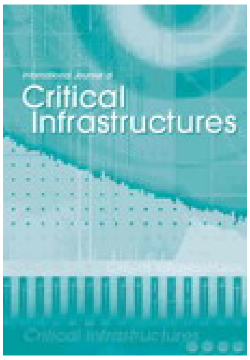

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Social and economic risk analysis of natural gas distribution networks

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Abstract: The continuity of service as well as with its safety and security represent a crucial issue for natural gas transmission and distribution networks and a detailed analysis of the associated risks is essential to increase their reliability. In particular, natural gas distribution networks are characterised by a high number of users and present a very complex structure (with nodes and stretches and presenting mixed typologies, e.g., point to point, star, meshed) which make often difficult to forecast the effects of localised failure events, especially by a social and economic point of view. In this work, the authors develop a methodology for the analysis of the economic and social risk associated with natural gas distribution network failures and for the quantification of the related consequences on residential, commercial and/or industrial users. To this aim, the authors present and discuss the case study represented by a city distribution network located in southern Italy. The results demonstrate the developed method is effective in identifying the structural criticalities of the network, allowing the quick detection of the most critical areas affected by significant risk of service disruption.

Keywords: failure analysis; risk analysis; distribution network; natural gas.

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1 Introduction

Natural gas (NG), in the current world energy scenario, is one of the most important sources of energy. In 2019, it represented 24.2% of the primary energy consumed in the world (BP Statistical Review of World Energy, 2020), and according to British Petroleum (2019) estimates, demand will grow by 1.7% per year until 2040, despite the rapid growth of renewable energy sources (RES). A share of about 32% of the total world gas demand is consumed by the industrial sector, whereas 40% is used to produce electrical energy, whereas the residential sector represents about 22% of the total demand (British Petroleum, 2019). Furthermore, the NG transmission and distribution infrastructure will continue to maintain a central role in the energy transportation even in the energy transition, thanks to the possibility of its use in the distribution of ‘green’ substitute gases such as biogas, hydrogen and their mixtures (Pellegrino et al., 2017; Guandalini et al., 2015; Perna et al., 2020; Canale et al., 2021). In Europe, the NG transmission and distribution infrastructure consists of approximately 136,000 km of high-pressure pipelines and approximately 1,800,000 km in medium and low pressure (CEER, 2018). The former has the purpose of transporting gas from the production sites over long distances through transnational networks, the latter is aimed at distributing the gas within inhabited centres, reaching even small residential and commercial users (Canale et al., 2019).

The network infrastructure that allows NG to be conveyed from production sites to consumption centres is considered a critical infrastructure as failure events can have significant consequences in terms of health, safety and economic well-being. The failure of a component or the breakdown of a pipeline segment, in fact, can endanger the safety of people, as well as cause disruptions which may have significant economic and social consequences. In recent decades, various supranational trade associations have collected information on accidents relating to NG infrastructures (Goodfellow et al., 2018; National Transportation Safety Board, 2002; Hilgenstock, 2006; EGIG, 2018). The information related to gas accidents is in fact essential for the estimation and management of the risk associated with the transmission and distribution of NG. In particular, the European Gas Pipeline Incident Data Group (EGIG), a cooperation body of 17 NG transmission system operators (TSOs), continuously updates a database of accidents affecting the NG transmission networks in Europe. In particular, EGIG records the episodes in which an unintentional release of gas has occurred through onshore steel pipeline segments, located outside regulation or metering plants and exercised at a minimum pressure of 15 bar (EGIG, 2018). In the UK, United Kingdom Onshore Pipeline Operators’ Association (UKOPA) collects and analyses data related to accidents involving NG transmission pipelines with a minimum pressure of eight bars of 11 British TSOs (Goodfellow et al., 2018). The Research and Special Programs Administration Office of Pipeline Safety (RSPA-OPS) of the US Department of Transportation (DOT) collects data on major accidents in the NG transmission networks in the USA, by updating a database (https://www.phmsa.dot.gov/data-and-statistics/pipeline/distribution-transmission-gathering-lng-and-liquid-accident-and-incident-data) containing information on accidents that have resulted in:

a death or injury with hospitalisation

b economic damages (i.e., damage to property or lost gas) summing at least $50 k

c shutdown of liquefied NG (LNG) facilities.

On Canadian territory, the task of drawing up an annual report on the performance of the grid concerning the accidents occurred, is entrusted to the National Energy Board (NEB, 2005). The NEB, following consultations with the Canadian Energy Pipeline Association (CEPA) and the Canadian Association of Petroleum Producers (CAPP), has identified safety indicators with reference to the damage caused to people (i.e., number of deaths and injuries) by accidents that have affected gas pipelines. These are further divided into three categories:

1 employees of the company that manages the network affected

2 employees of contractors working on the network affected

3 people not involved in work on the network affected.

Integrity indicators are also defined (i.e., numbers of outages with the respective causes) and environmental indicators (i.e., gas releases both in terms of frequencies and volumes dispersed). In Italy, the Italian Gas Committee (CIG), on behalf of the Regulatory Authority for Energy, Networks and the Environment (ARERA) (Deliberazione 574/2013/R/GAS, 2013), in collaboration with distribution companies, collects data on accidents affecting the gas distribution in Italy. In particular, the CIG develops an annual statistical survey, containing the list of gas accidents occurred aiming at:

1 monitoring the progress of events and obtaining useful information for the definition and development of prevention actions

2 monitoring the impact of laws, regulations and technical standards on the matter

3 identifying the population groups most exposed to the risk of accidents.

With regard to this last point, the composition by age and nationality of the injured and death people is analysed in order to identify conditions that may lead to an increase in the probability of occurrence (e.g., disadvantaged social contexts). The data collected by the CIG are presented in an annual conference and made available in an annual report (Comitato Italiano Gas (CIG) commissione statistiche incidenti ed emergenza da gas, n.d.) in which elaborations that mainly concern post-meter accidents are reported. With regard to accidents relating to plants owned by the distribution system operators (DSOs), no information is reported allowing the calculation of the associated risks (i.e., construction characteristics, operating conditions).

The risk associated with an event can be defined as the product of the probability of occurrence of an event and the magnitude of the consequences of the event itself (Muhlbauer, 2015). The risk analysis, based on the identification of the possible dangers associated with a given activity and the estimation of their probability of occurrence, determines the extent of the risk with the aim of being an aid to decisions aimed at its management (Matanovic et al., 2014).

Depending on the consequences of gas accidents, it is possible to distinguish the following types of risk:

1 individual risk

2 social risk (SR)

3 economic risk (ER).

Individual risk is associated with the individual, in a given period of time in which it is assumed that his position does not vary. SR is the measure of the total risk affecting a community or group of people associated with a given fixed position (Aloqaily, 2018). Finally, the ER accounts the economic consequences of an accident or breakdown.

In the literature, the methods applicable for risk assessment and analysis are generally classified into three categories:

1 quantitative

2 qualitative

3 hybrids (Matanovic et al., 2014).

Quantitative methods are based on statistical models which rely on historical data collected in international databases. Qualitative methods, although based on the subjective experience of experts and professionals, generally require careful validation. Among the qualitative methods, Han and Weng (2011) propose the assessment of three risk indices:

1 an index associated with the cause (e.g., corrosion, third parties, material failures, etc.)

2 an intrinsic risk index (e.g., operating conditions, installation defects)

3 an index associated to the consequences (e.g., danger of gas leaks, damage to things/people).

A weighting coefficient is assigned to each of the indices for the purposes of assessing the total risk. The proposed methodology was validated by comparison on two case studies with different extensions. Han and Weng (2010) also propose an integrated quantitative risk analysis (QRA) method for NG distribution networks by considering the consequences on service quality (gas leakage, pressure/flow rate drops) and those related to possible dangers for people (gas leakage, physical damage, probability of fatal accidents, etc.). In particular, the considerations regarding the quality of the service are used to assess the risk in terms of economic losses. These losses are considered proportional to the possible pressure drop arising as a result of a localised gas leak, considering that the production capacity of the industrial user is proportional to the value of the supply pressure in the area where the industrial activity is located. Ma et al. (2013) propose a QRA methodology in NG distribution networks based on the geographic information system (GIS) cartography system, through which service managers are provided with the possibility of delimiting high-risk areas that require more frequent inspection/maintenance interventions. Vianello and Maschio (2014) apply a QRA methodology to a portion of the Italian transmission network by defining a function for the evaluation of the consequences of the rupture of a pipeline, based on the diameter and operating pressure of the same and evaluating the individual and SR associated with it based on the breaking frequencies provided by the EGIG. Sacco et al. (2019) propose a methodology for optimising the process of identifying and planning maintenance interventions on a NG network based on the results of a risk analysis. This methodology, by identifying the pipeline segments whose maintenance/replacement would have a significant impact on risk reduction, can allow to reduce the magnitude and probability of occurrence of faults in the network.

The issue of seismic risk associated with NG pipelines is much debated in the literature. In this regard, Cavalieri (2020) proposes a seismic risk analysis methodology depending on the network topology and operating conditions (i.e., pipeline capacity and pressure at the nodes). This method is then tested in a reference network consisting of 135 nodes and 170 pipeline segments. With a similar approach, Esposito et al. (2015)

propose an analysis of the seismic risk in terms of the probability of service interruption, measured through performance indicators based on connectivity or on the evaluation after a seismic event of the existence of a path connecting the nodes in which the gas is injected into the network with the nodes from which it is withdrawn. The subject of the analysis was the part of the medium pressure network of the city of L'Aquila. The analysis was carried out through the use of a specific object-oriented programming software for assessing the risk of 'lifelines' developed by the authors themselves. Lustenberger et al. (2019) developed a methodology for the evaluation of the performance of the European transmission network in failure scenarios, based exclusively on opensource data. In particular, the cartographic data necessary for the modelling of the network were obtained from the maps made available by European Network of Transmission System Operators for Gas (ENTSOG) (https://www.entsog.eu/maps) while the consumption necessary to determine the flows in the network were defined on the basis of the demographic distribution of the different regions crossed by it and by the position of gas-fired electricity production plants. In order to assess a risk of interruption, the authors calculated an exposure for the pipelines based on their average life and on the damage associated with seismic events recorded in the Energy-related Severe Accident Database (ENSAD) (Kim et al., 2018).

This paper presents an analysis of the economic and SR associated with the disruption of the NG distribution service to residential and commercial/industrial users in an urban distribution network. In estimating the SR associated with residential users, the consequences that a network failure can determine on the service level were assessed on the basis of the number of citizens affected by the disruption of the distribution service, as well as their vulnerability associated with the age. The proposed methodology was tested on a real case study consisting of a distribution network in an urban area inhabited by about 18,000 citizens in southern Italy.

2 Methods

The risk analysis and assessment process can be summarised as in Figure 1:

- description of the system and identification of possible risk scenarios
- evaluation of the frequency of occurrence of events
- evaluation of the consequences of breakdown and emergency events.

2.1 System description and identification of possible risk scenarios

The medium and low-pressure distribution of NG in the city networks is located in the final phase of the NG supply chain (http://australianenergymarketoperator.blogspot.com/) downstream of the city gates on the border with the high-pressure transmission network (Figure 2).

Depending on the type of risk, it is possible to identify different scenarios. For example, individual risk and SR foresee the consequences for people's health following accidents are taken into consideration. In particular, individual risk is defined as the probability that an average unprotected individual, permanently localised in a specific area, is injured or killed due to an accident consequent to a risky activity, while societal risk is defined as the relationship between the frequency and the number of people injured/killed by a potential accident (Han and Weng, 2010). In fact, since NG is a primary good, the impossibility of meeting the demand can have significant social consequences. SR is usually represented in terms of *F*-*N* curves, which describe the expected frequency *F* that a given accident occurs involving a number of *N* people. The ER, on the other hand, focuses on the economic consequences that a failure event leading to service disruptions can cause. In the distribution network, in fact, NG is used by commercial or industrial activities for which the service disruption can directly lead to a loss of earnings (i.e., the impossibility of guaranteeing a service or certain levels of production).

Figure 1 Schematic representation of the risk analysis associated with a NG distribution network (see online version for colours)

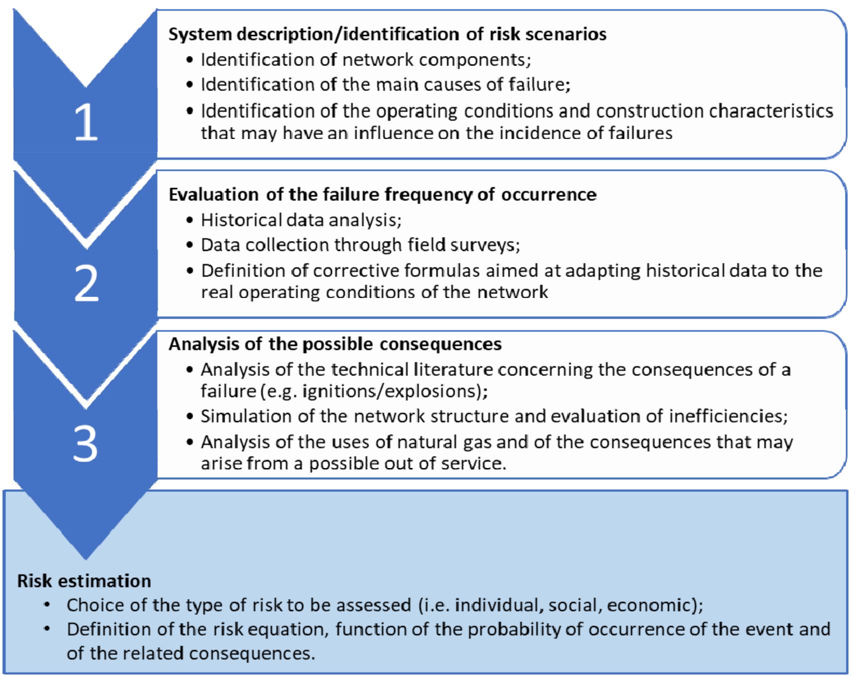
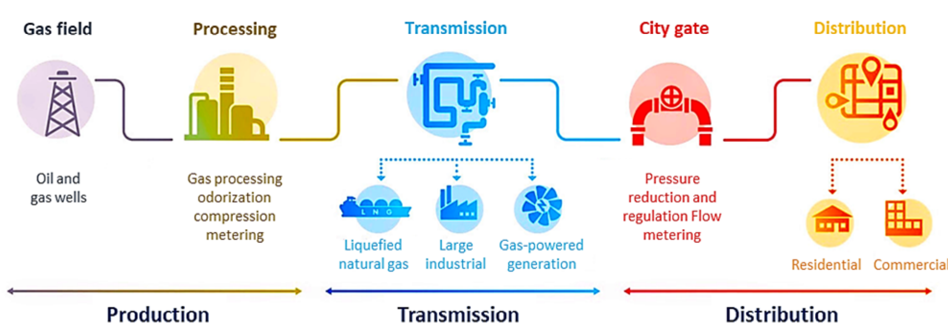


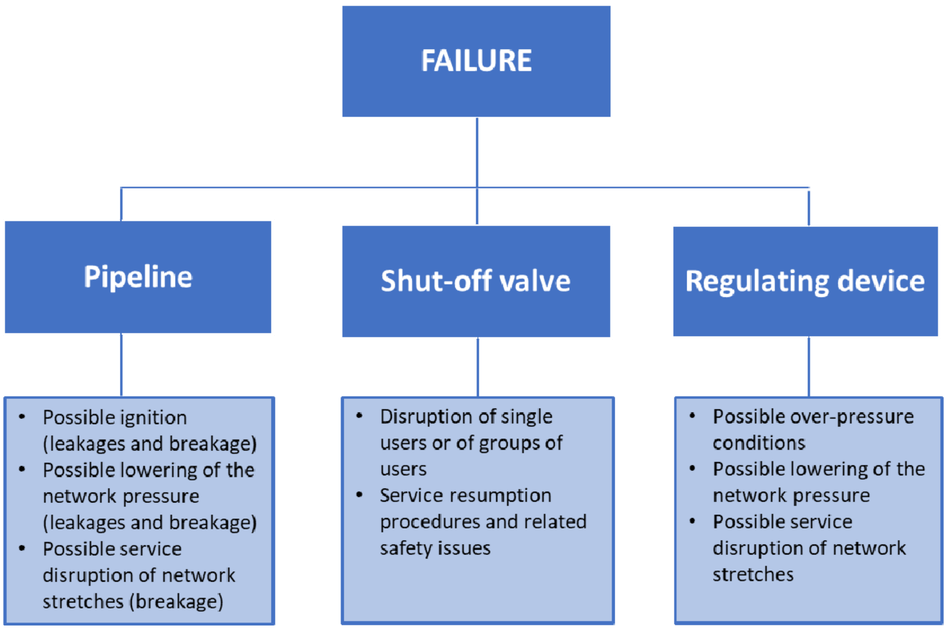
Figure 2 NG supply chain (see online version for colours)



Source: http://australianenergymarketoperator.blogspot.com/

One of the most used tools to conduct a risk analysis is the event tree analysis (ETA). It is an inductive method allowing to graphically represent all the possible consequences deriving from an accidental event. Figure 3 shows an event tree for a failure in a distribution network for which the number of components is limited to the pipelines and pressure regulation devices.

Figure 3 ETA of a failure in a distribution network (see online version for colours)



2.2 *Estimation of failure frequency occurrence*

To carry out a risk analysis, it is necessary to determine the failure occurrence frequencies to the events that cause the failure scenarios. This operation can be handled starting from the analysis of historical data (Canale et al., 2019; Guandalini et al., 2015; Cavalieri, 2020) or, when available, from data collected directly by the DSO in charge of managing the network. The estimation of the occurrence frequencies starting from historical data may require the introduction, when necessary, of appropriate corrective factors allowing to consider the possible differences in the constructive characteristics of the networks (i.e., pipeline materials, diameters, type of joints, age), as well as the different operating conditions (i.e., operating pressures) (Han and Weng, 2010). The total frequency of failure can be expressed as the sum of the frequencies of the different types of failure (e.g., drilling of the pipeline, shearing of the pipeline) through equation (1):

$$\varphi = \sum_i \varphi_{i,k} K_k \left(a_1, a_2, a_3, \ldots\right) \tag{1}$$

where

φ is the expected total failure frequency associated to a k^{th} cause ($1{,}000^{-1}$ km^{-1}year^{-1})

I is an index depending on different failure typologies (e.g., partial damage to the pipeline, complete shearing of the pipeline)

$\varphi_{i,k}$ is the base frequency occurrence of i^{th} failure event associated to a k^{th} cause ($1{,}000^{-1}$ km^{-1}year^{-1})

K_k is the correction factor associated to a k^{th} cause (e.g., depth of cover – DC, operating pressure, type of soil)

a_i are the influencing factors of the correction factor associated to a k^{th} cause.

Aimed at defining the breakdown frequencies, in this paper, the authors used the data collected in the 10th Report of the EGIG (2018) which refers to the decade 2007–2016, which is considered more significant as the measures adopted in safety have led to a significant reduction in accidents in NG transport networks. Even if the aforementioned data refer to the NG transmission sector in Europe (i.e., high-pressure pipeline networks, $P_{\min}$ = 15 bar), for the purposes of this paper the information obtained from the survey conducted by the EGIG is significant also for urban distribution networks. In fact, the only cause of failure is the one associated with the third part activities (i.e., excavation operations) for which a corrective factor K_{DC} was assessed as a function of the DC of the pipeline. This choice is justified by the fact that the failures attributable to excavation operations, in fact, are more frequent in small diameter pipelines present in urban areas (EGIG, 2018). Furthermore, in this paper, the possible different entities of the fault were not considered [i.e., summation with i^{th} index in equation (1)] since, regardless of the extent of the damage, in order to avoid collateral damage consequent to a gas leakage, the related network stretch needs to be closed. This implies that, in terms of service continuity, all types of faults from which an unwanted gas leak may arise lead to the same effect.

The basic breaking frequency can therefore be expressed as a function of the diameter of the pipeline starting from the data reported in Table 1.

Table 1 Failure frequencies per 1,000 km year

Pipe diameter (mm)	*Unknown*	*Pinhole/crack*	*Hole*	*Rupture*	*Total*
0–120	0.0068	0.0779	0.1200	0.1489	0.3537
120–280	0	0.0204	0.0623	0.0742	0.1569
280–430	0	0.0086	0.0223	0	0.0310

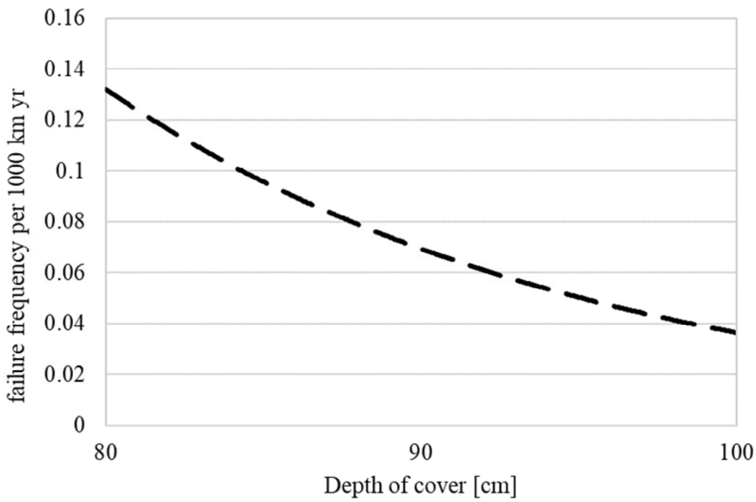
Source: EGIG (2018)

Since the failure frequencies data are available for diameter classes, different diameters are therefore associated with each of the breaking frequencies. It can be noticed the breaking frequency shows a decreasing trend as the pipe diameter increases. Therefore, data in Table 1 have been used to derive a regression function that allows this effect to be considered also for the different diameters belonging to the same class. To this aim, a mathematical function was then derived through a linear regression which, given the diameter of the pipe, allows to obtain a basic breaking frequency as per equation (2).

$$\varphi_{i,k} = -0.001d + 0.4038 \tag{2}$$

One of the critical factors to be accounted for determining the failures frequency is represented by the DC of the pipelines (Kinsman and Lewis, 2000). Figure 4 shows the breaking frequency associated with external interference as the DC varies (EGIG, 2018).

Figure 4 Frequency of breakage due to external interference as a function of the DC



Source: EGIG (2018)

For this reason, a correction coefficient has been calculated due to the variability of this factor. The EGIG report makes available the data relating to the kilometres of pipeline by DC for each of the years in the period 2007–2016. Through this information, the corrective factor K_{DC} was evaluated, indicating the weight of a given class of DC on the total frequency of the fault [see equation (2)].

$$K_{DC} = \frac{\varphi_{DC}}{\varphi_{third\_part}} \tag{2}$$

where

φ_{DC} is the failure frequency due to external interference for single DC class ($1{,}000^{-1}$ km^{-1}year^{-1})

φ_{third_part} is the total failure frequency due to external interference ($1{,}000^{-1}$ km^{-1}year^{-1}).

In Table 2, the typical K_{DC} values are reported.

Table 2 Correction factors for DC classes

Depth of cover	*Depth of cover failure reduction factor (K_{DC})*
Below 80 cm	3.42
Between 80 and 100 cm	0.88
Above 100 cm	1.19

Source: Authors' estimates in reference to EGIG (2018)

2.3 Analysis of the failure effects

The consequences of accidents affecting gas networks can be classified into two main categories:

1 consequences for the health of people attributable to the toxicity or flammability of the gas

2 consequences on the level of service from which inconvenience to users or economic losses may arise.

In the first case, it is necessary to perform a modelling of the gas release resulting from the failure [e.g., fracture of a pipe segment or failure of a regulating device (Gao et al., 2002; Montiel et al., 1998)]. The estimate of the potential effects, in terms of toxicity and possibility of ignition, depends on the extent of the fault, the type of substance transported inside the pipelines, the quantities released, as well as the environment surrounding the release area (i.e., air temperature and pressure, morphology of the ground and of the surrounding urban environment). In this paper, due to the fact that the NG chain is characterised by a lower fatality rate than other fossil sources as well as considering that the NG shows the least consequences for people due to accidents (Burgherr and Hirschberg, 2005), the authors have chosen to focus attention on the social and economic consequences of the service disruption. This can be analysed through the drop in quality of the distribution service caused by a failure and of the related effects to the different types of network users. As for example, a failure or intentional tampering affecting a section of pipeline or a regulating device can cause a pressure drop which may result in the impossibility to meet the gas demand for a certain number of users who can be characterised by different uses of NG (e.g., residential, commercial, industrial).

A service level analysis can be performed through simulation models allowing to evaluate the behaviour of the network in different operating scenarios, calculating the distribution of pressures, according to user demand, before and after the failure event. To this aim, numerous SW are available on the market that allow modelling the network by calculating pressures and flow rates in different critical sections and nodes (e.g., DinGas, InfoWorks WS Pro Gas, Pipe2020, Synergi Gas).

Typically, the modelling of the network requires a schematisation in nodes and pipeline sections. In particular, the nodes represent:

1 gas entry points into the system

2 points where gas is withdrawn from the system and supplied to end users

3 points where a pipeline undergoes a change in diameter or division into two or more stretches.

The resulting scheme is imported in the form of a digital map containing geometric information (e.g., position, length and diameter of the pipes) and technical information (e.g., pipeline materials, pressure reduction units, valves). It is also necessary to define which of the two available approaches to simulations to use:

1 pressure-driven approach

2 demand-driven approach (Dell'Isola et al., 2020).

The results discussed in this paper were obtained through a demand-driven approach providing the definition of a network load profile in terms of the quantity of NG distributed among users, which reliably describes the real trend in consumption. In this case, assuming that the gas demand does not vary for a full hour, the simulation returns as a result the pressure values at the nodes of the network. Therefore, the distribution of consumption can be obtained using the measures carried out by the network operators to balance the network itself. By modifying the parameters of the model, it is possible to change the status of each individual pipeline segment by closing it and assessing the consequences of this operation in terms of service anomalies.

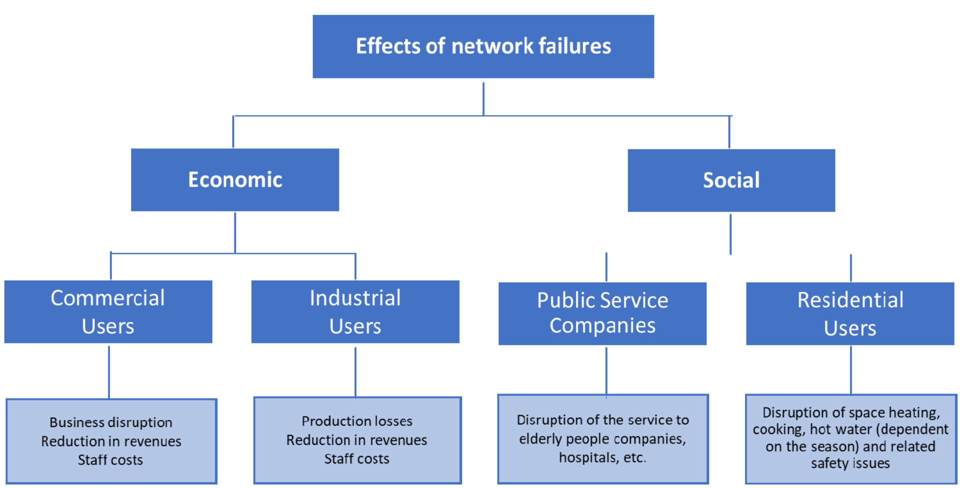
For the case study described in the present paper, the authors used the PSS®Sincal SW developed by Siemens. The SW, once the topology and geometry of the network has been imported, organises the information within an access database that can be consulted and modified by the user. By intervening on the database through a java script, it was possible to simulate the systematic out of service of each of the pipeline sections of the network and to evaluate each time the distribution of the pressures in the network nodes upon reaching the new steady state of equilibrium.

The social and economic consequences of the failures depend on the type of user, as described in Table 3 (i.e., residential, commercial or industrial) and on the period of occurrence (i.e., time, day, season). For some users, the seasonal component is relevant (e.g., space heating), whereas for other users specific assessments must necessarily be performed (e.g., type of commercial/industrial activity).

Table 3 Classification of distribution network users

Category	*Description*
Public utility	Public service (e.g., school, hospitals, public sport facilities)
Residential	Space heating, domestic hot water, cooking
Industrial	Food industry, light industry (manufacturing), artisan industry
Commercial	Space heating, domestic hot water production (e.g., hotels, personal care facilities) and cooking (e.g., restaurants, catering)

Figure 5 Social and economic effects of failures for different NG distribution users (see online version for colours)



In fact, aiming at assessing the economic damage, industrial users may incur in a loss of production, whereas for commercial users, given the multiplicity of activities (e.g., catering, personal care, sport centres, offices of various kinds), loss of earnings it can be estimated by adopting reference statistical data related to the average annual turnover by category (http://dati.istat.it/Index.aspx?QueryId=20596). For residential and public utility users, the service disruption does not directly lead to loss of earnings, but inconveniences whose relevance depends on the season, number and type of users concerned. These latter may also include plants using gas for the production of electricity. If a failure involves such users, the possible disruption could also extend to networks other than the gas one, resulting in consequences whose analysis requires considering the interdependence between the various infrastructures. In this paper the consequences for the users of the service and consequences for the network manager have not been taken into consideration. The latter could occur if there are users which supply is non-interruptible by contract (e.g., industrial users, hospitals). Despite this, the proposed methodology is also aimed at increasing the reliability and quality of the service provided by DSOs. Figure 5 schematically shows the consequences of failures for the aforementioned user's categories.

2.4 Risk estimation

Performance analysis in terms of service continuity can be conducted according to two approaches:

1 connectivity-based

2 flow-based (Aloqaily, 2018).

The connectivity-based approach uses the network scheme, and through the graph theory, evaluates the number of nodes disconnected from the rest of the network when a failure occurs. In the flow-based method, adopted in this paper, the real behaviour of the network after the failure occurrence is simulated and the distribution of pressures, according to the NG demand trend, are calculated by a simulation software. In this case, the service disruption condition is associated with a minimum pressure threshold at the final redelivery point.

According to this approach, each simulation, where a specific pipeline segment is considered in failure, allow to assess the number of residential, commercial and industrial users involved in the failure scenario. It is important to note that, the impacted users, commercial and industrial activities may be not directly connected to the disrupted pipeline.

In the case of failure for commercial or industrial facilities, the ER associated with the failure event was determined by the authors using the average annual company revenue data of the specific activity (http://dati.istat.it/Index.aspx?QueryId=20596). The ER can therefore be expressed through equation (3):

$$ER = R_{av} \cdot \varphi \cdot L \tag{3}$$

where

ER is the economic risk (€ year^{-1})

R_{av} is the average annual company revenue (€)

φ is the expected breakage rate ($1{,}000^{-1}$ $\text{km}^{-1}\text{year}^{-1}$)

L is the pipeline length (km).

The equation associates a greater risk with activities presenting higher annual turnover since the outage of these activities potentially leads to greater impact. In the case of residential users, on the other hand, the consequences can be quantified through the number of citizens not provided with the NG distribution service, and to this aim, the pressures on all the nodes of the network were estimated by putting out of service all the pipelines segments of the network, one at the time (i.e., $N - 1$ analysis) following the interruption of each of the pipeline segments with which it is constituted. Each of the network nodes is associated with one or more redelivery points (i.e., meter installed at the customer's) through which a certain number of citizens access the service. The estimation of the number of citizens associated with the individual network nodes was carried out using the population census data conducted periodically by the national statistical institutes.

The aforementioned data also allow to categorise citizens into age groups, thus enabling the identification of inefficiencies involving more fragile people, at a greater risk. In particular, among the subgroups of the population at higher risk as regards the effects of low temperatures on health, the elderly represents one of the most susceptible groups. For this reason, it would be beneficial to introduce specific coefficients considering an increase in the SR if the service disruption affects elderly people (e.g., over 65).

With regard to the impact that a failure affecting the NG distribution system may have on elderly people, two factors can be taken into account:

1 elderly people spend on average more time at home, thus increasing the likelihood of be affected by any inefficiency in the network

2 a greater health risk is associated with elderly people since the efficiency of the body's thermoregulation system decreases with age (Hughes et al., 2019; Effetti del freddo sulla salute ed interventi di prevenzione, n.d.).

To take this effect into account, in the calculation of the citizens associated with the node, two corrective coefficients are introduced depending on the age and allowing to properly consider the different probability of being at home when a fault occur.

As regards the effects on health, epidemiological studies in the literature extensively documented the short-term effects of low temperatures on health, highlighting increases in mortality and hospital admissions (Effetti del freddo sulla salute ed interventi di prevenzione, n.d.). These effects have a higher incidence in the elderly, for which a greater increase in the relative risk of the occurrence of consequences due to low temperatures has been observed (Hajat et al., 2006).

Therefore, an additional coefficient will be introduced to account an increased risk if the failure affects a greater number of vulnerable people.

$$NP_w = \left(k_{>65} \cdot C_{>65} \cdot NP_{>65} + C_{<65} \cdot NP_{<65}\right) \tag{4}$$

where

NP_w is the weighted number of people involved in the service disruption

$NP_{>65}$ is the number of people above 65 years old involved in the service disruption

$NP_{<65}$ is the number of people below 65 years old involved in the service disruption

$C_{>65}$ is a corrective coefficient for the average occupancy rate in indoor environment by people above 65 years old, assumed by authors equal to 0.80

$C_{<65}$ is a corrective coefficient for the average occupancy rate in indoor environment by people below 65 years old, assumed by authors equal to 0.60

$k_{>65}$ is a corrective coefficient taking into account the higher vulnerability of people above 65 years old, assumed by authors equal to 1.03.

Aiming at defining the corrective coefficients relating to the average occupancy rate of domestic environments, differentiated by age groups, in this paper the authors referred to data collected by the National Institute of Statistics (ISTAT) (Rapporto ISTAT "I tempi della vita quotidiana" Anno 2014, 2016). In particular, it can be estimated that in average people above 65 years age spend about 80% of the day at home, with peaks exceeding 90% for people above 80 years age. On the other hand, people below 65 years age are expected to spend in average about 65% of the day at home (Rapporto ISTAT "I tempi della vita quotidiana" Anno 2014, 2016). This gives rise to a greater probability for elderly people of being at home when a service disruption occurs and of suffering the related consequences. As regards the definition of a coefficient considering the increase in the consequences of the service disruption perceived by the elderly, literature studies are available allowing to correlate the increases in the mortality rate associated with climatic conditions to various factors that characterise the population (i.e., age, sex, comorbidities) (Analitis et al., 2008; Smolander, 2002).

Therefore, the SR associated to a service disruption in a NG distribution network can be obtained through the following equation:

$$SR = NP_m \cdot \varphi \cdot L \tag{5}$$

where

SR is the social risk (citizens year^{-1})

φ is the expected breakage rate (1,000^{-1} km^{-1}year^{-1})

L is the pipeline length (km).

2.5 Limitation of the method

The above described method allows to get a first estimate of the social and ER associated to failures and disruption of NG distribution networks. For the sake of truth, the developed method relies on objective data and related estimations, however limitation and uncertainties are also inherent, such as:

- Historical data available typically refer to transmission pipelines, therefore, in the proposed method only fault by third part activity have been considered, since these are regularly registered.
- Since data relating to the breakdown of network components that are not conducted are not available in the literature, data related to breakdown of single components are not often available and consequently, the risk analysis is limited to pipelines faults.

- Several input parameters of the analysis are estimated as average values (e.g., the number of people involved, the production losses for industrial users, the reduction of incomes for commercial users), making the consequent estimation of the social and ER affected by uncertainty related to these estimations.

3 Case study

The case study presented in this work refers to an urban distribution network that feeds a city in southern Italy on an area of about 36 km^2 inhabited by about 18,000 citizens. The investigated distribution network is made up of approximately 40 km of pipelines and it is fed by a single city gate (i.e., interconnection with the high-pressure transmission network) where the gas NG entering is measured, odorised and laminated up to a pressure of 0.5 bar. Within the investigated network, there are no further pressure reductions, and therefore, no final reduction units (FRU) are available. The redelivery points supplied by the network are represented by 6,718 residential users and 115 commercial/industrial users (see Table 4).

Table 4 Main characteristics of the investigated network

Low pressure pipelines, km	0
Medium pressure pipelines, km	40
City gates	1
Redelivery points (total users)	6,824
Residential redelivery points	6,718
Industrial/commercial redelivery points	106
Number of citizens	18,393

The investigated network was entirely reproduced in a GIS environment, digitising and defining the information of the relevant physical elements of the system:

1. the geometric characteristics of the network (i.e., diameters and lengths of each pipe segment, reciprocal position of all components of the network)
2. the hourly measurements of the volumes of gas entering and the ones leaving the remote-read users (i.e., the ones equipped with modern smart meters)
3. the number of inhabitants for each of the suburban areas divided by age groups
4. the average annual company turnover recorded by ISTAT of the single categories of commercial/industrial users
5. the historical data relating to accidents occurring in the gas transmission networks collected by the EGIG.

The above reported data have been imported into the PSS-SINCAL simulation software. A demand diagram was created for each remote-read user on the basis of the real consumption measured. For the other users, on the other hand, an average demand diagram was constructed starting from the difference between the hourly volumes entering the network and the remotely read leaving ones. In this way, the operation of the network in the 24 hours of a typical day of the heating season was simulated. Finally, in order to calculate the breaking frequency per unit of length, the network was divided into pipeline segments according to the pipeline diameter (see Table 5).

Table 5 Pipeline stretches and related diameter classes

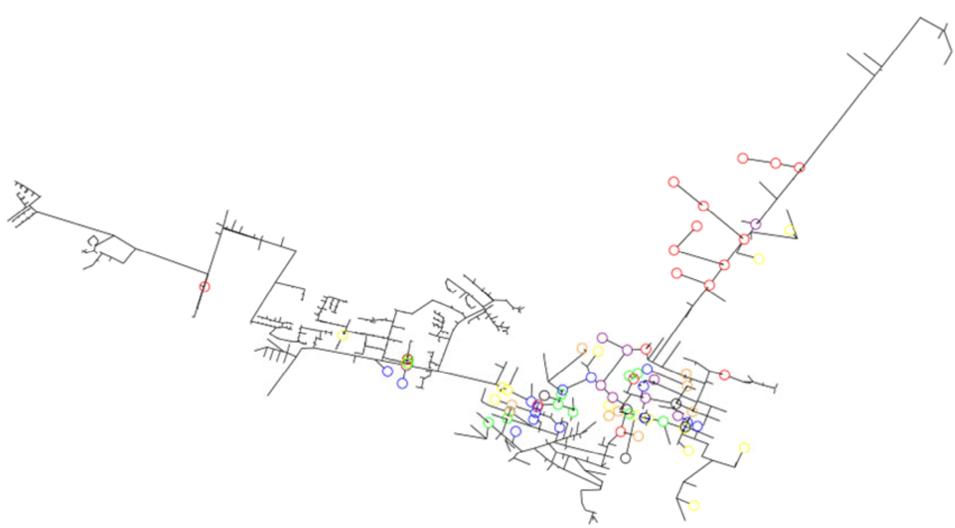
Diameter (mm)	*Number*	*Length (m)*	*% of total length*
0–50	484	4,637.76	12.6%
50–70	35	732.95	2.0%
70–100	312	16,042.85	43.5%
100–150	186	8,250.46	22.4%
> 150	100	7,187.58	19.5%

Although a lower DC is allowed in some specific circumstances, the general technical rule for the design of pipeline networks adopted in Italy establishes pipelines must be installed at a minimum depth of 0.9 m (Decreto del Ministero dello sviluppo economico 17 aprile 2008, 2008). For the estimation of the failure frequency, since no punctual detailed information on the DC was available, the authors considered an average DC of 0.9 m.

3.1 Economic risk

The ER assessment was obtained considering the probability of failure of a given pipeline segment and the estimate of the potential loss of earnings due to the service disruption that may affect some adjacent portions of the network.

Figure 6 Location of commercial and industrial users in the investigated network (see online version for colours)



The data related to the intended use of the gas of individual residential and commercial/industrial users, available from the network manager, were represented in cartographic form in the GIS environment, in which the single commercial and industrial activities in the area have been punctually located (see Figure 6 and Table 6). In particular, from Figure 6, the presence of limited areas in which different users belonging to the same category are concentrated (i.e., industrial areas, commercial areas) can be observed. In particular, the area of the network with greater presence of industrial users is the one located in the peripheral part of the network, characterised by less mesh if compared with the more urbanised central area. A smaller mesh corresponds to a smaller number of redundancies in the pipeline plot that feeds the aforementioned area. It follows that the results of the risk analysis could highlight a fragility of the network stretch that feeds this portion of the network. The results of the ER estimate conducted on the network are summarised in Table 7. In particular, 122 pipeline segments whose interruption determines a disservice affecting at least one commercial/industrial user (i.e., with a not zero ER associated) have been identified.

Table 6 Commercial and industrial users in the network (see online version for colours)

Acronyms	*Description*	*Number*	
Ris	Hotels and restaurant (e.g., B&B, hotel)	31	○
PU	Public services companies and structures (e.g., schools, hospitals, public sport features)	18	○
Est	Personal care services (e.g., hairdressers, beauty centres)	18	○
CS	Private sport structures (e.g., dance schools, gyms, swimming pools)	11	○
Ind	Industrial activities (e.g., food industry, tailoring industry)	18	○
Med	Private medical structures and analysis laboratories	8	○
Uff	Space heating for offices	11	○

Figure 7 Cartographic representation of pipeline segment interrupted by event 117 in Table 7 (see online version for colours)

Table 7 ER estimates

Pipe Id	*ER*	*Pipe Id*	*ER*	*Pipe Id*	*ER*	*Pipe Id*	*ER*
1	15.02	32	0.63	63	0.95	94	2.99
2	5.54	33	3.46	64	4.53	95	2.61
3	1.76	34	36.93	65	116.06	96	2.69
4	1.23	35	8.33	66	54.67	97	4.47
5	0.35	36	0.59	67	1.84	98	7.92
6	0.33	37	2.23	68	4.25	99	56.08
7	105.28	38	2.44	69	12.14	100	1.16
8	4.74	39	683.97	70	34.99	101	0.96
9	6.61	40	7.78	71	16.82	102	0.91
10	8.38	41	0.3	72	7.93	103	0.7
11	2.53	42	1.14	73	1.25	104	10.96
12	7.89	43	0.14	74	6.34	105	3.1
13	9.86	44	0.3	75	0.11	106	2.47
14	171.38	45	0.09	76	1.15	107	218.99
15	32.35	46	63.45	77	0.29	108	4.12
16	7.25	47	0.97	78	9.62	109	0.28
17	0.58	48	3.92	79	9.17	110	41.54
18	23	49	0.76	80	34.48	111	202.88
19	1.94	50	45.07	81	2.67	112	125.3
20	2.54	51	295.33	82	3.08	113	349.21
21	0.71	52	2.12	83	22.22	114	0.73
22	213.09	53	2.7	84	23.06	115	16.39
23	2.21	54	22.98	85	1.11	116	6.55
24	6.66	55	5.44	86	0.22	117	3,965.83
25	31.45	56	2.01	87	1,011.1	118	692.63
26	10.72	57	3.13	88	20.35	119	448.05
27	17.72	58	2.49	89	0.91	120	17.78
28	2,278.38	59	3.02	90	5.37	121	32.27
29	9.41	60	1.69	91	33.26	122	0.66
30	1.35	61	30.36	92	0.45		
31	31.54	62	3.33	93	4.17		

Finally, Figure 7 shows a diagram of the network in which the pipeline segment characterised by the highest ER index (i.e., 117) has been highlighted in red. It can be observed, in fact, that an interruption of this segment will lead to the disruption of the service in the portion of the network in which almost all the industrial users present (pink circled area on the map).

3.2 Social risk

The estimate of the SR relies on the evaluation of the consequences in terms of people not supplied by the service after the breakdown of each of the pipeline segments of the network, considering their expected breakdown frequencies. To this aim, a simulation was conducted for each of the pipeline segments and the related distribution of pressures on the network nodes due to the failure event has been analysed. In this way, it is possible to estimate the number of nodes not reached by the service (i.e., with a pressure below the threshold value of 15 mbar). Subsequently, through the open source software QGIS, the layer of demographic data of the investigated suburban areas (defined in the 15th ISTAT population census at sub-municipal level) and the layer with the network nodes position were superimposed, in order to evaluate, in the hypothesis of homogeneous distribution of the population, the number of citizens involved in the service disruption divided into two age groups (i.e., above and below 65 years age). Figure 8 shows the results of the performed SR analysis.

Figure 8 Graphical representation of the results of the performed SR analysis (see online version for colours)

As it can be seen in the map in Figure 6, the NG distribution service of large areas of the city, especially the peripheral ones, is guaranteed by few pipelines stretches and this creates a greater risk for those segments that, if interrupted, exclude large areas of the network from the service. Finally, Figure 9 shows the trend of the cumulative frequency *F* of a segment breakdown, as the number of citizens affected by the interruption of the service varies (*F*-*N* curves). As expected, the analysis of the graph shows that the pipes with a smaller diameter typically present in the most meshed areas of the network and with higher failure frequency, present minor consequences when a failure occur.

The uncertainty of the method should be also estimated through the knowledge of the single uncertainty of the input data of economic and SR and by applying the propagation law (JCGM 100:2008, 2008) to the calculated *ER* and *SR*. Unfortunately, such data were not available for the case study and the authors roughly estimated the following uncertainty contributions ($k = 2$):

1 breakage rate $U_\varphi = 1.0\%$

2 pipeline length $U_L = 0.1\%$

3 company revenue $U_{R_{av}}$ ranging 5% to 10%

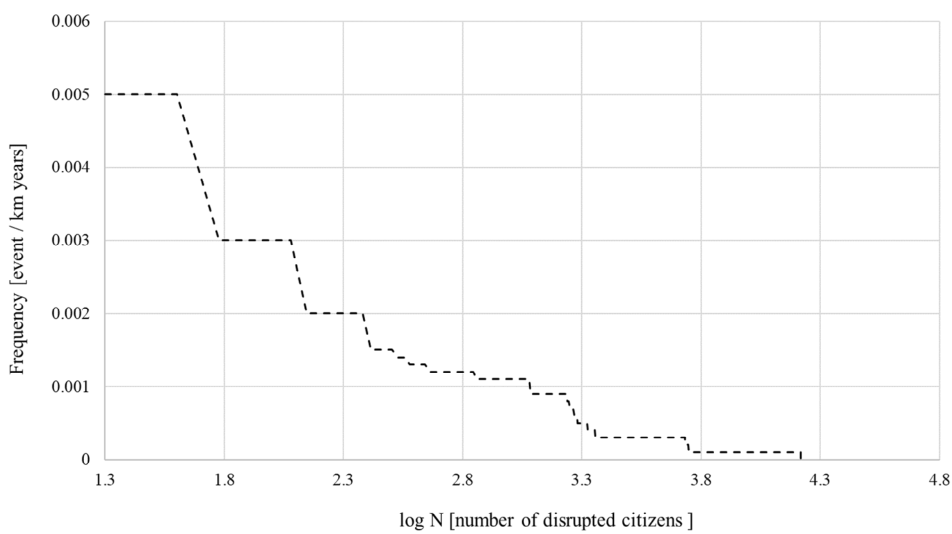
4 coefficient C for the average occupancy of people below/above 65 years old U_C ranging 5% to 10%

5 number of people below/above 65 years old U_{NP} ranging 1.0% to 3.0%

6 coefficient $k_{>65}$ for the vulnerability of people above 65 years old $U_{k_{>65}}$ ranging 5% to 10%.

In this case, overall uncertainty values U_{ER} and U_{SR} ranging 5.1% to 10.1% and 5.5% to 12% respectively for *ER* and *SR* have been estimated.

Figure 9 *F-N* curve of the investigated network



4 Conclusions

In this paper, the authors present a methodology for the analysis of the social and ER consequent to failures in a NG urban distribution network. In particular, the proposed methodology is based on a specific developed software capable to assess different operating scenarios by systematically simulating the effects of the breakage of the single stretches of the network.

The proposed methodology has been validated in a real case study distribution network in southern Italy, demonstrating the capability:

- to highlight structural criticalities
- to identify the related likely causes, such as the lack of redundancies in the meshing of the peripheral areas of the network actions

- to detect worst risk scenarios both from the social and economic point of view
- to effectively consider the presence of energy-intensive users with specific constraints (e.g., interruptible supply) or requiring greater protection as public services (e.g., hospitals)
- to assess the reliability of risk acceptability thresholds set by the network manager.

It is worthy to observe that the increasing spread of smart meters in networks will allow more accurate end-users load profile, and therefore, more accurate results of the simulations will be expected. Finally, the developed methodology could be extended with few adjustments also to interconnected energy networks (e.g., electric and gas networks) through the definition of more complex management logics including the risk of propagation of failures from one network to other.

The developed methodology can be useful both in the decision-making process when planning structural interventions and in the development of emergency management plans aiming at correctly allocating resources when a failure in a stretch of the network occurs.

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Acronyms and symbols

CEPA	Canadian Energy Pipeline Association
CAPP	Canadian Association of Petroleum Producers
CIG	Italian Gas Committee
DOT	Department of Transportation
DC	Depth of cover
DSO	Distribution system operator
EGIG	European Gas Pipeline Incident Data Group
ENSAD	Energy-related Severe Accident Database
ENTSOG	European Network of Transmission System Operators for Gas
ER	Economic risk
ETA	Event tree analysis
FA_m	Average annual turnover
GIS	Geographic information system
K_k	Corrective coefficient of failure frequency
K_{dp}	Weighting coefficient of a depth of cover class
L	Pipeline length
LNG	Liquefied natural gas
NEB	National Energy Board
NG	Natural gas
NP_m	Average number of people involved by service disruption
QRA	Quantitative risk analysis
RES	Renewable energy sources
RSPA-OPS	Research and Special Programs Administration Office of Pipeline Safety
SR	Social risk
SW	Software
TSO	Transmission system operator
UKOPA	United Kingdom Onshore Pipeline Operators' Association
a_i	Influencing factors of the breakage
φ	Expected breakage frequency per unit of length
φ_{DC}	Total frequency of a depth of cover class
φ_{third_part}	Total frequency of failures associated to third part activities
φ_k	Base failure frequency per unit of length