Resilience-Based design of Natural Gas Pipelines

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SUMMARY:
The concept of Disaster Resilience has received considerable attention in recent years and it is increasingly used as an approach for understanding the dynamics of natural disaster systems.
No models are available in literature to measure the performance of natural gas network, therefore in this paper a new performance index measuring functionality of gas distribution network have been proposed to evaluate the resilience index of the entire network. It can be used for any type of natural or manmade hazard which might lead to the disruption of the system. The gas distribution network of the municipalities of Introdacqua and Sulmona two small towns in the center of Italy which were affected by 2009 earthquake have been used as case study. Together the pipeline network covers an area of 136kmq, with 3 M/R stations and 16 regulation groups. The software Synergee has been used to simulate different scenario events. The numerical results showed that, during emergency, to ensure an acceptable delivery service, it is crucial the functionality of the medium pressure distribution network and the best retrofit strategy to improve Resilience of the entire network is to include emergency shutoff valves along the pipes.

Keywords: Resilience, Resilience-Based Design, Natural Gas, Pipelines, Performance.

1. INTRODUCTION

Earthquake safety of lifeline systems has attracted great attention in recent years since significant amount of damage was observed during recent past earthquakes. Lifelines are systems that are necessary for human life. Those systems are commonly used to transport water, oil, natural gas and other material. Their disruption due to earthquakes can have a devastating impact on human losses and economic stability within a given community. Therefore, due to their vulnerabilities, it is important to assess and mitigate seismic risk of lifelines. In literature, there are very few studies on seismic risk analysis of gas networks that take into account all the aspects of the component of risk (hazard, vulnerability, loss and restoration) and calibrate the analysis on real systems. Gas distribution network disruptions can induce significant consequences on the population and businesses in the community, as well as triggering fires, polluting waterways etc. The literature related to the seismic performance of the gas networks has focused mainly on the seismic vulnerability of gas pipelines when subjected to permanent ground deformations and liquefaction (Jeon and O'Rourke, 2005; Choo et al., 2007).
Recently (Poljansek et al., 2012) analyzed the seismic vulnerability of the gas and electricity network from the topological point of view. Various performance measures have been considered, but the restoration process is never taken in account during the analysis. Further research is required to evaluate the economic and social consequences caused by the reduced functionality of a damage gas distribution network and its consequences (Cimellaro, 2013). This paper proposes a model to evaluate performance of a gas distribution network including the restoration process right after an extreme event.

2. RESILIENCE-BASED DESIGN FOR NATURAL GAS SUPPLY SYSTEMS

Resilience (*R*) is defined as a function indicating the capability to sustain a level of functionality or performance for a given lifeline network, or community, over a period defined as the control time T_{LC} that is usually decided by owners, or society (usually is the life cycle, life span of the system, etc.).
Resilience index is defined graphically in Figure 1 as the normalized shaded area underneath the functionality function of a system $Q(t)$ which is a non-stationary stochastic process and each ensemble is a piecewise continuous function as shown in Figure 1. Analytically, Resilience is defined as (Cimellaro et al. 2010a, 2010b)

$$R_{ES} = \int_{t_0}^{t_6} \frac{Q(t)}{T_{LC}} dt \tag{2.1}$$

For the natural gas supply system functionality has been defined by the authors as a combination of the normalized gas flow rate and the total length of the network in service before and after the event. Therefore analytically functionality $Q(t)$ of the gas network is given by the following expression

$$Q(t) = \begin{cases} \left[w_1 \cdot \dfrac{F_{NF}}{F_E} \right] \cdot 100 & t \le T_I \\ \left[w_2 \cdot \dfrac{F_E}{F_{NF}} + w_3 \cdot \dfrac{L_E}{L_{NF}} \right] \cdot 100 & t > T_I \end{cases} \tag{2.2}$$

where F_{NF}=flow in normal operating conditions; L_{NF}=length of network working in normal operating conditions; L_E=length of network working during the transition period (phase two); F_E=flow in emergency operating condition during the transition period; w_1, w_2, w_3=weight factors.
Graphically, functionality of the gas network is shown in Figure 1, where the control time T_{LC} has been divided in two phases:

- *Phase 1*: corresponds to the period when after disruption, the network is repaired in order to go back to partial service;
- *Phase 2*: corresponds to the transition period when the network is partially in service;

Within the two phases T_{NF}= time of disruption event; T_B= network balancing time; T_M= operating time =(1 hour); T_I= repair time to bring the network to partial service; T_E= transition time during which the network is partially in service; T_{RE}= T_B+T_M+T_I+T_E= recovery time, T_{LC}=control system time.
The flow variation in the network after disruption is shown in Figure 2. After the pipeline breaks, the flow in the network increases to the maximum system capability F_{MAX}. Then after the network goes back to partial service the flow reduces to lower values with respect to normal operating conditions F_{NF}.

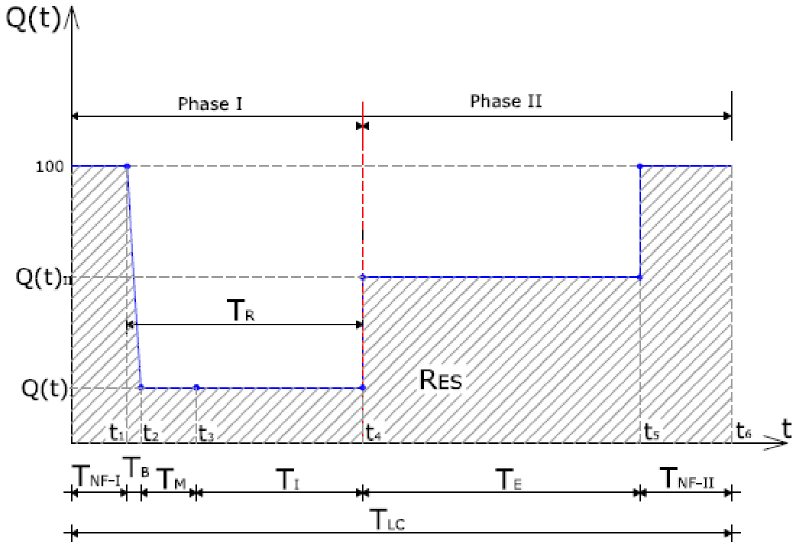


Figure 1. Functionality of Natural gas network after disruption

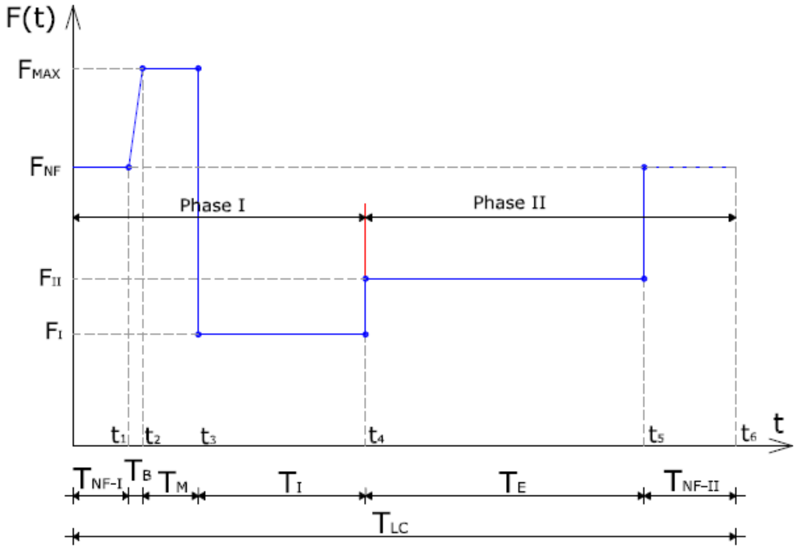


Figure 2. Flow rate inside the pipelines during the emergency condition

3. DESCRITION OF ITALIAN NATURAL GAS SUPPLY SYSTEM

Principal components of Italian gas supply system include: (i) high-pressure transmission lines; (ii) metering pressure reduction stations (M/R stations); (iii) medium pressure distribution networks; (iv) reduction groups; (v) low pressure distribution network; (vi) demand nodes; (vii) gas meters.

The Italian gas supply system is divided in *transport*, *storage* and *distribution*.

The natural gas injected into the Italian National Network comes mainly from import. The import gas is injected into the National Network via seven entry points where the network joins up with the import pipelines (Tarvisio, Gorizia, Passo Gries, Mazara del Vallo, Gela) and the LNG regasification terminals (Panigaglia, Cavarzere). Domestically produced gas is introduced into the Network through 51 entry points from the production fields or their collection/treatment plants; natural gas storage fields are also connected to the transmission network.

The transport of natural gas is an integrated service connected with the Import lines from Russia, Northern Europe and North Africa, with the re-gasification plants and the production and storage centres located in Italy up to the redelivery points of the Regional Network, (connected to local distribution utilities and large industrial and power plants) where the gas is redelivered to the users of the service (End Users). The Italian distribution network is divided in 8 classes according to the gas pressure. The RE.MI. (“Regolazione di misura” in Italian) stations are supply systems of the natural gas distribution network and are intended to allow the physical connection between the pipeline and the transport network to the customer. Pressure reduction systems are equipments designed to reduce and adjust to a predetermined value the pressure to vary the flow rate. In particular, the reduction gear is the equipment which has the function of calibrating the gas supply pressure to a predetermined value, which depends on: (i) supply pressure of the utilities; (ii) type of downstream network;

3.1. Comparison with other gas networks: Japan and USA

The American gas supply system is very similar to the European supply system. It is possible to distinguish four phases:
Supply: the majority of production takes place on the national territory through central extraction and treatment of the gas.
Transport: natural gas is transported through large diameter pipelines formed by a main line and lateral branches that tend to form a complex network. Along the network there are compression stations whose purpose is to increase the pressure and the flow velocity.
Storage: empty deposits of oil / gas, aquifers and salt caverns for the storage of gas in order to manage the gas demand;
Distribution: pipeline network organized with local facilities and infrastructure similar to those described previously.

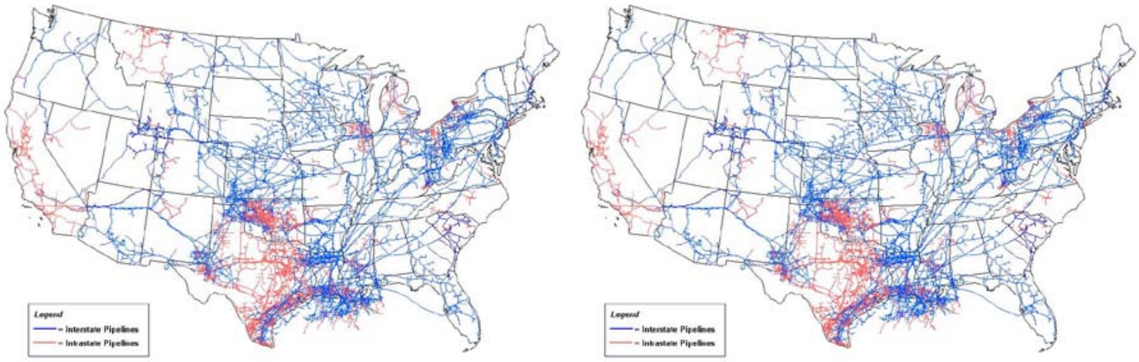
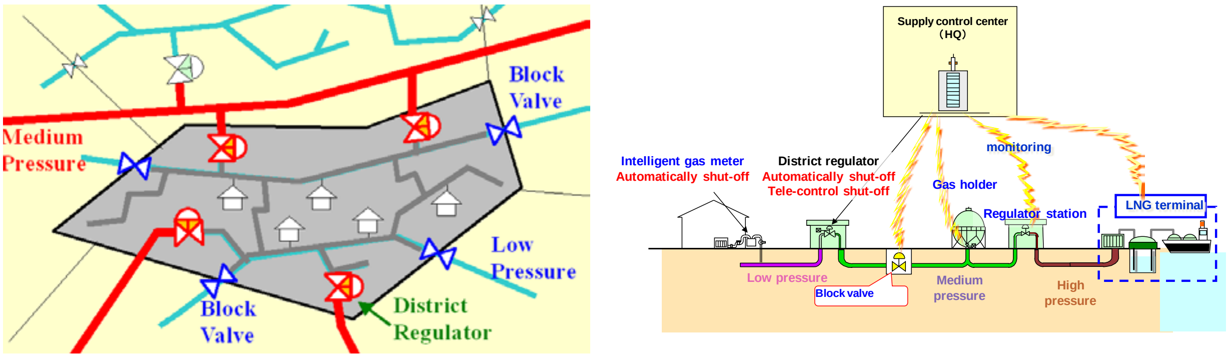


Figure 3. (a)Transportation and distribution network (b) Flow rate of import and export gas

The gas supply system in Japan is carrying LNG (liquefied natural gas) in the receiving terminals located throughout the territory only through the LNG tankers. In the network it is possible to observe the lack of transportation pipelines at national level. The LNG is stored in special containment basins and then regasified and injected into the high pressure network. After passing through the regulation stations, the gas is transported in medium pressure network up to the pressure reducers which are arranged at the boundaries of each district. Inside the districts it starts the low pressure network. In Japan, the Tokyo gas network is the most advanced in developing disaster countermeasures. About 4,000 seismographs are installed in different locations throughout our supply area so that local gas supply for each district will be shut off automatically in the event of a major earthquake.
Segmentation of gas networks is carried out in two levels: one for medium-pressure (MP) lines and another for low pressure (LP) lines (Figure 4a). Emergency shutoff of gas networks can be carried out for these units, called K-blocks for medium pressure lines and L-blocks for low pressure lines.
In this way it is possible separating areas with more damage from areas with less damage minimizing the impact on the less affected areas. This method can be used to quickly shut off the gas supply to the affected areas only. For the areas where the gas supply is stopped, personnel is trained to restore the supply as early as possible.

The “Supply Control Center” (Figure 4b) comprehensively monitors and controls everything from the production to supply of gas during the emergency. The center plays an important role in shutting off the supply of gas by remote control as necessary and transmitting the direction of midair diffusion to each station. Tokyo also has a Supply Control Sub-Center for a backup in case of an emergency.



(a) (b)

Figure 4. (a) Japanese gas supply system; (b) General Supply Control Center

4. NUMERICAL MODELLING OF THE GAS NETWORK DISRUPTION

SynerGEE is pipeline simulation commercial software which analyzes meshed networks. It can model large, complex, integrated, multipressure-level systems that include regulators and compressors. You have full control over the gas constraints (gravity, heating value and viscosity), friction factor calculations and heat transfer methods. It uses nonlinear fluid dynamic equations which provide levels of pressure, flow ecc. The first Kirchhoff law is used to solve the mesh network. The nonlinear continuous equation matrix related to each node is then solved using Newton-Raphson methods. The flow is evaluated using Darcy-Weisbach equation (SynerGee).

Different disruptions of the gas distribution network in the town of Sulmona Introdacqua were simulated assuming pipes shear failure in the medium and low pressure network.

The pipe failure mechanism has been analysed defining the typology and the value of the flow of methane gas dispersed in the atmosphere. The Dutch TNO model (TNO, 1997) has been used to describe the disruption behaviour of pressurized pipelines. The gas is modelled using the equation of ideal gases and the flow is considered adiabatic and isentropic.

In the model three types of failure mechanisms are considered (Figure 5):

- Small break;
- Misalignment;
- Shear Failure;

Small break failure appears when upstream pressure remains constant during the gas leakage, while *shear failure* appears when the pressure inside the pipes goes to zero.

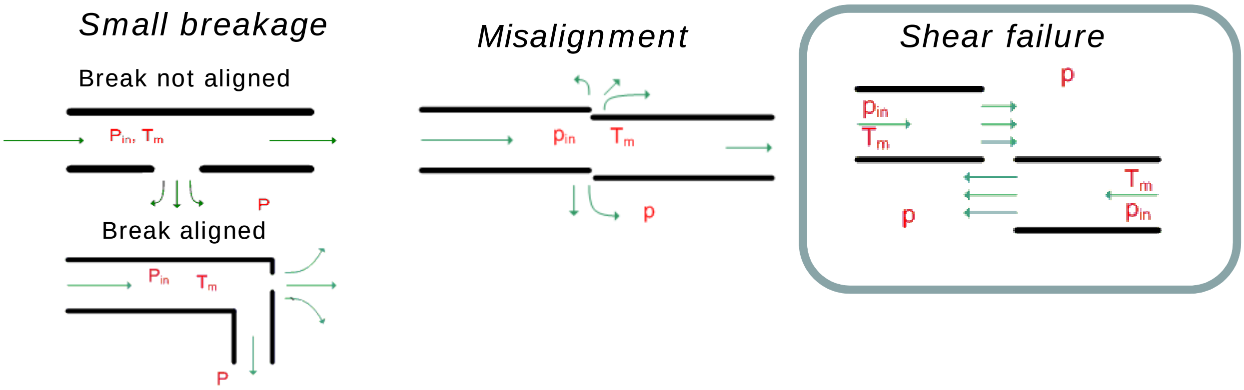


Figure 5. Assumption of the pipeline failure mechanism

Two failures location have been considered: (i) Failure in the main pipes; (ii) Failure in the mesh network. The failure in the main pipes results in gas leakage from a single trunk of pipe which is connected to the network. The shear failure in the mesh results in gas leakage from both sides of the pipes, therefore the total flow of gas released at the end of the transient discharge, will be equal to twice the flow released from each section.

5. PROTECTIVE SYSTEMS FOR THE GAS NETWORK

Four types of protective systems have been considered for the gas network in order to detect the optimal performance:

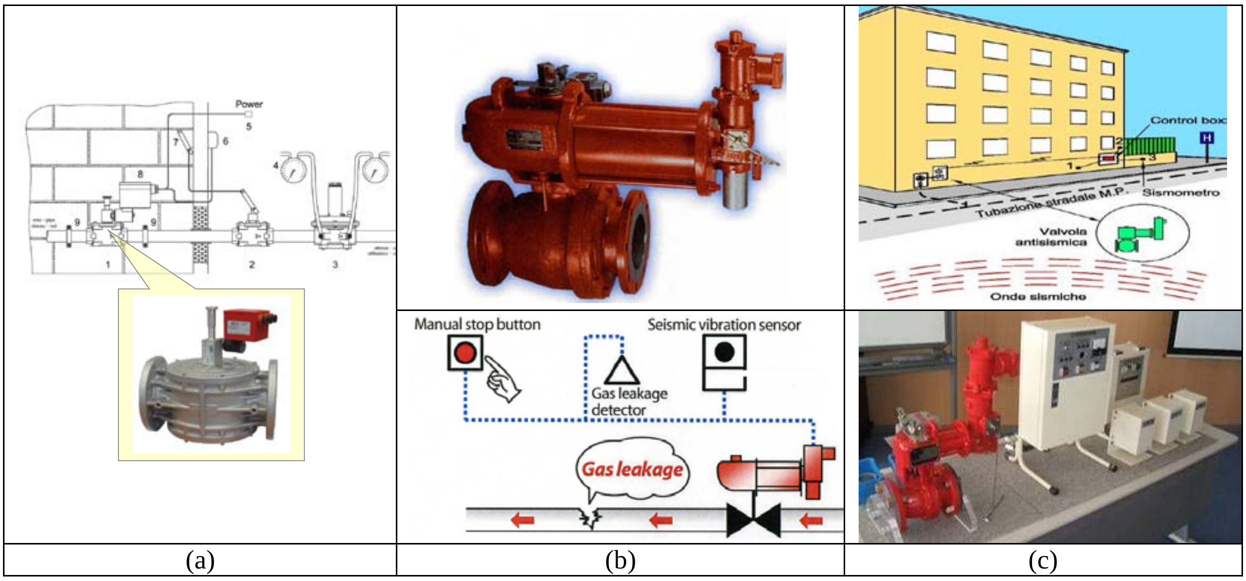
1. Automatic shut-off valves that work when predefined acceleration thresholds are exceeded.
2. Remote centralized gas detection valves, which are able to shut-off certain parts of the network to evaluate potential damage caused by earthquakes for example.
3. Automatic shut-off valves that work when predefined flow rates are exceeded, produced by an uncontrolled release of gas, for example due to the pipeline rupture;
4. Manual shut-off valves installed in correspondence of gas meter and/or underground gas connections.

The first type are solenoid valves with seismic sensors (Figure 6a) are able to shut-off the network when there is an earthquake event, or if there is a remote command. After the valve closes it can be opened only manually after inspection.

In the network there are also emergency shut off valves which are able to interrupt the gas flow in certain part of the network (Figure 6b).

The third protective system is made with automatic shut-off valves are inserted in the M/R stations which work when the flow rate increases due pipelines rupture.

Emergency shut-off valves (ESV) are usually installed to protect housing units and strategic buildings such as hospitals, schools, etc (Figure 6c). Near the end users can be found also the excess flow valves (EFV) which shut off the flow rate if the downstream flow is too high (Figure 7). They will automatically re-open again when the gas flow goes back to normal operating conditions.



(a) (b) (c)

Figure 6. (a) Solenoid valve with seismic isolator; (b) Isolation valves in the distribution network; (c) Emergency shut-off valves (ESV) installed near the end user

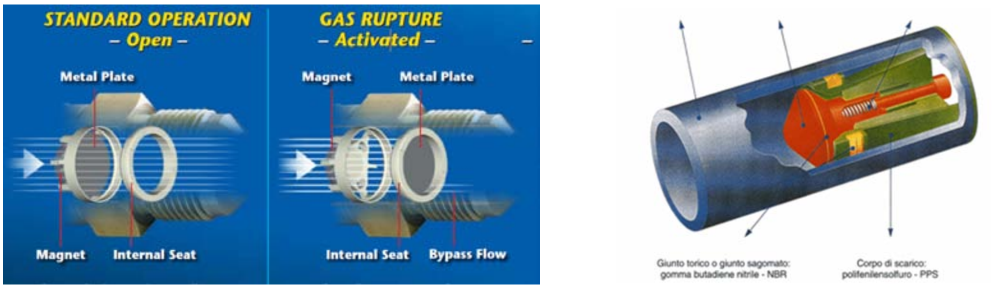


Figure 7. Excess flow valves (EFV)

6. CASE STUDY OF THE NATURAL GAS SUPPLY SYSTEM IN THE TOWN OF SULMONA IN ITALY

The distribution of gas involved the municipalities of Sulmona, Introdacqua, covering 96% of domestic consumption, while the remaining is manufactories' consumption. The connection of Sulmona and Introdacqua distribution medium-pressure network (MP=64bar) to the national high-pressure transmission lines is operated via three Metering/Pressure Reduction Stations, M/R Stations (RE.MI.) (Table 1; Figure 8).

Table 1 Re.Mi. M/R stations

Identification code	Location	DN	Nominal Flow for a Minimum pressure of 6bar	Maximum flow
IPRM 1	Introdacqua Via la Torre	DN50	4600 m^3/h	1734 m^3/h
IPRM 2	Sulmona Via del lavoro	DN80	11500 m^3/h	290 m^3/h
IPRM 3	Sulmona Via Lapasseri	DN100	18500 m^3/h	7380 m^3/h

RE.MI. stations are hosting internal regulators and mechanical equipment (heat exchangers, boilers and bowls) and the gas undergoes the following operations and processes: (i) gas preheating; (ii) gas-pressure reduction and regulation; (iii) gas odorizing; (iv) gas-pressure measurement. Two M/R/ stations (IPRM1 and IPRM3) are connected to the national network of SNAM pipelines which operates the high-pressure transmission lines. They are welded-steel pipes, with an internal diameter of *103.9 mm* and a thickness of *5mm*. The distribution network of the two municipalities has a total length of approximately *136.9km* of which *109.8k m* are steel coated and *27.1km* are polyethylene. Steel pipes have welded connections and are provided with a coating of bitumen-based material. The distribution network, consisting of steel pipes for a total length of about 110 km is currently protected cathodically with system of sacrificial sink at impressed current, equipped with automatic feeders.

7. NUMERICAL RESULTS

Different shear failures mechanisms in 14 locations of the gas network of the town of Sulmona Introdacqua were simulated (Figure 8) in the medium and low pressure network. Then for each damage scenarios the flow, pressure and speed of the gas inside the network was evaluated using the software SynerGee and results of the simulation were used to quantify the resilience index.

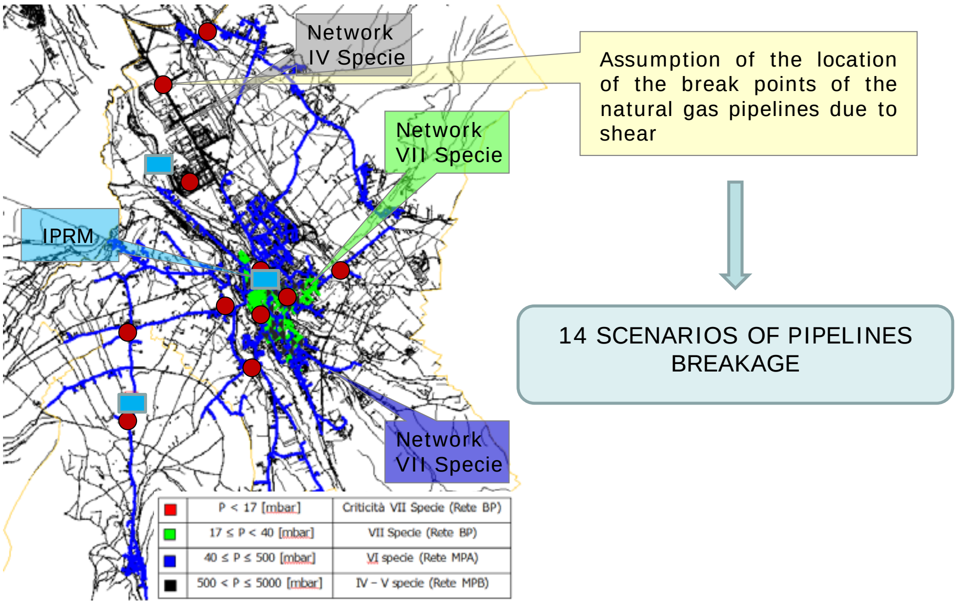


Figure 8. Sulmona gas network distribution

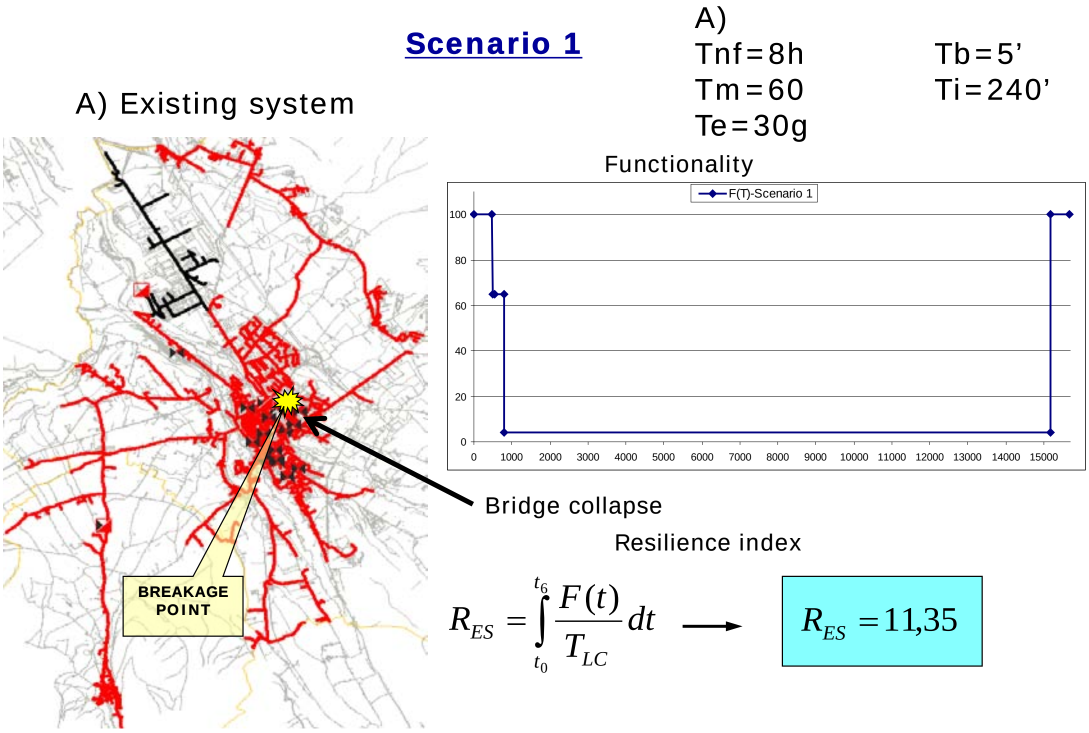
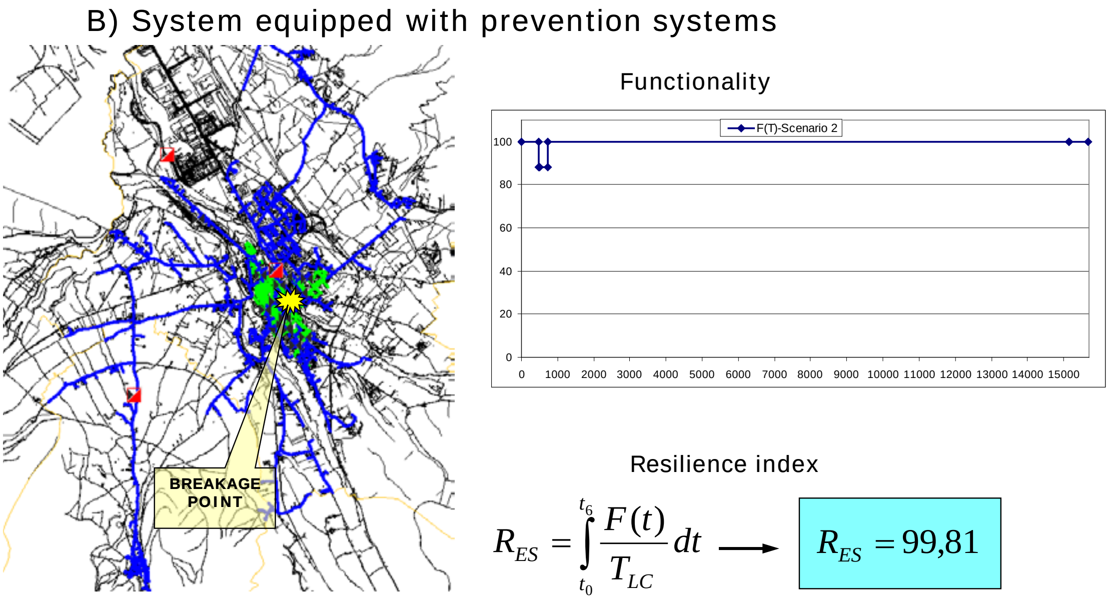


Figure 9. Bridge collapse scenario 1

Scenario 1-2-3-10 correspond to pipe shear failure due to bridge collapse. Scenarios 4-5-6-7 correspond to shear failure of pipe VI type (0.04<MOP<0.5 bar, where MOP=maximum operating pressure). Scenarios 8-9 correspond to shear failure of pipe IV type (1.5<MOP<5 bar). Scenarios 11-12-13-14 correspond to shear failure of pipe VII type (MOP<0.04 bar).

For each scenario simulation of the existing network and of the network retrofitted with emergency shutoff valves, which can be controlled remote and manually were performed. Each valve costs around *1000Euro*/each including the setup costs. A flow divider was setup for both RE.MI. stations which is able to control remote the gas flow reducing acoustic emissions and the quantity of gas used. Each system costs about *80000Euro*/each. For each pressure reduction group, control valves were set up to control remotely the gas flow. They also cost about 1000Euro/each.



$$R_{ES} = \int_{t_0}^{t_6} \frac{F(t)}{T_{LC}} dt \longrightarrow \boxed{R_{ES} = 99{,}81}$$

Figure 10. Gas network equipped with prevention systems

In summary n. *32* shut off valves were installed for *32000Euro*; n.*2* flow dividers for a total of *160000Euro*; n. *16* valves on the pressure reduction group system. As shown in Table 2 the network performs better for all the scenarios when prevention systems such as shutoff valves are installed in the network. Flow dividers are expensive, but they do not improve resilience during emergency as well as emergency shutoff valves. The scenario where the Resilience improvement is so evident is scenario 1-2-3 that correspond to bridge collapse (Figure 9, Figure 10). The most difficult parameter to simulate is the recovery time T_{re}, which corresponds to the time necessary to restore the gas network to the initial conditions. It is a parameter characterized by high uncertainties due to the difficulty to evaluate and distinguish between the shutoff time and the repairing time. From the simulated analysis the worst scenarios correspond to shear failures on the medium pressure network with respect to the low pressure network and the best retrofit strategy from the resilience point of view is to insert emergency shutoff valves in the network.

Table 2 Resilience index summary for different scenario events

RESILIENCE VALUES				
Scenario	Existing network	Network with prevention systems	Flow divider	Valve
1	11,35	52,63	11,45	52,53
2	11,80	99,81	11,83	99,77
3	11,35	97,60	11,45	97,50
4	34,44	94,75	34,87	94,32
5	34,44	89,65	34,87	89,42
6	17,35	81,02	17,53	80,83
7	14,46	94,03	14,61	93,89
8	94,30	97,04	94,73	96,61

9	94,30	97,04	94,73	96,61
10	11,35	99,42	11,45	99,32
11	83,33	95,81	83,38	95,76
12	80,78	92,03	81,21	91,60
13	80,98	94,34	81,38	93,92
14	81,27	94,95	81,62	94,59

8. CONCLUDING REMARKS

Currently they don’t exist models in literature to measure resilience of a gas network. The paper defines a framework to quantify resilience of gas network using an unique analytical function that combines information from technical and organizational fields, from seismology and earthquake engineering to social science and economics.

The framework integrates the information from these fields in a unique function that reach results that are unbiased by uninformed intuitions or preconceived notions of how large or how small the risk is.

The application of the methodology to the natural gas supply system is presented in order to show the implementation issues. Several scenarios with different failure mechanisms are simulated using the software SynerGee. Numerical analysis of the gas distribution network of the town of Sulmona in Italy show that the best retrofit strategy in order to improve the resilience of the network can be achieved by including emergency shutoff valves directly in the pipes.

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