005), HAMS-GPS (HAMSAGARS) and Phast and Safeti (DNV-GL, 2018) are available for accident modelling. They are simpler and faster than most CFD tools. A majority of QRA software tools lacks the capability of considering complex effects of geometry and equipment in the simulation and cannot model evolving accident scenarios. But this study considers the effect of complex geometry and/or equipment and models cascading events and their impacts using the following five steps.

In step 1, LNG release scenario, pool formation, vaporisation and dispersion of LNG vapour are modelled using FLACS. These phenomena are simulated with careful consideration of plausible scenarios.
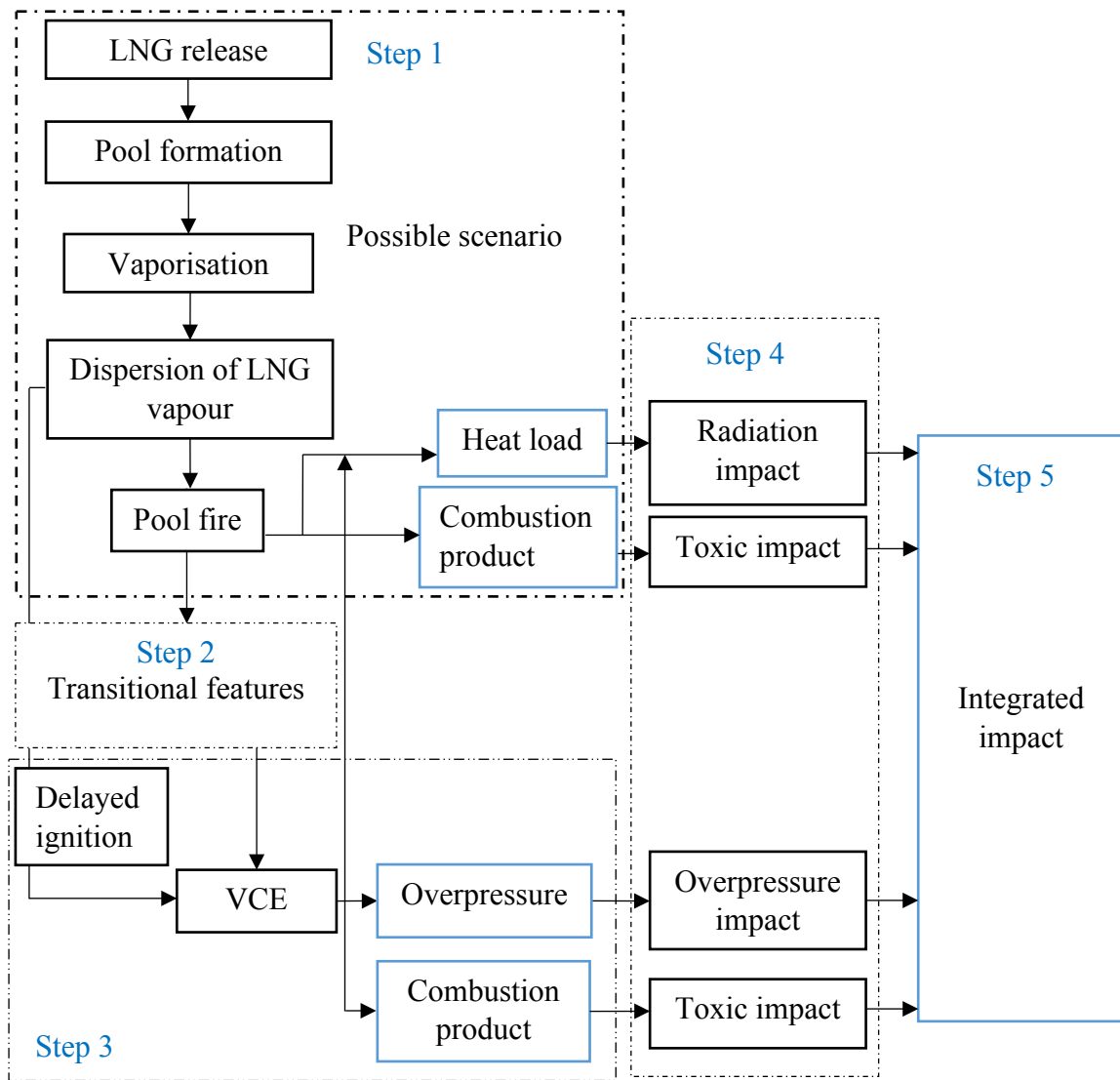
Fig. 2. Proposed methodology for modelling an integrated impact of transitional events to human during an LNG spill.

In step 2, the potential transitional phenomena are considered by attending to a series of events such as dispersion of LNG vapour, pool fire and VCE. The phenomenological changes to spilled LNG and vaporisation due to a culmination of atmospheric effects and thermal radiation are considered for assessing the occurrence of potential cascading events. The thermal load obtained from the pool fire is used as the source of ignition for the VCE. For transitional events to occur, some minimum conditions need to be fulfilled. For instance, a dispersion event can transit to pool fire only if the flammability condition is met. Similarly, a VCE occurs when pertinent conditions such as confinement, turbulence, ignition source, and flammable gas cloud are present (Atkinson et al., 2017; Center for Chemical Process Safety, 1996). These pertinent conditions are considered as stimuli for the transitions (events) (Alzbutas, 2015). During a release, with the vaporisation and dispersion of LNG in air, only a

vapour concentration in the range of 5-15 vol.% will sustain the propagation of a flame upon ignition. The concentration of the vapour above the upper explosion limit may act as feed gas to the fire. However, if the dispersed vapours accumulate in nearby semi-confined or confined areas, the fire may transform to a VCE upon ignition. This may increase the severity of consequence in total. If the flammable gas release is not ignited immediately, a vapor plume will form which will drift and disperse by the ambient winds and/or natural ventilation. If the vapour is ignited, but does not explode, it will result in a flash fire, in which the gas cloud within the flammable range burns very rapidly. If the vapour is not isolated during this time, the flash fire may burn to yield a jet fire at the source of the release, under the condition that the concentration range is appropriate, and the leak is present.

In step 3, the heat released from the pool fire is modelled as the potential ignition source to ignite the flammable gas accumulated at a position away from the pool fire location such that the fire did not consume the rich vapour cloud from this location. It was assumed that this location did not get direct fire flame and the presence of high thermal radiation from the fire resulted in an autoignition of the vapour or influenced other ignition sources to ignite. During a release of a flammable gas, if the ignition is delayed by 5-10 min, a VCE may be the outcome (Assael and Kakosimos, 2010; Soman and Sundararaj, 2012). For ignition to take place, the vapour cloud must be within the flammable range, while at the same time a source able to supply the required energy must be available (Assael and Kakosimos, 2010). To model a pool fire transiting to a VCE, thermal radiation and other parameters such as temperature and pressure development are extracted from the previous step. There are various models available for gas explosion modelling, like empirical, phenomenological and CFD (Lea and Ledin, 2002). According to Tam and Lee (1998), CFD codes are inherently more flexible than both empirical and phenomenological models and are applicable to all fields. Some commonly used CFD models for explosion simulations are EXSIM, FLACS and AutoReaGas (Lea and Ledin, 2002). FLACS developed by the Global Explosion Consultants (GexCon AS) has been used widely for the modelling of gas dispersion and explosion in onshore or offshore facilities (Hansen et al., 2005). In this study, FLACS is used to model the fire and explosion scenarios.

In step 4, the consequences of fire, explosion and/or combustion product release are analysed individually using probit functions. The heat load obtained from the fire is used to assess the fire impact to assets and people. The probability of human impacts from the heat radiation is calculated by Eq. (2), considering the probit model given in Eq. (1).

Probit function $(Pr) = c_1 + c_2\ln D,$ (1)

The probability of injury or death $(P) = F_k\frac{1}{2}\Big[1 + erf\Big(\frac{Pr - 5}{\sqrt{2}}\Big)\Big],$ (2)

where D is the thermal dose $\Big(\frac{kW}{m^2}\Big)^{\frac{4}{3}} s$, c_1 and c_2 are probit coefficients, F_k is a clothes correction factor, and *erf* is the error function. The thermal dose is obtained from the post processing file using inbuilt utilities in FLACS.

Sudden large changes in pressure due to an explosion can lead to dramatic and possibly fatal damage to vital human organs such as lungs and ears. The impact of explosion is assessed based on the calculation of the probability (P) of injury or death employing Eqs. (3)-(8).

Probit function $(Pr) = c_1 + c_2\ln S,$ (3)

The probability of injury or death (P) $= \frac{1}{2}\Big[1 + erf\Big(\frac{Pr - 5}{\sqrt{2}}\Big)\Big],$ (4)

where variable S is defined according to the type of the effect calculated by $S = \Big(\frac{4.2}{\overline{P}} + \frac{1.3}{\overline{i}}\Big),$

where $\overline{i}$ is the scaled impulse $\Big(Pa^{\frac{1}{2}}.s.kg^{-\frac{1}{3}}\Big)$, $\overline{P}$ is scaled pressure (-) and c_1 and c_2 are probit coefficients (Assael and Kakosimos, 2010). Explosion effects on humans are usually categorised as:

1. Direct or primary effects

   The overpressure from the explosion can cause injury to sensitive human organs, or death.

2. Indirect effects

   The indirect effects are sub-divided into two categories

   a. Secondary effects refer to injuries or death caused by fragments or debris thrown by explosion's blast,

   b. Tertiary effects that refer to injuries or death caused by whole-body displacement and collision with stationary objects or structures, because of the explosion's blast waves.

The probabilities of impact to lung, eardrum rupture, head impact and whole-body displacement impact are calculated using Eq. (4). However, the *Pr* are different. In this study, the following probit functions are used for each type of impact (Assael and Kakosimos, 2010).

For lung damage, $Pr = 5 - 5.74 \ln S$ (5)

For eardrum damage, $Pr = -12.6 + 1.524 \ln P_s$ (6)

For head impact, $Pr = 5 - 8.49 \ln S$ (7)

For whole-body displacement, $Pr = 5 - 2.44\ln S$ (8)

where P_s is overpressure (Pa). According to Clancey (1972) cited in Crowl and Louvar (2011) 1-99% fatalities can occur when exposed to over 2 bar.

Toxicity of combustion products accounts for a major cause of death and injury from unwanted fires (Hartzell, 1992). The main combustion products are divided into two types: asphyxiant gases, which prevent oxygen uptake by cells, leading to loss of consciousness and death; irritant gases which cause immediate incapacitation affecting eyes and upper respiratory tract long-term damage in the lung (Hull and Stec, 2010). Because of these harmful effects, they can seriously jeopardise evacuation. During an LNG fire or VCE, carbon monoxide (CO) and nitrogen dioxide (NO_2) are the main toxic combustion products (Dadashzadeh et al., 2014).

In the step 5, the integrated impact of fire, explosion and combustion product release is estimated. For integration of fire and VCE effects a grid-based approach is used such that consequence severity can be mapped as an index. To estimate risk of each event, a risk-based approach was further adopted using a severity index and probability of each effect. The severity index for each type of effect (S_i) is estimated using expert judgment. The effects are ranked based on their severity of damages (**Table 2**) and experts' judgment on a scale of 1–10.

Table 2
Severity scores for human effects caused by fire and explosion (Dadashzadeh et al., 2013b)

	Fire			Explosion			
Effects	First degree burn	Second degree burn	Death	Lung damage	Eardrum rupture (injury)	Head impact (death)	Whole body displacement (death)
Score (S)	2	5	10	10	5	10	10

The severity index for each effect at any location of the plant is calculated as follows:

$$\text{Risk}_i = S_i \times P_i \tag{9}$$

Where, Risk$_i$ denotes the severity index for each effect and i denotes the effects (first degree injury, second degree injury and death for fire; lung damage, eardrum rupture, head impact and whole-body displacement for explosion). At each grid point, the maximum severity index among the various effects of each accident is considered using Eqs. (10) and (11) for a fire and explosion respectively.

$$\text{Risk}_f = \text{maximum}\left[\text{Risk}_{\text{First degree burn}}, \text{Risk}_{\text{Second degree burn}}, \text{Risk}_{\text{Death}}\right] \tag{10}$$

$$\text{Risk}_e = \text{maximum}\left[\text{Risk}_{\text{Lung}}, \text{Risk}_{\text{Eardrum damage}}, \text{Risk}_{\text{Head impact}}, \text{Risk}_{\text{Whole body displacement}}\right] \tag{11}$$

The total risk of fire and VCE (Risk$_{fe}$) at any location is estimated using Eq. (12),

$$\text{Risk}_{fe} = \text{Risk}_f + \text{Risk}_e \tag{12}$$

Using the Risk$_{fe}$ at any location of the layout, risk contour can be obtained considering cumulative effects of a fire and VCE.

The toxicity risk assessment is carried out according to the methodology proposed by Dadashzadeh et al. (2014). A hazard index (HI) was estimated at each grid point of the layout using Eq. (13) (National Research Council, 1998).

$$HI = \frac{Estimated\ concentration\ (mg/m^3)}{Reference\ toxic\ value\ (mg/m^3)} \qquad (13)$$

For toxic risk estimation of each contaminant of the combustion product, Eq. (13) can be written as in Eq. (14).

$$Risk_{combustion\ product} = \frac{Exposure\ concentration}{TLV - STEL} \qquad (14)$$

Where TLV-STEL is the Threshold limit value - Short Term Exposure Limit (mg/m³). By adding the hazard quotients (hazard indices) for the individual emission toxicants, the hazard quotient of all toxicants is obtained as shown in Eq. (15). A risk of a health effect is assumed to exist at those exposure locations where the hazard index exceeds 1.

$$Risk_{Total\ combustion\ product} = Risk_{CO} + Risk_{NO_2} \qquad (15)$$

Finally, the integrated risk at any location of the facility is estimated by investigating the Risk$_{fe}$ and the Risk$_{combustion\ products}$ under any considered scenarios.

3. Application of the integrated methodology: a case study

The proposed methodology is applied to a typical layout consisting of several process equipment as shown in **Fig. 3**. Leak, vaporisation and dispersion are strongly dependent on the operating parameters and may need to consider prevalent operating conditions. In this case study, prevalent operating conditions are considered based on FLACS user's manual (GexCon AS, 2013). In this scenario, 10 kg/s of LNG is released at an LNG processing plant. According to Woodward (2010) the appropriate wind speed for flammable cloud dispersion is usually close to 2 to 4 m/s and thus, the wind speed is taken as 3 m/s with an ambient temperature of 20°C. A pool of LNG is formed at the release location and vaporization occurs due to the ambient conditions. The vaporized LNG is then dispersed by the wind and a fuel vapour cloud is formed in the process area. At 125 s, an ignition occurs in the process area which leads to a pool fire. After 55 s the fire transits to a VCE in the congested and confined portion of the facility. This time is chosen based on the presence of the maximum thermal radiation in the layout. The heat load released due to the fire enhances the LNG vaporization over the LNG

pool and causes a VCE. A transitional scenario is developed considering the inherent characteristics of the LNG spill and various potential events (such as pool formation, spreading, vaporization, and vapour dispersion) are modelled.
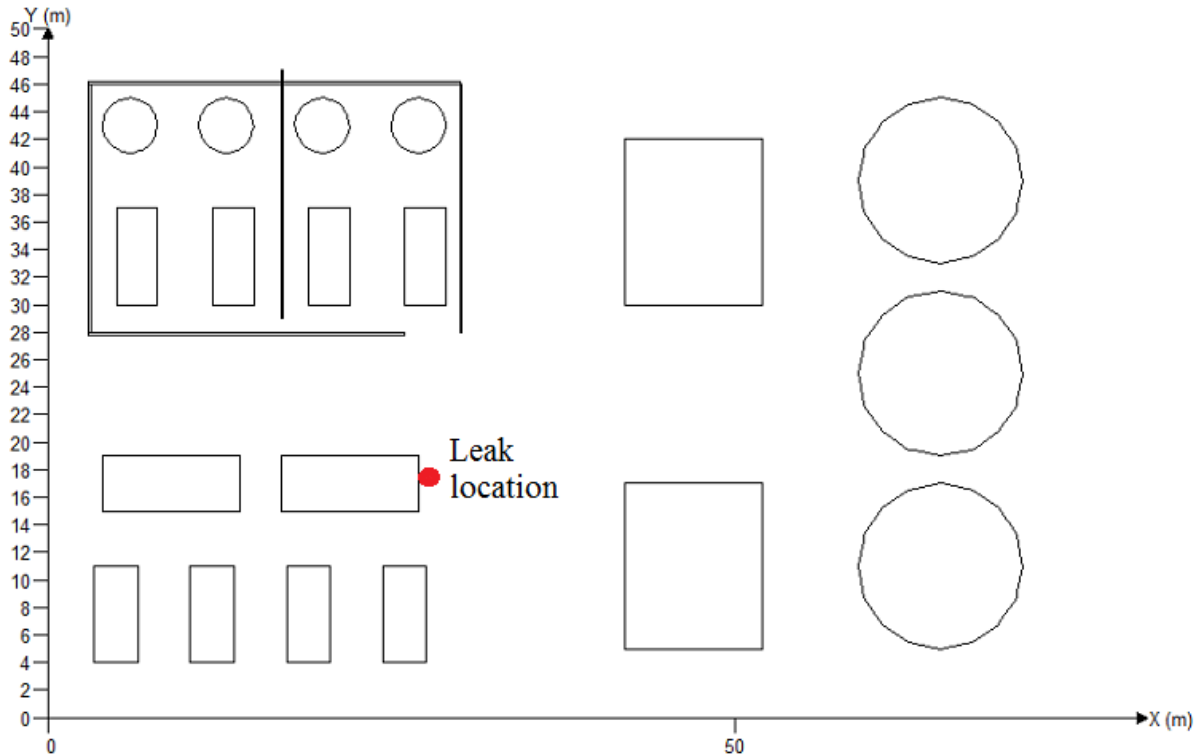

Fig. 3. A layout chosen for the transitional events modelling

3.1. Release, pool formation, vaporisation and dispersion modelling

In this scenario, an instantaneous release of LNG is considered which led to a pool formation and formed a flammable vapour plume upon vaporisation. A pool fire is considered with a delayed ignition. The entire layout 85 m × 55 m × 20 m is considered for simulation with a grid resolution of 0.4 m for the x and y directions and 0.3 m in the z direction. A sensitivity analysis was performed using volumetric concentration to select the grid size for a solution independent of the mesh size. Around the leak location, the grid resolution was adjusted to 0.2 m while at the locations far from the pool area, grids were stretched according to grid refinement guideline given in GexCon AS (2013). The LNG was assumed to be composed of 85% methane, 10% ethane and 5% propane. According to Pitblado et al. (2005) the maximum credible puncture hole is 250 mm. Thus, a point leak is considered from a 0.05 m² hole for 120 s forming a pool. A dynamic pool model (PM3) is chosen which means that the pool spreads with non-uniform pool temperature due to the influence of heat and mass transfer in each control volume (GexCon AS, 2013). A constant evaporation rate of 0.14

kg/(m^2s) is considered based on the OPG (2010a). The considered leak parameters are given in **Table 3**.

Table 3
Leak parameters considered in the release scenario

Leak type	Jet
Leak position	(26.5, 20, 1.2) m
Leak direction	+X
Start time	5 s
Duration	120 s
Outlet	
a. Area	0.05 m^2
b. Mass flow rate	10 kg/s
c. Relative turbulence intensity	0.02 (Low)
d. Turbulence length scale	0.025 m
e. Temperature	-160°C

The initial and boundary conditions assigned for the simulation are provided in **Table 4** and **Table 5** respectively. The Euler boundary condition is a zero pressure condition and demands significant distance in all directions (GexCon AS, 2013).

Table 4
Initial conditions used

Parameters	Values
Characteristic velocity	0.1 m/s
Relative turbulence intensity	0.1
Turbulence length scale	0.01 m
Temperature	20 °C
Ambient pressure	100 kPa
Ground roughness	0.001 m
Reference height	2 m
Pasquill stability class	F

Table 5
Boundary conditions

Name	Type
XLO	Wind
XHI	Euler
YLO	Wind
YHI	Euler
ZLO	Euler
ZHI	Euler

All parameters required for post processing are given in **Table 6**.

Table 6
 A list of simulated parameters

Output parameters	Unit
Pressure (P)	barg
Maximum pressure (PMAX)	barg
Velocity vector (VVEC)	m/s
Combustion product mass fraction (PROD)	-
Temperature (T)	K
Mass fraction of carbon monoxide (CO)	-
Radiative heat flux (QRAD)	kW/m^2
Total heat flux (Q)	kW/m^2
Mass fraction of soot (SOOT)	-
Heat dose (QDOSE)	$((kW/m^2)^{4/3}s)$
Mass fraction of Nitrogen Dioxide (NO_2)	-
Probability of death (PDEATH)	-
Toxic probit (PROBIT)	-
Toxic concentration (TCONS)	mg/m^3
Toxic dose (TDOSE)	mg/m^3.minute

The vaporised fuel concentrations in the layout are monitored during the dispersion as shown in **Figs. 4** and **5**. The presence of flammable concentrations (0.05 - 0.15) indicates that the fuel

has the potential to be ignited in several areas of the layout. This would likely contribute to the occurrence of transitional events or evolving accident scenarios.

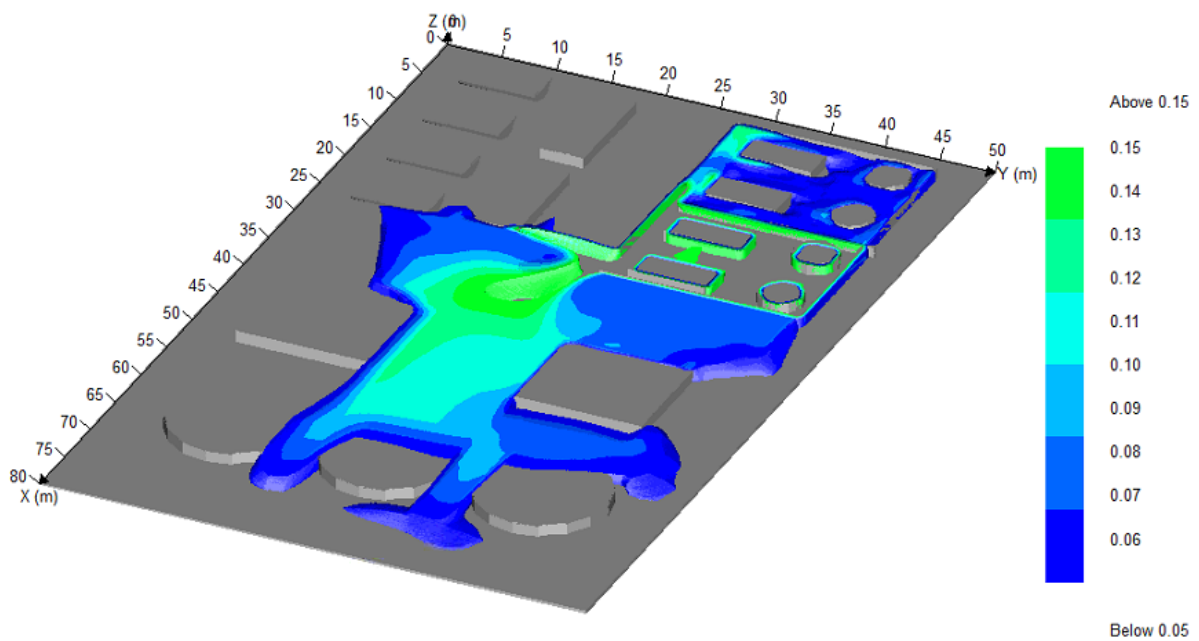**Fig. 4.** Dispersion of vaporised LNG over the layout (m³/m³) at time 125 s

Fig. 5. 3D dispersion of fuel in the layout (m³/m³) at 125 s which shows the maximum volume of gas cloud.

3.2. Assessing the possibility of transitional features

A VCE is considered as the final event and to identify transitional features, fire modelling is considered. Based on the dispersion characteristics of the LNG vapour, a pool fire is modelled with a delayed ignition 125 s using the FLACS fire model as demonstrated in **Fig. 6**. In the fire simulation, the Discrete Transfer Method (DTM) model is used because this is the most accurate radiation model (GexCon AS, 2013). Emissivity of 0.85 is used because it is applicable to most steel surfaces. To provide numerical stability, radiation start ramp is considered to be 1 (GexCon AS, 2013). The Eddy Dissipation Concept (EDC) is chosen as the combustion model. The Formation Oxidation model is chosen as the soot model. For typical hydrocarbons, the soot yield is in the order of 1% (GexCon AS, 2013). Radiation, smoke and engulfment are the main hazards of a pool fire (Jagger and O'Sullivan, 2004). The possibility of ignition of the accumulated LNG vapour due to the thermal radiation release from the fire needs to be assessed for transitioning to a VCE.

Fig. 6. 3D pool fire model at 125 s

The main purpose of the transitional event modelling is to analyse if the fire or dispersed vapour can cause a VCE or flash fire in the presence of an existing fire. The most likely location of a VCE can be identified based on the presence of a flammable concentration of LNG vapour, confinement/equipment congestion and ignition source. An autoignition can be a source of ignition of the vapour or heated objects due to the thermal radiation from the fire (Planas-Cuchi et al., 1997; Zheng and Chen, 2011). According to the fuel concentration and its developed pressure during LNG vapour dispersion, a transition of the pool fire to a VCE is modelled. The

transition from fire to VCE is considered after 55 s of the start of the fire, that is at 180 s. The small pressure developed during LNG vapour dispersion is demonstrated in **Fig. 7**.
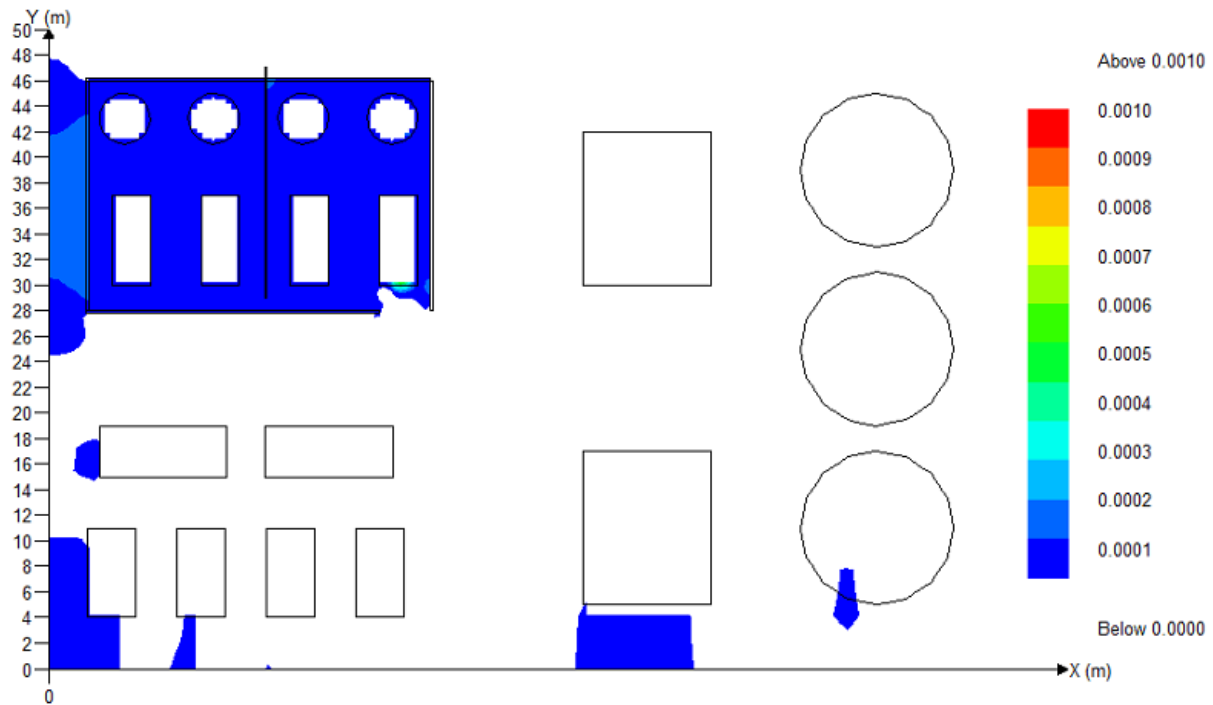

Fig. 7. Pressure developed in in the layout during dispersion of the fuel (barg)

3.3. Toxic potency assessment of combustion products

During LNG (mainly methane) fire, CO, Carbon dioxide, NO_2, unburnt methane and water are produced as combustion products depending on complete or incomplete combustion reaction. In this study, only CO and NO_2 are considered for toxic potency assessment owing to their high toxicity (Dadashzadeh et al., 2014). The different symptoms and health effects of CO and NO_2 are found in Purser et al. (2015) and the National Research Council (1998) respectively.

3.4. Integration of impact analysis

In this current study, an integrated impact analysis is conducted according to the step 5 of the methodology. The risks severity of combustion products was not directly normalised with those of thermal radiation and overpressure. However, an integrated impact analysis is conducted by investigating the risk contours of fire, VCE and combustion products. Similar to Dadashzadeh et al. (2013b), an integrated risk contour is used for assessing the impact of transitional accident scenarios in the facility.

4. Results and discussion

4.1. Results for transition modelling

The released LNG dispersed in the air resulted in a flammable vapour concentration over the plant not only adjacent to the leak location but also away from it. The autoignition temperature of LNG (primarily methane) is 1004°F (813.15K) (Foss et al., 2003). High temperatures and radiation from the fire reach the congested/confined areas, indicating that during the fire, there is a possibility of transitioning the fire into a VCE. The range of radiation and temperature generated during the fire are given in **Figs**. **8** and **9** respectively.

Fig. 8. Temperature distribution over the layout during the pool fire (K) at 180 s

The maximum temperatures and thermal radiation are 2300K and 80 kW/m^2 respectively. These high temperature and thermal radiation may easily contribute in causing other fires in adjacent areas. The variation of air pressure in the layout in the presence of the dispersed vapour can be a useful information for assessing the potential location of a VCE. During gases dispersion, concentration in the air can create different initial pressure, which is one of the parameters on which the strength of explosion depends (Kundu et al., 2016). In this study, the maximum pressure developed during the dispersion of LNG vapour is 0.001 barg (illustrated in **Fig. 7**). The 1 mbar initial pressure may not have a substantial effect on the strength of a VCE. The output results obtained from the fire modelling and the dispersion modelling show that the transition to a VCE or a flash fire is possible.
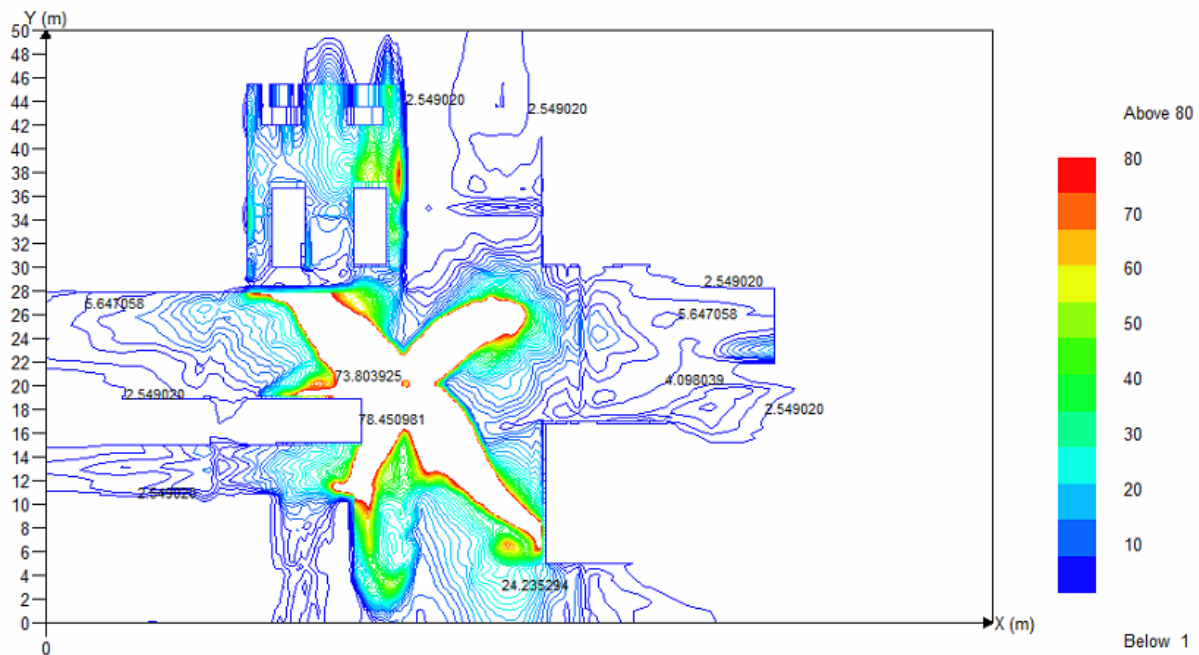
Fig. 9. Radiation from the fire over the layout (kW/m^2) at 180 s

4.2. Thermal radiation impact

The tenability limit for human beings is approximately 2.5 kW/m^2 (Mannan, 2012). The presence of thermal radiation greater than 2.5 kW/m^2 indicates that the fire can have serious effects to human and adjacent assets. The probability of injuries (first and second-degree burn) and the probability of death at different location of the plant are calculated using the thermal radiation. The maximum damage distance for various effects of fire is given in **Table 7**.

Table 7
Maximum damage distance for various effects of fire

Effects on humans	Heat flux (kW/m^2)	Maximum damage distance (m)
100% lethality in 1 min. 1% lethality in 10 s	37.5	26.2
100% lethality in 1 min. Serious injuries in 10 s	25	33.5
1% lethality in 1 min. First degree burns in 10 s	12	36.7
No lethality. 2nd degree burns probable.	4	39.8

Pain after exposure of 20 s.		
Acceptable limit for prolonged exposure	1.6	43.5

The fire risk index of all grid points was calculated and plotted over the layout as demonstrated in **Fig. 10**. The risk index (Risk$_{fe}$) varies from 1 to the maximum value of 10 at the flame surface.
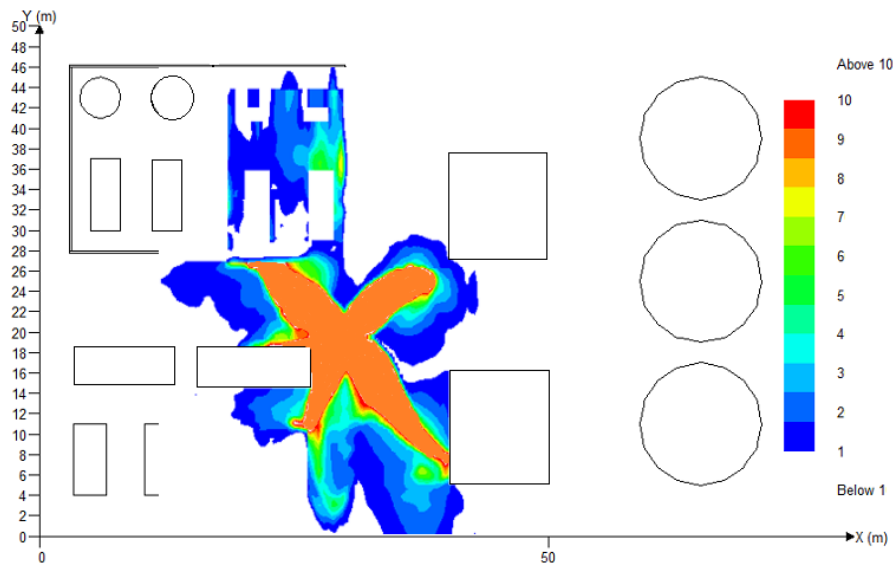

Fig. 10. Fire risk contour in the layout at 180 s

4.3.   VCE impact and risk assessment

The impact of the VCE and its subsequent risk are assessed based on the overpressure developed during the VCE. The explosion overpressure ranges from 0 to 2 barg over the layout and high pressures are found in the areas with a high congestion/confinement level as shown in **Fig. 11**. The developed pressures are limited within a portion of the congested layout. However, the developed pressures can result in damages to assets and humans in those areas of the facility. The damage distance from the VCE ignition point is illustrated in **Table 8**.

Table 8
Damage distance from the VCE ignition point

Effects	Distance from the ignition point (m)
100% fatality	4.60
60% fatality	6.25

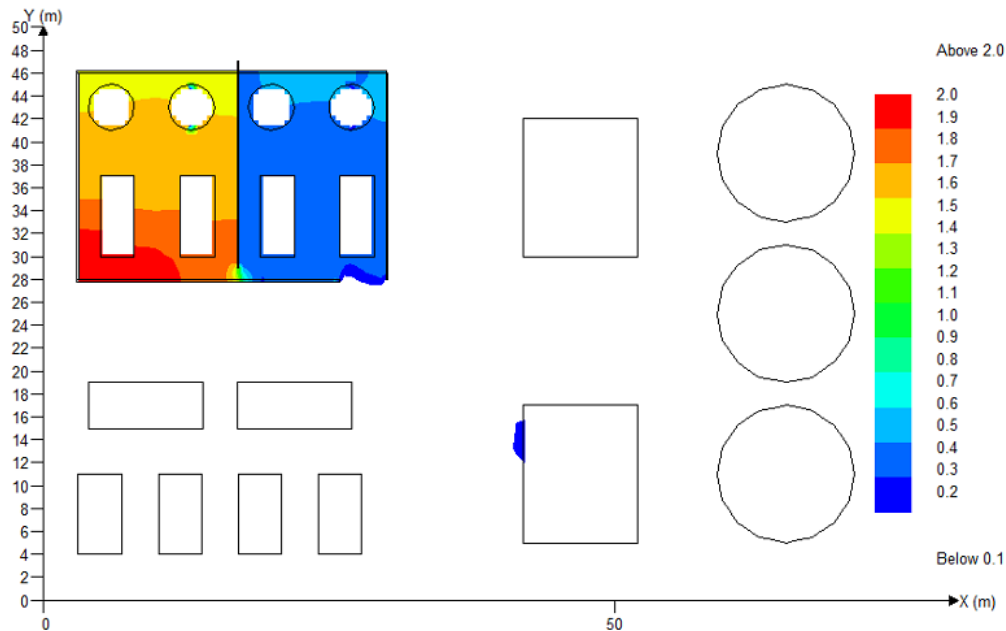| Fatal distance limit	7.80
Eardrum damage limit	10.30
Safe distance	15

Fig. 11. VCE pressure over the plant (barg) at 180 s

Using the probit model, the probabilities of injuries or death caused by the overpressure were estimated. Subsequently, the VCE risk index (Risk$_e$) was calculated and plotted over the facility as shown in **Fig. 12**. The values of the VCE risk index vary from 1 to 10. Index 1 corresponds to very low risk and the index 10 shows the maximum risk. A high-risk index is found in the congested/confined areas and vice-versa.
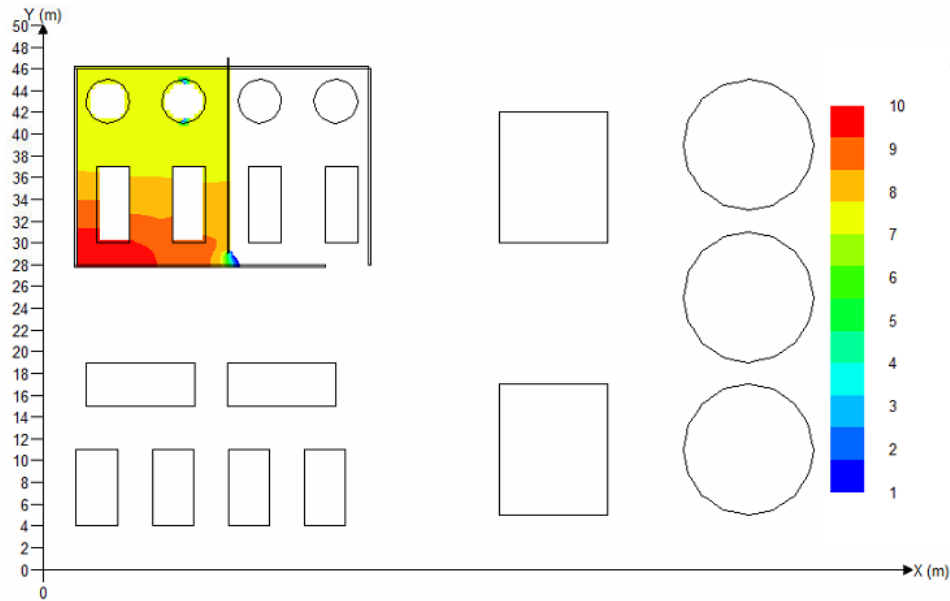
Fig. 12. Explosion risk profile at 180 s

4.4. Combustion product impact

The toxic concentration (mg/m^3) data obtained from the fire and explosion simulations were used for the toxicity assessment. The concentrations of contaminants are high near the fire and explosion locations and confined areas. The toxic concentration of NO_2 is given in **Fig. 13**. In confined areas, the concentration of NO_2 is more than 10^5 mg/m^3. Carbon monoxide is very toxic and a concentration of 1.28% leads to death within 2-3 minutes (Struttmann et al., 1998). The toxic concentration of CO is illustrated in **Fig. 14**. The higher concentrations of NO_2 are present in larger areas of the layout than those of CO. The obtained NO_2 and CO values are relatively high because these concentrations were measured when there was ongoing fire. Risk values are high around the fire and VCE locations due to higher concentrations of contaminants. This is because a risk value directly depends on exposure duration and concentration.
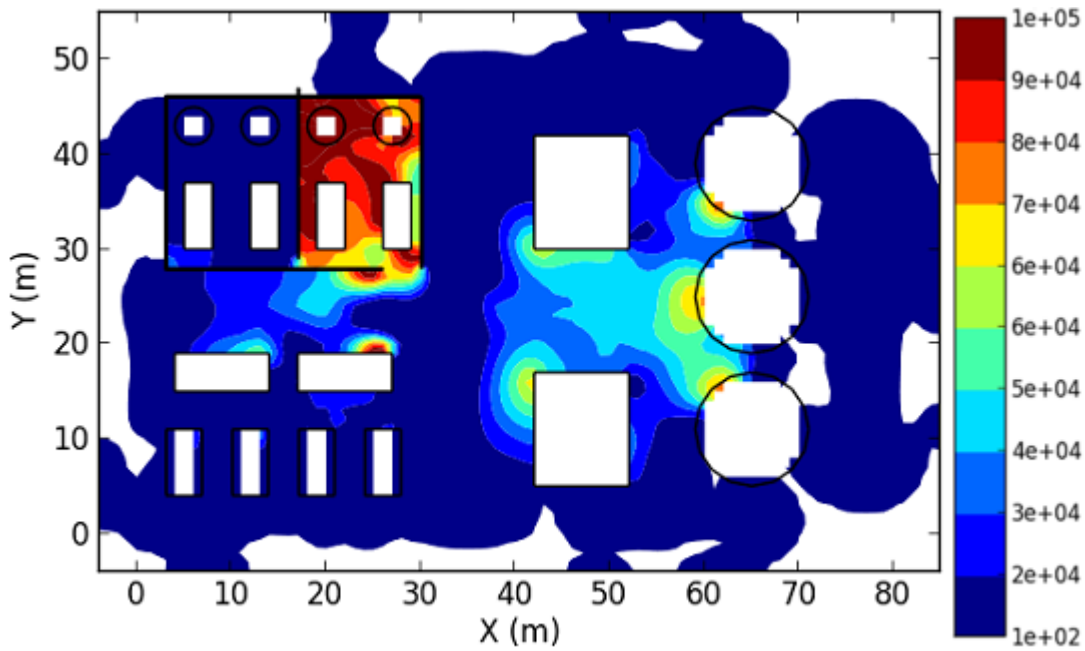
22

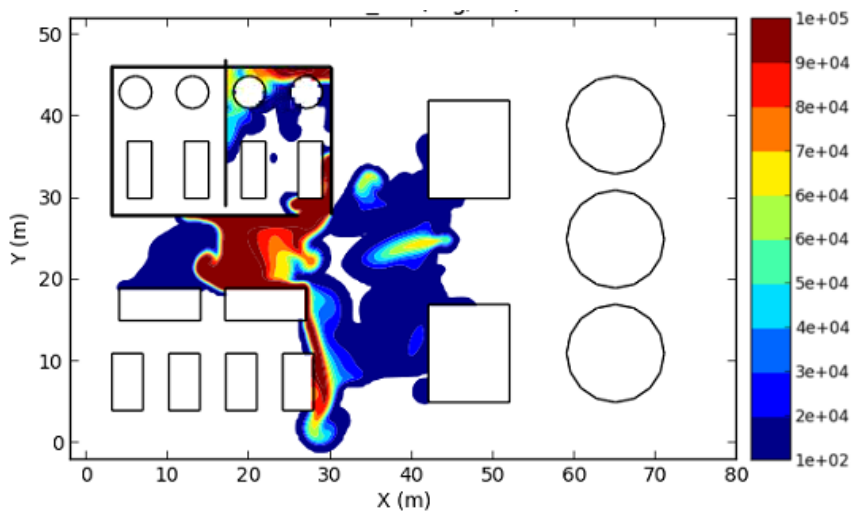**Fig. 13.** Concentration of NO_2 over the layout (mg/m^3) at 180 s

Fig. 14. Toxic concentration of CO (mg/m^3) at 180 s

4.5. Integrated impact during transition of fire to VCE

In most fire and/or explosion events, injury or fatality can be caused by combustion products in addition to radiation or overpressure hazards. **Fig. 15** demonstrates the integrated risk contours in the layout because of thermal radiation and overpressure during the fire and VCE. For simplicity, the range of risk index is normalised between 1 and 10 in the integrated risk profile. High risk indices are available in the fire location and the VCE area due to the inherent nature of those events.
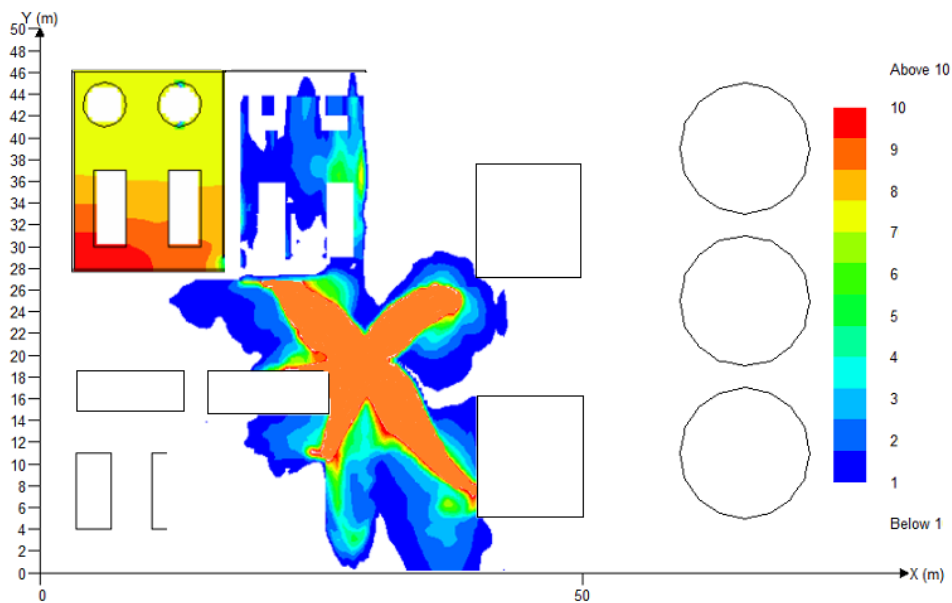
Fig. 15. Integrated risk profile of the fire and the VCE at 180 s

In toxicity risk assessment, an integrated risk of both contaminants is considered as shown in **Fig. 16**. The total combustion product risk shows that significant portions of the facility exceed the acceptable level of risk which is 1. The integrated risk profile of contaminants indicates that the high-risk area is larger than that of the integrated impact of fire and VCE as seen in **Fig. 15** and **Fig. 16**. However, due to the short exposure duration, the severity of the combustion products is lower than that of thermal radiation and overpressure. This shows that the impact of transitional events such as fire and VCE along with combustion products is more severe than an individual phenomenon because more portions of the facility exceeded the acceptable level of risk.

The current approach incorporates an additional feature to the previous integrated consequence studies such as Khan and Amyotte (2004) and Dadashzadeh et al. (2013b). Khan and Amyotte (2004) incorporated fire, explosion and toxic release damage indices, but did not directly assess the consequence. The adopted technique in Khan and Amyotte (2004) cannot be useful for visualizing the area directly affected by fire, explosion and combustion products. The severity of consequence would have been different if the impact of the combustion product was considered by Dadashzadeh et al. (2013b). During a fire and/or explosion, the potential risk from combustion products can be too simple to ignore because toxicity has been a major cause of death and injury from fires (Hartzell, 1992).

This paper illustrated only a specific case study. However, any changes in operating conditions such as wind speed, wind direction, snow, rain or other parameters can be

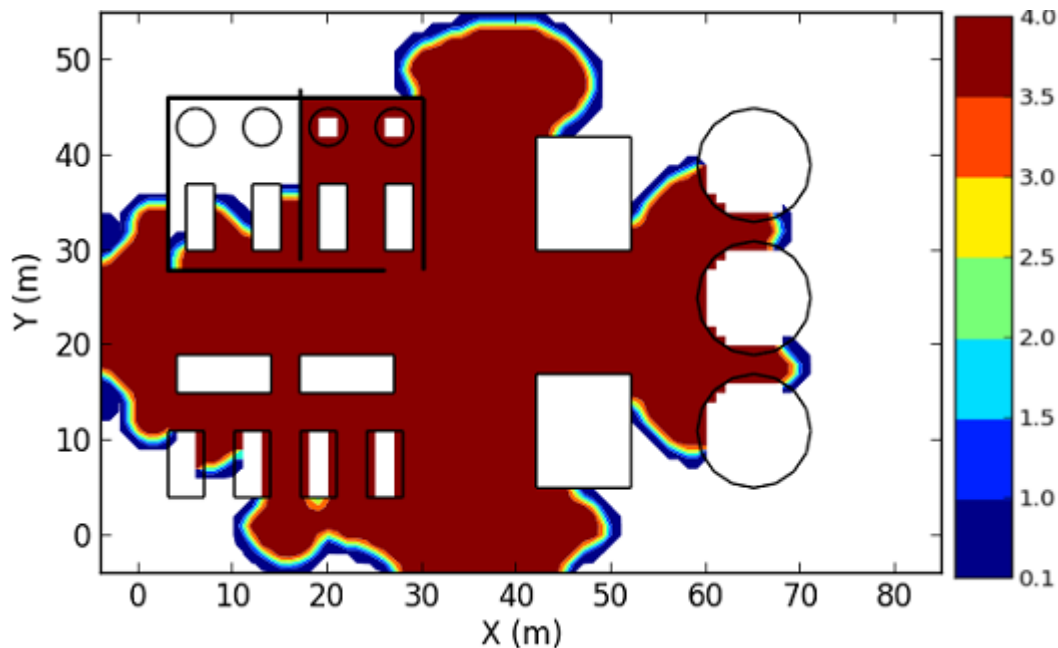incorporated in this approach. Therefore, a range of scenarios can be envisaged and evaluated accordingly.

Fig. 16. Integrated risk of combustion products at 180 s

5. Conclusions

In Liquified Natural Gas (LNG) processing facilities, there is a possibility of a fire transitioning into a Vapour Cloud Explosion (VCE) or vice-versa during an accidental release of hydrocarbons as demonstrated in various past fire and explosion accidents. Identification of potential location of transitional events is useful for understanding the occurrence of cascading accident scenarios. A framework has been proposed for modelling transitional events (fire, VCE and combustion product release) and their integrated consequences using Computational Fluid Dynamics (CFD). The proposed framework was applied to a case study considering an accidental LNG release, including vaporisation, a pool fire and a VCE. The impact of each individual event was assessed, and an integrated consequence was modelled using a risk-based approach. The severity of risk during each event in the layout was compared. By analysing the LNG spill, vaporisation, dispersion and subsequent fire in the layout, it is foreseeable that a pool fire can transit to a VCE because of the availability of required suitable conditions such as a flammable vapour concentration, ignition source and congestion/confinement. The risk of the overpressure was limited to confined spaces and was insignificant in other areas. The risk of thermal radiation was present in a larger area in comparison to the VCE. The risk of combustion products was present in a larger area than those of radiation and the overpressure,

but its severity was lower due to the short exposure duration. It was found that the integrated risk of transitional events was higher than that of the individual risk.

A change in weather conditions and source terms may affect the outcome of an analysis related to gas leak and dispersion. Responses to gas leak and its dispersion are strongly dependent on these parameters and one set of parameters may not represent all cases. For illustration purpose, this study has presented only a specific case. Once operating conditions such as wind speed, wind direction, snow, rain or other parameter changes, the response need to be evaluated accordingly. The current study serves to highlight the importance of transitional events modelling and expands the scope of the integrated consequence modelling approach. Despite having complex correlations among various parameters involved in LNG spill and subsequent events, the integrated risk profiles can be effective for designing safety systems to mitigate potential effects and risks of thermal radiation, overpressure and combustion products during fire and/or explosion events. Consideration of effects among thermal radiation, overpressure and combustion products in the transitional event modelling, makes the study unique and realistic in safety analysis of an LNG processing facility.

Acknowledgement

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