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Critical aspects of natural gas pipelines risk assessments. A case-study application on buried layout

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A B S T R A C T

The safety aspects of pipelines conveying hazardous materials are included neither under the umbrella of Seveso Directives aiming at preventing major accidents at industrial facilities, nor in other EU legislations, such as the Pressure Equipment Directive (PED). Starting from evidence that in the last decades the international natural gas market has been growing at a very high rate and continues to exhibit an increasing trend, in this paper we focus on consequences deriving from accidents on high pressure buried Natural Gas Pipelines (NGP) and related probabilities of the various outcomes. A survey on historical accidents occurred on NG pipelines in the USA, Canada and EU allowed the attainment of significant statistics concerning the main factors responsible for the accident evolution, namely failure mode, immediate and root cause, evolving scenario, degree of confinement produced by the surroundings and ignition timing. In this paper, we focus on a refined Event Tree framework, to overcome the limitations of the amply applied over-conservative IP UKOOA approach. In order to evidence the capability of the approach, the use of refined PET is exemplified by means of a real case-study of a high pressure buried NG pipeline, contrasting the actual results with those obtained by conventional methods, in terms of evolving scenario probability and damage. Conclusions are drawn about the effective application of the framework within risk assessment and the uncertainties and sensitivities in the pipeline accident modelling.

1. Introduction

Even though hazardous material transportation by pipelines is statistically recognized as the safest transportation mean, in terms of injury and fatality rates on the basis of evidence from pipeline incident reports since 1970, when compared with road and rail transportation modes (USDOT, 2013), notable high profile accidents involving gas pipelines still happen. The evidence of recurring releases of hazardous materials in the environment and their following escalation in fires, explosions and toxic dispersions implies that measures need to be enforced in order to adequately quantify and thereby mitigate the risks. In relative terms, the problem of pipeline risk assessment does not come with hazard analysis, or the estimation of failure frequency, but with the calculation of the consequences (Palazzi et al., 2014). The failure rates of pipelines in the last decade of the XX century was evaluated on the basis of European data to be in the range 2.1×10^{-4} to 7.7×10^{-4} [event km^{-1} $year^{-1}$], respectively for small and large diameter. This figure is higher than the standard acceptable probability according to the criterion set down in the Netherlands as 10^{-6} (Taylor, 1994): normalization to 1km is here referred as the hazard distance associated with the pipeline ranges from <20m for a small distribution pipeline at lower pressure, up to >1km for a larger pipeline at higher pressure (Vianello and Maschio, 2011). Analogously, in estimating CO_2 pipeline failure, Duncan and Wang (2014) argued that previous estimates of individual risk associated with natural gas pipelines being used in quantitative risk analyses, ranged from 1.2×10^{-4} to 1.6×10^{-4} per km year. In China, it was reported an overall failure rate of 3.0 [event 1,000 km^{-1} $year^{-1}$] based on the experiences of natural gas and oil pipeline (Zhou et al., 2016). It is noteworthy noting that, pipeline failure statistics from different sources e.g., ECIG (2014), Concawe (2018), provide data regarding the probability of different release sizes and a percentage breakdown of the failure causes, while, for example, failure frequencies are not so accurately categorized for other process equipment (e.g. OREDA, 2015). Natural gas (NG) assessed world resources are estimated (IGU, 2019) at nearly 800 TCM (Trillion Cubic Meters), around 45 % of which are unconventional gas (tight gas, shale gas, CBM), deposits of which are geographically more widespread than conventional resources. High-pressure natural gas transmission pipelines and installations

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present potential major hazards with different evolving scenarios, in the unlikely event of a loss of containment (LOC) connected to a broad range of natural or anthropogenic causes. The potential relevant impact of major incidents in onshore transmission pipelines, already pointed put by Hill and Catmur in 1994 and statistically evidenced by comparison with data collected from several public accident sources (Papadakis, 1999), attracted worldwide scientific interest in developing approaches to risk assessment and management. In this regard, in the late Nineties, the European Commission has carried out a thorough review and assessment on whether pipelines conveying dangerous substances need a level of control similar to chemical installations (Papadakis, 2000). In those years, several fundamental studies were carried out on the topic of quantitative risk assessment (QRA) of gas transportation pipeline, as reviewed by Muhlbauer, 2004. Relevant studies included both probability evaluation by innovative tools (e.g. Cagno et al., 2000; Yuhua and Datao, 2005), the definition of the source term for consequence assessment (e.g. Yuhu et al., 2003) and the overall pipeline risk evaluation in terms of in terms of cost of repair, supply interruption, material loss and damage to humans and buildings (Park et al., 2004).

Generally speaking, threats to pipeline safety can be categorized as follows (Kishawy and Gabbar, 2010): material and construction defects, such as a defective longitudinal pipe seam, pipe body or joint welds; mechanical damage from construction, maintenance or third-party excavation; incorrect operation; corrosion, creep, and cracking mechanisms; device failures and malfunctions; NaTech events e.g. earthquakes, landslips, or telluric currents, winds, rough seas, or cold/hot temperatures.

Sklavonous and Rigas (2006) reported that the accident rates of natural gas pipeline remained at the same level, in spite of increased safety measures and advanced safety management systems. They faced the issue of safety distances from NG pipelines, by applying an approach based on Event Tree Analysis, suitable to be adopted in safer land use planning. The need of improving Fault Tree Analysis in gas transmission systems represented a challenging topic faced by Yuhua and Datao (2005) with a method relying on an earlier fuzzy approach developed by Khan and Abbasi (2001) and combining expert elicitation with fuzzy set theories to evaluate the probability of the events. A multi-attribute decision model accounts the possible human, environmental and financial impact and ranking sections of gas pipelines into a risk hierarchy was proposed by Brito and de Almeida (2009).

Taking into account NG hazards and difficulties in prompt leak detection, Lu et al. (2015) proposed a risk matrix connected to a bow-tie model to evaluate the risk of pipeline conveying natural gas. More recently, a cloud inference approach was proposed to implement the transition between quantitative description and qualitative concept and solve the uncertainties in the risk assessment process of NG pipelines (Yanbao Guo et al., 2016). In order to meet the rapidly growing demand for natural gas, pipeline network construction is developing at a high speed (Dorao and Fernandino, 2011). Additionally, the peculiar context of NG pipelines represents an emerging research topic, given the increasing trend of underground storage into depleted natural gas production sites, where the exploration phase is exhausted. This technology is seen as a strategic option in Countries with negative NG commercial foreign exchange, allowing to cover and guarantee gas distribution during high rate demand: e.g. Italy where currently there are 12 underground NG geological sites located in Abruzzo, Emilia Romagna, Lombardia and Veneto. In this study, which takes inspiration from a recent work of the same authors (Pontiggia et al., 2019), we take a closer look at the evaluation of the possible consequences deriving from accidents on high pressure buried Natural Gas pipelines and the related probabilities of the different outcomes. On these bases, a newly developed Pipeline Event Tree (PET) is proposed to allow a better quantitative description of the ignition taxonomy considering on a statistical basis, immediate, delayed local and remote ignition probability. The remainder of this paper is as follows: in Section 2 we summarize pipeline accident statistics form different sources, in order to consider the uncertainty in consequence assessments (Milazzo et al., 2015); in Section 3 we discuss pipeline risk assessment and the structure of a bow-tie graphically evidencing the relationships between possible threats (or causes of damage), outcomes and barriers that can be used both in prevention or mitigation. Section 4 considers the development of a brand-new event tree (PET) by making a cross-over between IP-UKOOA original event tree and the event tree obtained from an HSE report upon proper consideration of actual ignition probability. In Section 5, PET application is exemplified by contrasting the results of the approach on a high pressure buried NG pipeline, with those obtained by conventional methods, in terms of evolving scenario probability and damage, presenting a possible future lines of development as well. Final conclusions are drawn in Section 6.

2. Pipeline accident statistics

A review of relevant past accidents can provide statistical evidence on the extent to which pipelines present a hazard potential comparable to that of Seveso installations and the extent to which the pipeline hazard is adequately controlled. The occurrence of the failure of a pipeline can be due to a number of different causes such as external interferences, corrosion, material or construction defects, hot tap made by error; ground movement; other causes, such as fatigue, operational and maintenance errors. Sulphur compounds, often present as by products in many industrial processes (Chiarioni et al., 2006), may severely endanger the mechanochemical properties of materials and alloys used in pipelines, thus triggering failures. Over the last 20 years, the interest of integrity managers has been focused in failures and damage mainly related to the following conditions: S S Stress Corrosion Cracking (SCC); Electrical Resistance Welding (ERW) and old repairs; lack of materials identification; lack of data on operating conditions; increase in population around pre-existing pipelines. Pipeline ageing is a common item in Europe and resulted in notable accidents, with potentially high environmental impact in case of proximity with sensitive areas (Vairo et al., 2017a). Some of the main gas distribution pipelines are more than 50 years old: integrity issues of these aged pipelines are related not only to material problems such as low toughness and in-service damage, but also to the way demographic expansion has affected conditions in metropolitan areas (Vairo et al., 2017b). As commented by Otegui (2014) the usually uncontrolled increase in dwelling around (and sometimes along) the right of way has influenced integrity requirements for operators of gas pipelines in various ways, i.e.

- by a reduced acceptable risk of blowouts and other failures, representing a serious burden for integrity teams, especially in suburban areas where most of the pipelines are un-piggable;
- by increased consequences of failures in gas treating and compression plants, due to enhanced production requirements and space constraints;
- by an increased risk of third party damage;
- by changes in soil conditions.

Dealing with expected frequency based on historical statistical analysis, different values can be calculated, as exemplified by Hill, 1992 who obtained over the time span 1983–1991, figures of 5.8×10^{-4} and 7.4×10^{-4} [ev/km/y] referred to the overall pipeline accidents and respectively based on data by CONCAWE (European Oil Company Organization for Environment, Health and Safety) and US-DOT. Crude oil and oil products are the main fluids extensively

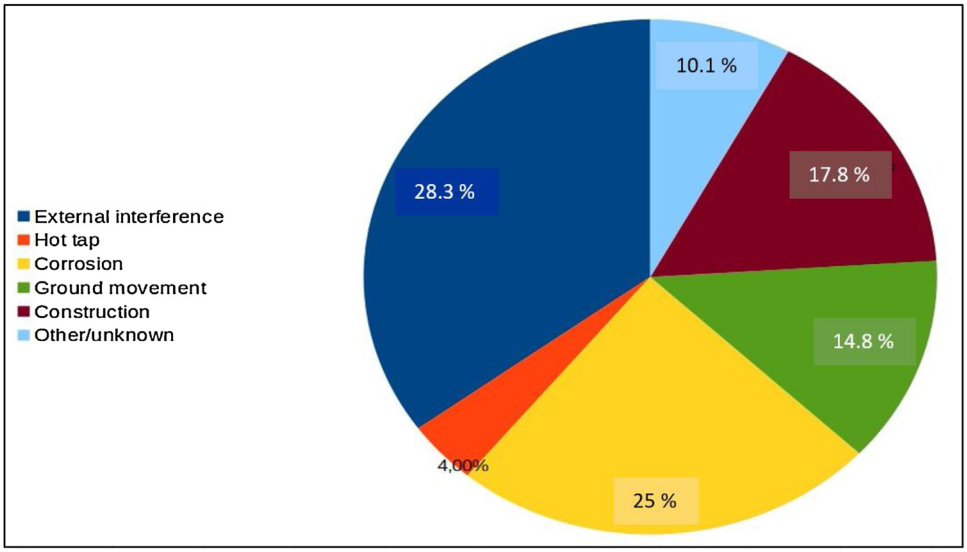

Fig. 1. Immediate causes of pipeline failure (ECIG, 2018).

conveyed in European networks and as detailed in the following, different fire scenarios may result from the failure of a flammable material pipeline, whereas only for liquid releases it is considered pool fire scenario (Palazzi et al., 2017). Leak sizes range from pinholes up to hole sizes which represent critical or unstable defects for particular pipeline parameters. Unstable defects result in ruptures. A rupture release is a full-bore, double-ended break or equivalent from which gas is released into a crater from both sections of pipe. In relative terms, the problem of HazMat pipeline risk assessment does not come with hazard analysis, but with the calculation of the consequences (Palazzi et al., 2014). Interestingly, considering the time span 1968–2009, Siler-Evans et al. (2014) argued that in the United States hazardous liquid pipelines resulted much safer with a sharp accident reduction, while gas distribution pipeline incidents remained fairly constant, even though the resulting severity decreased. In most cases, the rupture scenario will dominate the risk from Natural Gas pipelines. In the peculiar case of buried pipelines, wave propagation and permanent ground displacement (PGD) are usually considered as the most severe hazards connected to seismic and landslide events, resulting in high severity damages (O'Rourke et al., 2005). Commonly, failure frequency data are quoted for the sum of all hole sizes, and these should be classified into specific hole sizes to permit the development of the risk assessment. In order to determine the range of the LOC sizes to be considered in the consequence assessment, the hole size which gives an equivalent outflow to the critical length of an axial defect for specific pipeline parameters should be determined. Critical defect length and equivalent hole diameter applies to external interference where axial, crack-like defects can occur; the equivalent hole sizes which relate to such defects do not apply to rounded punctures, or stable holes due to corrosion or material and construction defects. The maximum possible hole size in high-pressure gas pipelines is limited to the critical defect size. According to US DOT (2010) the immediate causes of NG pipeline failures are connected to corrosion (28 %), construction material failure (23 %), followed by excavation damages with a percentage of 20 %. Relevant NG pipeline accidents occurred in the USA, Canada and the EU, for which detailed accident reports are available from various sources, (HSE, 2000) were analysed, with following considerations on major events and immediate causes:

- the full rupture was the common type of failure that occurred for all the cases.
- 54 % cases were characterized by immediate ignition and the other 38.5 % by delayed ignition. In one case ignition timing is unknown.
- 38.5 % cases of failure were caused by corrosion generally localized in the bottom part of the pipe, 31 % of cases characterized by third-part damage, 23 % of cases by the failure of girth weld and one case of hydrogen stress cracking.
- a vertical jet fire has occurred in all the cases, only in one case a grounded jet fire or trench fire has been reported. In two cases the jet shape was unknown.
- fireball has occurred in 31 % of the cases but for two of them it was considered only as probable.
- a flash fire has occurred only in one case (Fig. 1).

It stands to reason that pipeline system suffers as well possible security issues, regarded following Aven (2014) as intentional situations and events (terrorist attacks, burglary, etc.) in contrast to safety, which covers the accident type of situations and events. Different from unintentional events, intentional attacks on energy supply systems may result in more severe consequences affecting the sustainability and reliability of supply chain. In Nigeria, a total of 15,718 deliberate attacks on oil pipelines occurred during the time span 1993–2008. More recently, the Abqaiq oil plant was attacked by drones on September 14, 2019, leading to a 50 % reduction in Abqaiq's oil production and a nearly 15 % increase in the crude oil price. Focusing on oil and gas pipelines, two main categories of security threats can be sorted i.e., theft and sabotage (Chen et al., 2021). Both theft and sabotage can lead to high profile consequences: theft has been a long-standing security concern for oil and gas pipelines, while terrorist attacks threat has become a more pressing priority frequent only in certain geographical areas.

3. Pipeline risk assessment

Risk assessment approach within the context of HazMat pipelines relies on standardized approaches originally conceived for process plants implying the amply known steps of HazId (hazard identification), frequency estimation, consequence estimation and risk calculation (Uijt de Haag and Ale, 1999). Scientific literature addresses the most relevant questions connected to QRA in this peculiar sector and those question are mainly related to frequencies, release rate, release direction (Kooi et al., 2015).

Here we anticipate that applying default values for ignition probability, such as 0.15 for immediate ignition and 0.3 for delayed ignition, implies a degree of uncertainty as they do not account for specific release conditions that may influence probability values such as temperature, release material and an ignition source (Moosemiller, 2011).

The bow-tie analysis provides a readily understandable visualization of the relationships between the causes of accidents, the escalation of such events to a range of possible outcomes, the controls preventing the event from occurring and, should the event nevertheless occur, the preparedness measures in place to limit the consequences (Cermelli et al., 2018). The preventive and mitigation controls may be linked to activities, procedures, responsible individuals and competencies, thereby demonstrating the crucial connection between risk controls and a Safety Management System for ensuring their ongoing effectiveness. This visual representation underlines the connections between threats, potential impacts and preventing/mitigating elements. Starting from the main failure causes previously discussed, the representative bow-tie is shown in Fig. 2 to provide a description of major events resulting from a Natural Gas release from a buried pipeline and relevant preventive barriers. Design and procedural weaknesses can be identified in the left-hand side and probabilities of the various outcomes from an accidental event can be determined. The right-hand side is to be designed according to an event tree analysis (ETA) illustrating all possible final major hazard phenomena resulting from the critical event, considering whether installed safety barriers are functioning or not and additional/contributing factors. The barriers related to the external interference are safety signs and the escalation factor related ones can be the lack of respect for this signal. For mechanical failures, the main barriers are connected to inspection program, vibrating monitoring system and the related escalation factors can be the delay in the execution of the survey and the failure or malfunction of the vibrating monitoring system. For corrosion, the barriers are inspection programs and corrosion prevention and monitoring system. The escalation factor related to the inspection program can be the delay in the realization of the control, and for the prevention and monitoring system can be the inadequate set-up of the anti-corrosion system. Dealing with ground movement, the main barriers are foundation inspection, drainage system and piles. The related escalation factors for inspection are the delay or negligence of the survey, the failure or malfunction of the drainage system, and the wrong application of standards. The main ignited consequences are fireball, jet fire, trench fire and flash fire while the non-ignited consequence is the dispersion of natural gas. For all the ignited consequences the typical recovery preparedness measures are low-pressure detectors, ignition source absence, emergency depressurizing and block of equipment. The escalation factor for low-pressure detectors can be a failure or inadequate set-point.

In the following, we focus our attention on the right-hand side of the bow-tie to highlight and discuss critical aspects of event tree analysis. ETA represents a fundamental step and can be used to identify all potential scenarios and sequences in a complex system following a step-by-step inductive logic chain:

1 identification and definition of a relevant initiating event, which may give rise to unwanted consequences;
2 event tree construction;
3 description of the potential resulting accident sequences;
4 determination of the frequency of the accidental event and the (conditional) probabilities of ET branches;
5 calculation of the probabilities/frequencies for the outcomes or resulting scenarios.

A simple ETA approach was developed by Stephens (2000), in his study aiming at sizing high consequence areas associated with NG pipelines. Fig. 3 depicts the well-known IP-UKOOA event tree (IP-UKOOA, 2006), usually applied within a QRA procedure, in order to evaluate the probabilities of possible outcomes and incidental scenarios deriving from a given pipeline release.

Table 1
Overall ignition probabilities from different literature references related to various type of failures.

Source	Failure	Ignition probability
Townsend and Fearnehough (1986)	Leaks	0.1
	Rupture	0.5
Jones and Fearnehough (1986)	Rupture	0.26
	All sizes	0.16
	Pinhole/cracks	0.02
	Holes	0.03
EGIG (2014)	Ruptures <16"	0.05
	Ruptures >16"	0.35
	All sizes	0.03

Leak frequency or failure frequency can be derived from different literature sources (e.g. IGEM, 2015), while the overall ignition probability can be calculated by using the "look-up correlations" mainly depending upon the estimated release mass. Following the estimation of the overall ignition probability, the second branch considers the early ignition probability. The term used is "early" rather than "immediate" and can be applied to ignitions occurring up to 60 s after the start of the release. During this "early" period a substantial vapour cloud can form which, if ignited, would give rise to an explosion with large overpressure. Given that the split between "immediate" and "delayed" is primarily intended to distinguish between "fire only" and "explosion plus fire" in our event tree this will be considered as immediate ignition. Finally, the last branch takes into account the explosion and consequently the flash fire probabilities. As anticipated, in order to develop a refined ETA approach, the most critical step is connected to the actual estimation of ignition probability, as discussed in the next section. As amply known, ignition probability estimate usually relies on information, like the ignition probability review carried out by the Energy Institute (2006). However, utilizing literature data including the look-up correlations developed by the UKOOA, which are reproduced in tables by the OGP (OGP, 2010), implies several issues as discussed in more detail in (Pesce et al., 2012). Table 1 summarizes the overall ignition probabilities for natural gas pipeline deriving from three different literature sources and divided in full-bore rupture and minor leak summarized by HSE (2015).

The values provided in Table 1 evidence significant variability, depending on a number of assumptions, namely probability is based on sizes of release (larger the release and larger will be the likelihood of ignition); unknown data sources (offshore + onshore); inclusion of immediate ignition. From the analysis of historical data for rupture incidents, a trend was observed and a correlation for full rupture was proposed on overall ignition probability as follows, without any consideration regarding failure cause and pipeline localization (HSE, 2015):

$$P_{IGN} = 0.0555 + 0.0137pd^2;\ 0 \leq pd^2 \leq 57 \quad (1)$$

$$P_{IGN} = 0.81;\ pd^2 > 57 \quad (2)$$

Where:

- P_{IGN} = overall probability of ignition
- p = pipeline operating pressure [bar]
- d = pipeline diameter for ruptures [m]

The influence of the differences in environmental conditions along the pipeline is mainly due to the temperature at release, which can affect the flammability limits (relevant parameter in release modelling), and to the population density. Relatively high

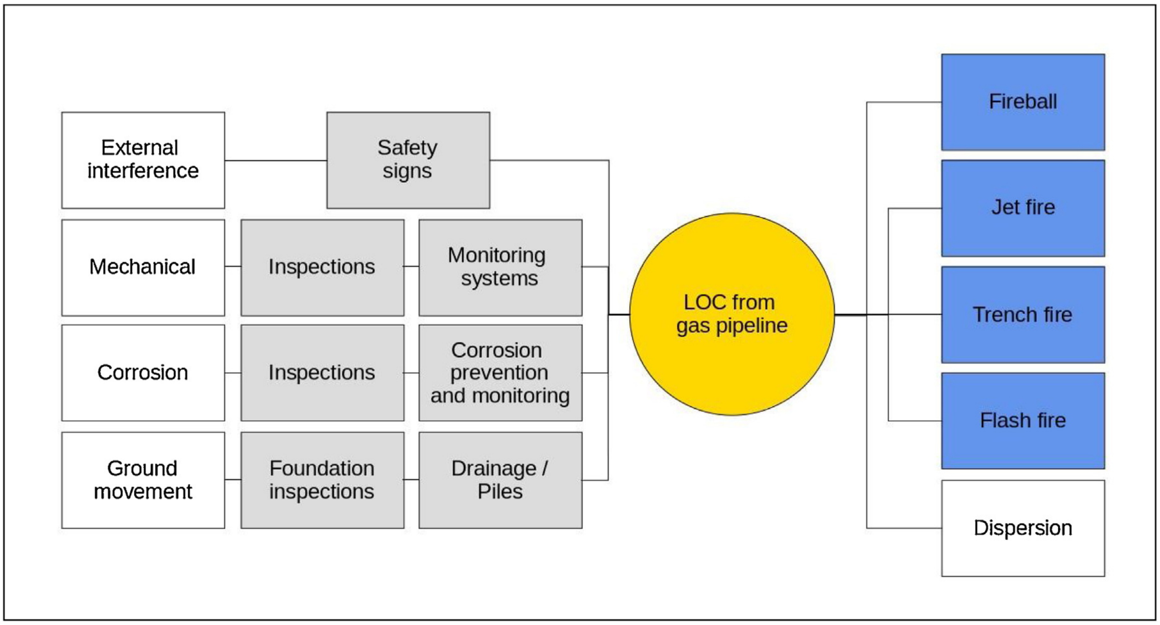

Fig. 2. Bow-Tie for centred on loss of containment from gas pipelines.

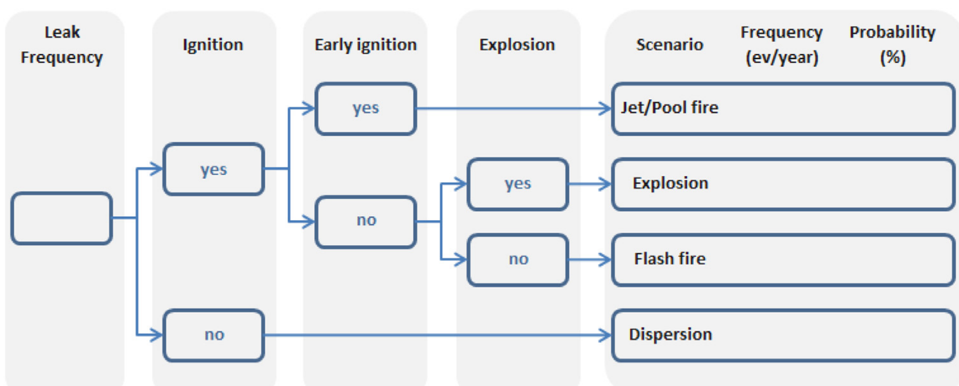

Fig. 3. Standard event tree developed according to IP-UKOOA methodology.

population density generally results in more excavation activities (Xu et al., 2019), which may consequently pose additional hazards and increase the ignition probability. Entering in more detail into ignition evaluation, a distinction is usually made between immediate and delayed ignition. The former occurs typically in case of third-party damage on rural pipelines and the friction sparks provides the source. The term "prompt" is considered more appropriate, representing an ignition from a close source occurring within nearly 30-40 seconds before the formation of a large gas cloud. The latter can be distinguished into (HSE, 2015):

- local: in this case there is an ignition source near the release point, but the gaseous plume does not respect the ignition requirements, being outside the flammability range and the main consequence is a Jet fire;
- remote: it occurs if the ignition sources close to the release point are insufficient and the gaseous plume requires a certain amount of time to disperse at concentrations below UFL; the main consequence is a Flash fire.

Concerning this classification, some consideration can be done:

- the flammability of the vapour cloud is not uniform because of the presence of "pockets" in which the ratio fuel/oxygen is variable (some zones are richer of fuel than others);
- the division between local and remote delayed ignition is made to grant a better detail for the comprehension of the scenario;
- in case of high momentum releases, the jet fire is possible.

Immediate (or better prompt) ignition corresponds to the case in which ignition occurs near the release point, but before the formation of any vapour cloud. The immediate ignition probability taken from literature ranges from 0.1 and 0.3, so the assumed value of 0.25 by HSE report seems acceptable.

The evaluation can be properly refined as follows, by considering two relevant parameters affecting immediate ignition, namely:

- P_{AI} = autoignition potential related to T and AIT;
- P_{SD} = potential for static discharge related to MIE and release energy for released material (assumed by definition as $P^{1/3}$) and so the immediate ignition probability will be written as:

$$P_{immediate\ ignition} = P_{AI} + P_{SD} \tag{3}$$

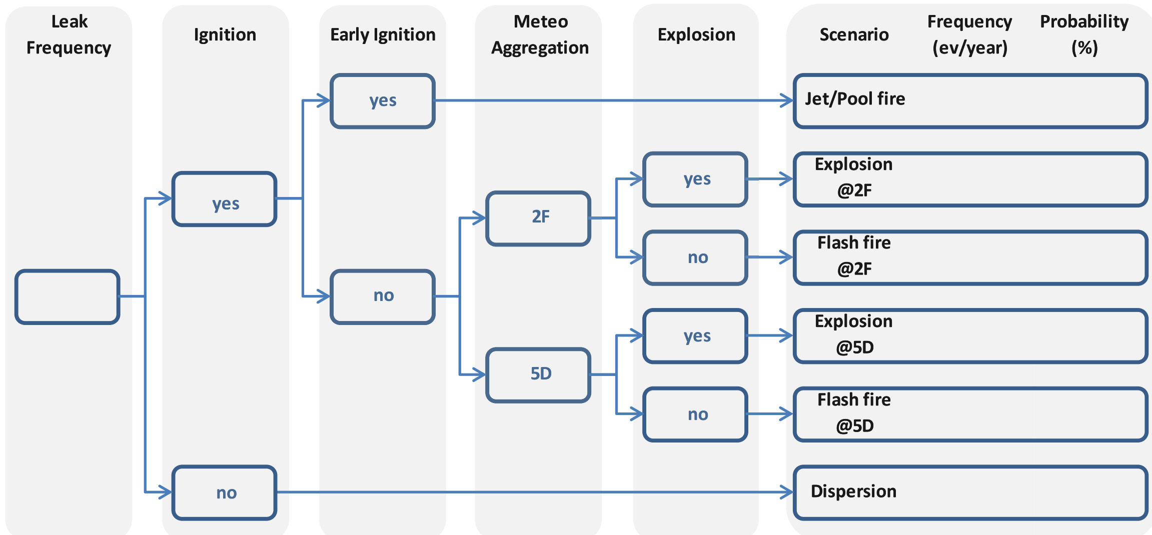

Fig. 4. Development of the newly conceived Pipeline Even Tree (PET).

$$P_{immediate\ ignition} = \left[1 - 5000e^{-9.5\left(\frac{T}{AIT}\right)}\right] + \left[\frac{0.0024P^{1/3}}{MIE^{2/3}}\right] \quad (4)$$

Where: T and AIT [°F], P [psig], MIE [mJ].

For these formulas, the following limits are indicated:

- T_{MIN} = 0 °F;
- if T/AIT < 0,9 then P_{AI} = 0;
- if T/AIT > 1,2 then P_{AI} = 1;
- $P_{immediate\ ignition\ maximum}$ = 1.

When T < AIT + 200 °F than it will occur a delayed ignition with $P_{immediate\ ignition}$ < 0.98. Such an approach allows for a more specific calculation of immediate ignition conditional probability when compared to the IP-UKOOA, where only very general values (mainly based on risk analyst judgment) are provided.

Generally speaking, literature focuses mainly on the distinction between the immediate and the delayed ignition probabilities and far less on the differences between the delayed local and remote. The delayed ignition occurs in case of large cloud formation, ignited by a remote source and has a default probability value of 0.3, but it requires refinement owing to the variables influencing release conditions, i.e. obstructed or unobstructed release. From literature, it has calculated the obstructed/unobstructed release probability depending on the crater angle α from the top of the pipeline, being α = 19° in case of obstructed jet angle and α = 71° for unobstructed jet. The probability of an obstructed or unobstructed release is independent on the substance because its chemical-physical characteristics do not affect neither the location of the puncture nor the jet impingement probability. The following definitions allow explaining the difference (HSE, 2015):

- unobstructed release: it derives from the puncture close to the top of the pipeline and determines the formation of a narrow, high velocity vertical-jet;
- obstructed release: gas leaving from the side or the bottom of the pipeline and it is obstructed by the impact with the crater and can affect the jet modifying its width, velocity and direction. A crater with a diameter equal to 10 times the pipeline diameter can be formed.

In order to derive the obstructed/unobstructed release probabilities, UKOPA considers 73 real accident cases for which all information are available, deriving an unobstructed release probability equal to 0.63 and correspondingly obstructed release probability equal to 0.37.

4. Development of a refined pipeline event tree

Taking into account previous considerations, in the following, a brand-new pipeline event tree (PET) is presented based on critical crossover with IP-UKOOA (2006) and HSE (2015) methods, to attain a better and more detailed description of all the possible outcomes and the relative probabilities. As working hypothesis, toxic effects are not considered relevant compared to flammable damage, considering the rather low concentration of toxic compounds (H_2S) also in conventional natural reservoirs.

Compared with a simple approach, the PET reproduced in Fig. 4 accounts for the meteorological aggregation which takes into proper account the wind stability classes in case of delayed ignition. Following a standard QRA approach, two atmospheric stability classes were considered for consequences and risk calculations following a conservative approach, namely stable atmosphere (Pasquill class 2, representative of night conditions) and neutral atmosphere (Pasquill class D, representative of day conditions). For the Pasquill class F, a wind velocity of 2 m/s is used (hence, class 2F) and for the Pasquill class D 5 m/s (hence, class 5D). These values are considered in the branch of delayed ignition. As amply known, more stable conditions are associated with lower dilution and higher concentration at ground level, due to a more difficult mixing of the pollutant within the vertical layers of the atmosphere. More unstable classes (A, B and C) are associated to a higher dilution therefore to lower hazard distances. IP-UKOOA standard event tree allows for a detailed description of the effect of discharged mass flow rate in the ignition probability calculation; boundary conditions are also resumed by means of empirical fitting coefficients (gradient and coefficient in the probability of ignition equation). However, it should be evidenced that the above mentioned PET model was developed to allow calculation for the widest range of release condition while it does not include any directionality, or congestion effect that can be relevant for a specific representation of buried pipeline releases.

In order to perform ET analysis, the overall ignition probability y is derived from the "look-up" correlations adopted according to the conventional IP-UKOOA scheme:

$$y = 10^{m\log_{10}(x)+c} \quad (5)$$

where y is the ignition probability, x is the mass release rate (kg/s), m is the gradient of the correlation and c is the y-axis "offset" of the correlation. Such a definition allows the application of the model to a wider range of release cases, including full-bore, leaks and pinhole. Release rate shall be assessed with dedicated models and relevant level of detail can be selected by the risk analyst based on the specific project requirements.

The second branch of the PET depicted in Fig. 4 is characterized by the choice between an obstructed or unobstructed release, and this part relies on HSE approach, allowing for a more specific representation of the accidental scenario development. As previously commented, the corresponding value depends on the actual release size because, as a matter of fact, for full ruptures the unobstructed probability is 0.63, while for obstructed release is 0.37. Instead, for leaks the unobstructed probability is 0.25 and consequently, the obstructed probability is 0.75. Obviously, the likelihood of an obstructed or unobstructed release depends on the type of damage on the pipeline; in case of external interference the unobstructed release will be more probable, while if the damage will be caused by corrosion or ageing related events, the release will be generally obstructed.

The third branch of the PET deals with the immediate ignition probability. HSE report suggests a default conditional immediate ignition probability of 0.15. In applying the PET, the probability is properly evaluated making reference to Eqs. (1) and (2).

Finally, the last branch accounts for either delayed local or delayed remote ignition probability. HSE-UK formula used to calculate the delayed local ignition probability is based on little experimental observation and a number of relevant parameters are to be defined based on expert judgment. On the other hand, remote delayed ignition probability value is uncertain. As a general approach, remote delayed ignition probability is assumed 0 in case of NG releases, as during a high-pressure methane release, initially the cloud will cool during expansion and so the cold dense cloud local ignition is frequent, contrary to evidences with other liquefied gases, such as LPG, for which a higher probability of delayed ignition has been estimated (Bubbico et al., 2016). Subsequently, during buoyant gas diffusion, the ignition for grounded remote sources is not possible and flash fire scenario is not considered. Although very infrequent, a flash fire has been observed at least once in the statistical data previously presented. In order to solve this issue, the relationship proposed by Kletz (1977) accounting for the total released mass has been considered to assess the delayed remote ignition probability, based on the critical value of 10 ton of NG released from the pipeline, value commented also in Lees (2012).

In order to respect the fact that in the proposed event tree the value of the overall ignition probability must be equal to the sum of the immediate and delayed ignition probability, being the latter defined as the sum of the local and remote delayed ignition probability, one can write:

$$P_{IGN} = P_{immediate} + P_{local} + P_{remote} \quad (6)$$

The value of the conditional ignition probabilities can be easily obtained as follows:

$$\bar{P}_{immediate} = \frac{P_{immediate}}{P_{IGN}} \quad (7)$$

$$\bar{P}_{remote} = \frac{P_{remote}}{1 - \bar{P}_{immediate}P_{IGN}} \quad (8)$$

$$\bar{P}_{local} = 1 - \frac{P_{remote}}{1 - \bar{P}_{immediate}P_{IGN}} \quad (9)$$

The actual local delayed ignition probability can be written as:

$$P_{local} = \bar{P}_{local}{}^{*}(1 - P_{immediate}) \quad (10)$$

Table 2
Discharge flow rate, discharge time and release frequency for the given Loss of Containments.

Hole size	Discharge flow rate [kg/s]	Discharge time [min]	Release frequency [ev/km/y]
¼"	0.2	> 60	4.38 E-5
4"	56	> 60	4.68 E-5
Full-bore	1,102	19	1.97 E-5

Table 3
Main design and operative characteristics of the given buried Natural Gas transport pipeline.

Parameter	Value
Temperature of natural gas	50 °C (122 °F)
Autoignition temperature of methane	600 °C (1112 °F)
Operating pressure	44 barg (638.17 psig)
Minimum ignition energy	0,22 mJ
Pipeline length	374 km
Pipeline diameter	24 in.(60.96 cm)
Volume of NG	107,989 m^3
Flow rate at the operating conditions	26 kg/s

where $\bar{P}_{immediate}$ is the conditional probability of immediate ignition given the ignition, $\bar{P}_{local}$ is the conditional probability of local delayed ignition given the delayed ignition (1-$\bar{P}_{immediate}$) and $\bar{P}_{remote}$ is the conditional probability of remote delayed ignition given the delayed ignition. All the conditional probabilities to be input in the event tree can be therefore calculated defining two input values, namely the conditional immediate ignition probability provided by the HSE-UK report and the delayed remote ignition probability (flash fire probability), as previously discussed. It is in any case recognised that the reliability of ignition probability is still limited, and an update is advisable when new reliable information be available.

5. Applicative case-study

In order to test the capability of the approach, in this section, we refer to a real buried Natural Gas transport pipeline comparing the results for the various outcomes obtained by the conventional IP-UKOOA method. The worked example is based on following design data of a NG pipeline: operating presssure 44 barg; total length 374 km; nominal diameter 24 inches; flow rate 26 kg s^{-1} ;total NG volume 107,989 m^3. We considered three LOC sizes, namely ¼ , 4 inches and full-bore rupture. Table 1 summarizes the calculated values for the discharge flow rates, the discharge time and the release frequency for buried NG pipelines for the three considered LOCs according to the modified ETA.

In this section, the new Event Tree, developed making a cross-over between IP-UKOOA and HSE data, is applied referring to a real buried Natural Gas transport pipeline. The focus is to make a comparison with the results for the various outcomes obtained for the same pipeline with the conventional ET method. In the given application, three holes sizes are considered, namely: ¼", 4" and a full-bore rupture (Table 2).

The main design and operative data of the considered pipeline are summarized in Table 3.

According to the five step-by-step logical chain of the PET outlined in the section above, the first term considered is the failure frequency, which is an input datum provided by the EGIG report. Then, the overall ignition probability is calculated according to Eq. (3). In case of ignition, as previously described, the calculation of immediate ignition probability is obtained by the Eqs. (3) and (4) with their boundary conditions, being the ratio T/AIT lower than 0.9. The actual local and remote delayed ignition probability are calcu-

Table 4
Outcomes values obtained according to PETA for a buried Natural Gas transport pipeline.

Hole size	Fireball + Jet fire 1	Jet fire 2	Flash fire + Jet fire 3	Trench Fire 1 + Fireball	Trench Fire 2	Flash fire + Trench Fire 3	Dispersion
¼”	8.9E-13	1.3E-08	1.3E-11	2,7E-12	3.9E-08	3.9E-11	4.37E-05
4”	1.1E-10	2.3E-07	2.3E-10	6,2E-11	1.4E-07	1.4E-10	4.64E-05
FB	7.04E-07	9.99E-06	1.05E-06	4.13E-07	5.87E-06	6.19E-07	0

Table 5
Outcomes values obtained with the IP-UKOOA ETA for the buried Natural Gas transport pipeline.

Hole size	Release Frequency	Jet fire/Pool Fire	Flash fire	Dispersion
¼”	4.38E-05	2.29E-08	5.33E-08	4.37E-05
4”	4.68E-05	1.10E-07	2.56E-07	4.64E-05
FB	1.97E-05	5.91E-06	1.38E-05	0

lated according to Eqs. (7)–(9). The subsequent step regarding the evaluation of distances to radiation/concentration thresholds have been calculated by means of PHAST software modelling package (DNV, 2007), assuming as working hypotheses vertical release for unobstructed releases, down-impinging on the ground release for obstructed releases and dispersion from crater surface in case of full bore-rupture. Results for all the evolving scenarios are summarized in Table 7.

Table 4 summarizes the data calculated for the three considered cases by applying the new ETA.

The scenario results obtained by applying the standard approach are summarized in Table 5.

From these two tables, it can be argued that the main difference between the two methods lays in the values obtained for the flash fire outcome, because in the new ETA the probability of flash fire is lower by three orders of magnitude compared to the probability obtained with the IP-UKOOA approach (Table 6).

The following considerations can be drawn from the evidences obtained by means of the two Event Tree Analyses:

- for the ¼” leak, jet fire frequencies for both ETAs are the same and radiation distances are comparable. In the new ETA, flash fire is absent respect to IP-UKOOA ETA;
- for the 4” hole, jet fire frequencies have the same order of magnitude with comparable radiation distances, while flash fire frequency according to the new model is three orders of magnitude lower;
- for the full-bore case, considering the sum for all the jet fire cases in the newly developed PETA, jet fire frequency is of the same order of magnitude of conventional ETA. According to the novel approach, the obstructed jet fire has the same consequences as can be seen in the table below. The radiation distances for unobstructed cases result to be longer at lower thermal radiation levels, but the maximum value of 37.5 kW/m^2 is never reached. The radiation distances for obstructed flash fire are the same for both cases, while for the unobstructed ones are negligible. The event frequency for flash fire is one order of magnitude lower considering the new ETA, compared to the IP-UKOOA one.

In order to evidence the actual implication of the novel approach, we refer to the location-specific individual risk (LSIR), i.e. the frequency of occurrence of a fatality considering cautiously that a person is permanently (24 h per day and 365 per year) positioned at a given point.

The risk of NG pipelines in terms of average fatality rate during the period 2002-2009 of the general public including independent contractors working on the pipeline according to US DOT was estimated at 7.2 × 10^{-7} per km year (Duncan and Wang, 2014). Starting from last EGIG database (2019), collecting 1,366 pipeline accidents it is possible estimating the average fatality rate of the public over the whole period of observation at 5.5 × 10^{-7} per km year. We must point out that this paper is not focused on strategies for routing pipeline to minimize risk, for which the best indicator would be the estimation of societal risk, i.e., the cumulative probability that a group of at least N people is fatally injured as a direct consequence of their presence within the impact area of the pipeline during a failure.

Beraing in mind this limitation of the paper, LSIR index was calculated considering pipeline-related Major Accidents Events as well as dropped object impacts. In general terms, the risk for people from all incidents and scenarios (immediate and delayed ignition of flammable gas releases, flash fire scenarios coming from gas dispersions) is combined to calculate the risk value to a permanently resident individual or asset at any given distance from the pipeline, indicated as LSIR. In particular, in order to calculate LSIR value, the total frequency of occurrence of releases along a whole section of the pipeline is not adopted, as a failure at a considerable distance from a target point will not cause any adverse effect at this distance. Similarly, the frequency of release per unit length is not used for the same reason. On these grounds, a simplified but realistic model to calculate the risk to a person exposed at a target point at a given distance from the pipeline is calculated using the “interaction distance” concept, where the interaction distance is the length of pipeline that can cause a given hazard level at a target point at a given distance from the pipe. People risk is therefore calculated as a function of the distance from the pipeline axis for a transect at 90° to the pipeline, for a theoretical person resident 100 % of the time, considering the contribution of all risk scenarios in a given point. In order to calculate the individual risk at any point along a transect perpendicular to the pipeline, the interaction length is split into small units (interaction length is defined as the distance from the pipeline at which the vulnerability is equal to zero). Subsequently, the risk is calculated for the relevant scenario for each unit. Calculations consider an ideal straight infinite pipeline, assuming as a simplifying hypothesis that border effects at the junctions of adjacent sections are negligible.

At last, the LSIR at a given distance L along the considered transect is obtained by considering all the contributions along the interaction length, as follows:

$$LSIR = \sum_{J=1}^{n} \left(F_{FAT}\left(L_j\right) {}^{*}\mathrm{N}x_j \right) \tag{11}$$

$$F_{FAT}\left(L_j\right) = \min(\sum_{j=1}^{ns} F_i {}^{*} V\left(L_j\right) ; \sum_{j=1}^{ns} F_i) \tag{12}$$

Where:

- Lj is the distance between step j and target point at distance L along the transect;
- F_{FAT} is the frequency of fatality per pipeline unit length at distance Lj by events originating in step j (event/year/km); it cannot exceed the release frequency calculated as the sum of frequency of all the scenarios;
- Nx_j is the length of the step j;
- F_i is the frequency of occurrence of scenario I (ev/year/km);
- V is the vulnerability at distance L_j;

Table 6
Comparison between event frequencies calculated with the IP-UKOOA ETA and the New ETA (where U stands for Unobstructed, O for Obstructed and FB stands for Full-Bore).

	Old ETA		New ETA	
	JF frequency [ev/year]	FF frequency [ev/year]	JF frequency [ev/year]	FF frequency [ev/year]
¼" U	1.31E-05	9.2E-06	1.31E-05	–
¼" O	3.94E-05	2.76E-05	3.94E-05	–
4" U	9.13E-05	6.39E-05	2.34E-04	2.34E-07
4" O	2.74E-04	1.92E-04	1.37E-04	1.37E-07
FB	1.97E-02	1.38E-02	–	–
FBU1	–	–	7.04E-04	–
FBO1	–	–	4.13E-04	–
FBU2	–	–	9.99E-03	–
FBO2	–	–	5.87E-03	–
FBU3	–	–	1.05E-03	1.05E-03
FBO3	–	–	6.19E-04	6.19E-04

Table 7
Comparison between radiation distances for jet fires and LFL and LFL/2 values for flash fire according to the ETA different approaches.

	JET FIRE					FLASH FIRE	
	Radiation distance [m]					Concentration distance [m]	
	3	5	7.5	12	37.5	LFL	LFL/2
Standard ET	[kW/m²]	[kW/m²]	[kW/m²]	[kW/m²]	[kW/m²]		
¼" U	10	8	7	6	4	–	–
¼" O	3	2	2	0	0	–	–
4" U	87	66	53	31	0	–	–
4" O	94	74	62	46	31	286	441
FB	160	132	116	93	59	586	925
PETA	[kW/m²]	[kW/m²]	[kW/m²]	[kW/m²]	[kW/m²]		
¼" U	7	5	5	4	2	–	–
¼" O	3	2	2	0	0	–	–
4" U	87	66	53	31	0	–	–
4" O	94	74	62	46	31	286	441
FB U1	368	281	228	142	0	–	–
FB O1	160	132	116	93	59	–	–
FB U2	263	200	162	99	0	–	–
FB O2	160	132	116	93	59	–	–
FB U3	176	134	109	66	0	–	–
FB O3	160	132	116	93	59	–	–
FB FFU	–	–	–	–	–	37	38
FB FFO	–	–	–	–	–	586	926

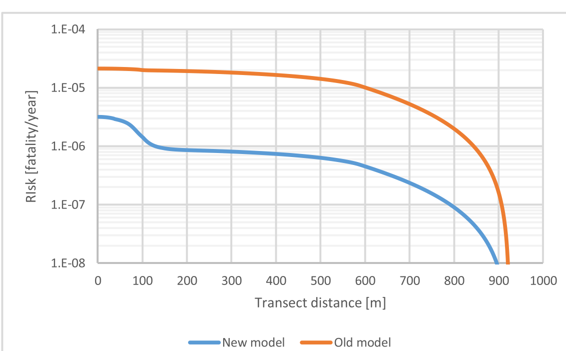

Fig. 5. Location specific individual risk as a function of the distance, according to the different ETA approaches.

• ns is the number of scenarios originating in step j (jet fire, flash fire).

The results are provided in terms of physical effects trend vs the distance from the release point (namely heat radiation vs distance) thus allowing for the calculation of the vulnerability trend vs distance (Fig. 5).

The LSIR curve above shows that with the usage of the refined PET a reduction of the fatality frequency by an order of magnitude can be observed at distances higher than 200 m from the pipeline. This effect is mainly due to the reduction in the over-conservative assumptions made in the prediction of flash fire events: IP-UKOOA approach predicts flash fire frequencies according to fixed delayed ignition conditional probabilities, which fits best releases occurring in industrial areas where ignition sources are frequently present at different elevations. On the opposite, the HSE-UK approach would have completely neglected the flash fire, thus leading to an underestimation of the transect risk. This study represents a first step towards the refinement of ETA in case of buried NG pipeline and, even if outside of the focus of this paper, we briefly examine how pipeline safety can improve by making use of Bayesian Network-based and other graphical models. Novel promising developments are under investigation to identify dependent relationships among various accident-causing factors in a qualitative and quantitative way (Ahmadi et al., 2020): referring to buried pipelines, an effective solution for the urban context integrating iDEMATEL and ISM approach was conceived by Li et al. (2019a). The state features of urban buried gas pipeline network and the corresponding vulnerability level assessment was recently faced on the basis of the Support Vector Machine (SVM) and Artificial Neural Network (ANN) methods (Li et al., 2019b). Recalling to the focus of this study, Bayesian inference represents a natural extension and refinement of FTA and ETA frequentist approach (Vairo et al., 2019).

Moving from frequencies to probability distributions allows incorporating local dependence between events and enabling both predictive and inference analysis. As previously commented, the main uncertainties associated to the bow-tie analysis are on the likelihood, and interdependence, of root risk events in FT and events

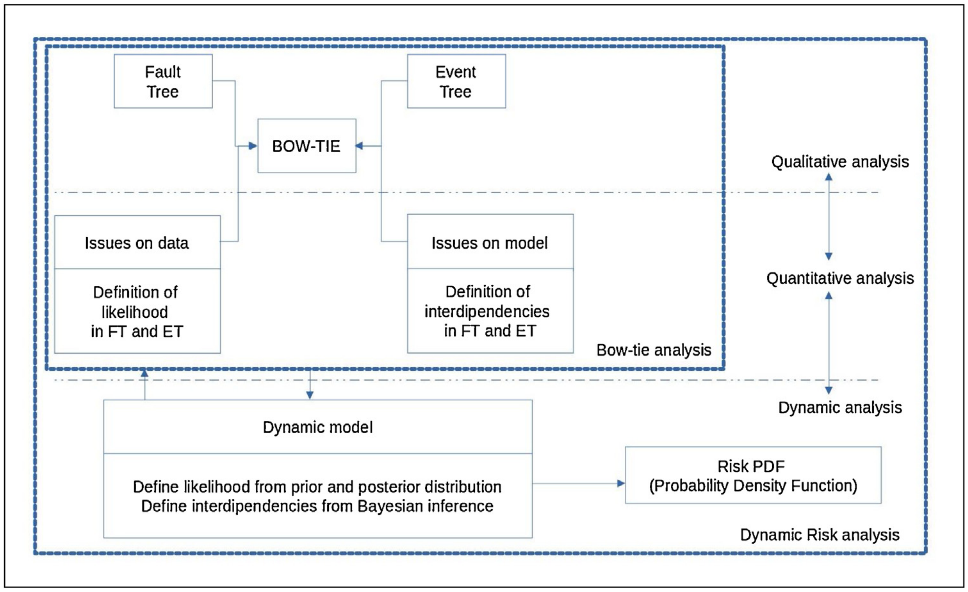

Fig. 6. A conceptual illustration of a framework for the predictive dynamic risk model.

in ET, and this is due to insufficient statistical data and knowledge. Consequently, such an analysis may lead to exact, but often unrealistic, results. As a future perspective under development, we propose to apply a Bayesian hierarchical modelling technique, in order to get a better appreciation of the uncertainties in the whole bow-tie structure. In this way, the failure/occurrence probability will be no more defined by an exact number, but rather by a Probability Density Function (PDF) As widely acknowledged, Bayesian hierarchical modelling is a statistical model written in multiple levels (hierarchical form) that estimates the parameters of the posterior distribution using the Bayesian method. Amin et al. (2020) recently outline such an approach in the process sector. The submodels combine to form the hierarchical model, and Bayes theorem is used to integrate them with the observed data and account for all the uncertainty that is present. The result of this integration is the posterior distribution, also known as the updated probability estimate, as additional evidence on the prior distribution is acquired (Allenby et al., 2005). Referring to the paper of Fang et al. (2019), Bayesian network established from the Bow-tie diagram can be used as a mapping algorithm, to identify critical influencing factors.

A conceptual illustration of a future pipeline dynamic risk model, relying on the described novel combined approach inspired from the paper by Amin et al. (2020), is depicted in Fig. 6.

6. Conclusion

This paper presents a critical discussion on pipeline ETAs accounting for a comprehensive description of possible outcomes from accidents on high-pressure buried Natural Gas pipelines. The structure of a bow-tie was created in order to represent graphically the relationships between possible threats (or causes of damage), outcomes and barriers that can be used for optimum decision making in both design and operation both in prevention and mitigation, accounting for technical and cost-effectiveness constraints. We focused on ignition probability and the physical conditions of the release, in order to identify the actual threats arising from a pipeline LOC under the different situations.

The main implication of the application of the new PETA, are mainly connected to flash fire scenarios and can be summarized as follows:

- minor leak (¼"): flash fire is negligible with respect to the results from IP-UKOOA ETA.
- medium LOC (4"): flash fire frequency results three orders of magnitude lower.
- full-bore case: the radiation distances for unobstructed cases result to be longer at lower thermal radiation levels, while but the critical value of 37.5 kW/m^2 is never attained. The event frequency for flash fires is one order of magnitude lower.

The quantitative results in terms of resulting effects of the new PETA can be visually evidenced by the LSIR curve showing a reduction of the fatality frequency by an order of magnitude, at distances higher than 200 m. The implications on the hazard distance from the failure point are mainly due to the reduction in the over-conservative assumptions made in the prediction of flash fire events. As anticipated, the paper represents a first attempt based on relevant statistical data from various sources, requiring further sensitivity studies and possibly further validation by means of small and full scale experimental facilities, to perform immediate, delayed local and delete remote ignition runs. Additionally, the refined approach should be assessed against realistic cases including all demographical and orographic characteristics of possible or actual routes, to include societal risk evaluation and possible domino effect implications.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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