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RESEARCH PAPER

Resilient Natural Gas Transmission Network Design Optimization: A Case Study

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Abstract

Nowadays, designing the resilient natural gas transmission network is an important and essential issue for industry experts and policymakers due to great economic, health, security and social losses created by relevant disruptions. This paper develops a two-stage approach for the design of resilient natural gas (NG) transmission network. In the first stage, the risk of each pipeline route is calculated based on distances of diffusion concentration. In the second stage, a multi-objective mixed possibilistic-stochastic programming model is presented to enhance the resiliency of the natural gas network by utilizing proactive strategies such as parallel pipeline, fortification and back-up turbo compressor under demand uncertainty and disruption risks. In addition, the proposed model considers different failure modes of the pipeline. Finally, the model validation is done by the data of a real case study. Our analysis shows that the performance of the natural gas transmission network is highly vulnerable to demand fluctuations. Also, results indicate that employing both pipeline fortification and back-up pipeline strategies have numerous impacts on the resiliency of the NG network. Important managerial insights are obtained from the model implementation in a case study.

Keywords:
Natural Gas Transmission Network;
Resiliency;
Disruption Risks;
Gas Leakage;
Multi-Objective Optimization

Introduction

The natural gas supply chain (NGSC) is accounted as one of the vital infrastructures for any country due to the dependency of many industries and fewer environmental emissions in the production of carbon dioxide than other fossil fuels ([16]). The complexity and extent of the natural gas (NG) network has led to more attention to supply chain management (SCM) in the NG industry ([34]). Dispatching centers support the main objectives of NGSC including the minimization of total costs and satisfying the demand by managing information, financial and, material flows among production fields and distribution centers. NGSC can be classified into six levels that are connected with pipelines. As illustrated in Fig. 1, in the first level, the oil and NG wells as well as imported materials supply the required NG for refineries. In the second level, refineries purify the NG and then transfer it to compressor stations at the third level. Compressor stations boost the losing pressure of NG due to relevant friction. Finally, in the fourth level, NG with the appropriate pressure range is sent to storage tanks and the rest to the fifth level i.e., city gate stations in order to meet the consumers demand in the sixth level ([32] ,[4]).

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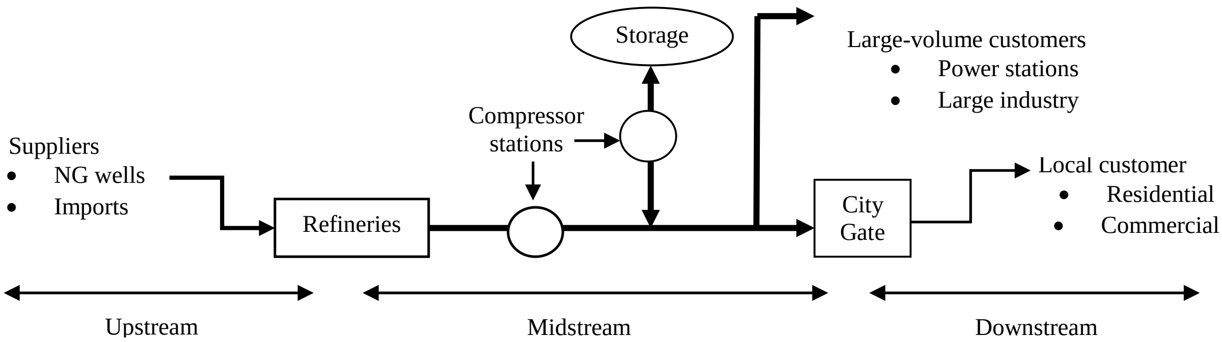

Fig. 1. Schematic view of NG network

NGSC planning decisions can be categorized into three levels, including strategic, tactical and operational decisions ([24]). Strategic Decisions include installing and locating pipelines and determining the capacity and location of compressor stations. The flow rate in each pipeline, the pressure in each node are the most important tactical decisions. Finally, operational decisions include determining the amount of gas consumed in compressors and scheduling network facilities and equipment. Appropriate decision-making in strategic, tactical, and operational levels entails the employment of powerful mathematical models not only to earn a well-structured NGSC but also to best the strategic and operational plans ([10] ; [9]). The NG pipeline network design has a significant impact on optimization and resiliency of NGSC. Therefore, the evaluation and analyses of NG pipeline routes with thermodynamic and physical criteria are essential before selecting and installing them.

NGSC is a risky industry due to the presence of hydrocarbon compounds in the raw material of NG and doing all the operations in high temperature and pressure that make the explosion and release of toxic substances ([2]). On the other hand, the complexity and expansion of the NG network makes it more vulnerable and cause damage to the production process, workforce, chemicals, and equipment that consequently, leads to the loss of a large portion of the national capital. Therefore, identification, evaluation, and prioritization of risks in this industry is the first step in designing the NGSC network ([31]). NGSC problem is threatened by operational and disruption risks. Operational risks are usual uncertainties that occur in high likelihood with low effects, such as a sudden increase in NG demand, supply and cost. Disruption risks happen in low likelihood but severe consequences which fall into three groups: (1) natural disasters (e.g. earthquake, flood and terrorist attacks), (2) human-made threats e.g. international boycott) and (3) technological threats (e.g. Failure of natural gas pipeline and compressor station) ([27]).

The happening of these risks has adverse effects in the financial health and operation process, which can be referred to as decreasing consumer consent, lack of trust in the firm, price swell, and longer lead time. Therefore, the supply chain should be planned appropriately in order to deal with different risks and uncertainties ([19]). This issue is more critical for vital infrastructures such as energy (i.e., NGSC), transportation, and telecommunications due to their primary role in the survival of communities ([18]). For example, a disruption in NGSC can stop the activities of residential consumers, industrials and power station which result in a decrease of quality of life and economic growth of societies. NG buried pipeline and aboveground facilities such as compressor stations, city gate stations and NG storage tanks are sensitive to seismic events that loss their functionality due to physical damage. Such vulnerabilities have other consequences such as explosion, fires, and environmental pollution besides economic losses. For example, the earthquake in Kanto Japan leads to the failure of four thousand NG pipelines in 1923 ([11]). Therefore, the NG supply chain network requires the utilization of proactive resilience strategies to resist different types of risks. [7] defined resiliency as the capability of a system to restore its performance to the primary state, even better conditions against disruption risks.

Supply chains become resilient by applying different strategies that can be categorized in eight groups according to the relevant literature: flexibility, redundancy, agility, velocity, visibility, collaboration, network structure, and culture ([13]). These proactive strategies are generally in conflict with cost objective. Resilience in NGSC can be defined in production (upstream), transmission (midstream), and distribution (downstream) sectors. Generally, incidents like an earthquake, flood, explosion, snow, heavy rain, and power outage, lack of equipment and spare parts and strike staff can disrupt the performance of these levels and make the situation difficult to meet the demand. For example, disruption in refineries causes the stop or decrease in capacity of production and therefore, results in miss balancing in gas supply and demand. Failure of compressor stations and pipeline due to corrosion, leakage and explosion in transmission lines can reduce the natural gas flow rate and the emergence of regional crises. Finally, disruption in the distribution pipeline will immediately and directly affect domestic and commercial consumption ([36]). Therefore, considering resilience strategies in NGSC is inevitable to withstand disruption. Resilience in the NG transmission network (NGTN) is defined as the ability of the NG network to transfer NG from refineries and imports to consumers and exports in abnormal conditions and return to normal performance in the shortest time.

The purpose of this research is to design a resilient NGTN according to relevant challenges and risks by selecting the most effective and efficient resiliency strategies. Despite the importance of NGSC resiliency, research efforts on this subject are very limited. Reviewing the relevant literature shows that only a few papers modeled resiliency strategies in the NGTN design problem. Also, most of these papers did not measure the impact of resiliency strategies on network vulnerability. The NGTN may be affected by both disruption (e.g., pipeline failure) and operational (e.g., usual fluctuations in demand) risks. The existed researches in the literature only consider one of the above-mentioned risks.

To fill the literature gap, this paper presents a two-stage approach to provide a resilient NGTN under disruption and operational risks which is able to reply quickly to shortages. In the first stage, the evaluation and quantification of risk at each pipeline route are done. Using the obtained risk coefficient, in the second stage, a stochastic-possibilistic optimization model is developed in order to specify the design decisions and the optimal resilience strategies. The proposed model is able to consider different resilience strategies and both partial and full disruption of pipelines due to different modes of failure. The efficiency of the developed model is evaluated via data collected by Iran Natural Gas Company that attempts to properly meet its consumer demands by designing the safest pipeline location and the most resilient NGTN.

The remainder of the paper is organized as follows. Section 2 reviews related works on NGTN design problem under operational and disruption risks. The problem definition and the proposed mathematical model are described in Section 3. Explanations about the case study are provided in Section 4. Computational results, sensitivity analyses, and interpretation of numerical results as well as some managerial insights are reported in Section 5. Finally, in Section 6, conclusions and suggestions for future studies are provided.

Literature review

This section reviews the related papers in the content of resilience NGTN design under operational and disruption risks in two different subsections. Then, literature gaps are identified using the reviewed papers.

Resilient Natural gas transmission network design under operational risks

Due to unpredictable weather conditions, price, population growth and unstable economic situation, the NGTN is faced with a high degree of uncertainty. Parameters such as NG demand, NG supply, NG purchase price, transmission cost and capacity are highly tainted by uncertainty. In general, randomness and epistemic uncertainty are two types of uncertainty in input parameters. Uncertainty is a type of randomness if there is frequent, available, and historical data about the uncertainty parameter. Stochastic programming can be applied to deal with this type of uncertainty. On the other hand, epistemic uncertainty existed when enough and reliable historical data about the uncertain parameter is not available. Possibilistic programming approach is usually used to cope with this type of uncertainty ([3]).

Amongst the reviewed works, [38] , [1] , [5] , [6] , and [17] consider the operational risks in NGTN. [38] formulated a stochastic optimal control model to optimize NG network inventories under demand uncertainty. [1] presented two conflict objective functions as minimizing cost and greenhouse emission for NGTN under demand, cost and capacity uncertainty. A fuzzy possibilistic programming approach was used to deal with operational risks. [5] mentioned that uncertainty of NG demand should be considered to increase the robustness of the daily planning of NGTN. The proposed model in this research aims to minimize power consumption. They developed an optimization algorithm based on stochastic-chance-constrained programming to deal with demand uncertainty. [6] investigated the role of the line-pack strategy in an uncertain parameter of demand. Stochastic programming is used to deal with demand uncertainties that provided an optimal way to determine the minimum pressure buffer. [17] proposed a two-stage approach to design the NGTN. In the first phase, the throughput of the pipeline is determined by predicting the demand in the future. Then, a mathematical model is presented to design the NG pipeline network that is solved with a particle swarm optimization algorithm with simulation annealing.

Resilience Natural gas transmission under disruption risks

Generally, strategies such as redundancy, flexibility, the physical structure of the network, and corporation culture are common ways to increase the supply chain resiliency ([13]). Despite the growing attention to resiliency in the various supply chain planning decisions in recent years, there are only a few papers that address the issue of resilience in NGTN. Amongst the relevant works in the literature, only [30] , [1] , [15] , [21] , [39] , [22] and [28] presented quantitative models for resilience strategies in NGTN. However, they failed to measure the impact of each strategy on the network resiliency. [30] developed a mathematical model to design NGTN in order to minimize the total cost. They employed NG wells and storages as multiple supplier's strategies to satisfy customer demands. [1] consider economic and environmental objectives to optimize NGSC. They applied NG storage to overcome the sudden increase in demand. [15] proposed a model in order to maximize the flow rate and the line pack while minimizing the fuel consumption in NGSC. They used a line-pack strategy to increase NG network resiliency. [21] applied a multi-period mixed-integer nonlinear programming formulation to optimize a pipeline network for gas distribution. Their model is capable of supplying natural gas from other sources such as external gas networks, injected biogas, and gasified liquefied natural gas (LNG) at terminals. They applied some resiliency strategies such as parallel pipeline and re-gasify LNG. [39] developed a mathematical model to optimize the operation of multi-state NGSC under uncertainty of demand and purchase price. They used four transport carriers, three states of natural gas, liquefied natural gas (LNG), compressed natural gas (CNG), and seasonal storage as resiliency strategies. [22] presented a mathematical model to find the best supplier and efficient way to transport the NG to consumers. They considered three alternative products as a resiliency strategy in which gas may be supplied by pipeline, as a CNG in containers or as LNG by tank Trucks with the aim of the lowest overall cost. [37] developed a multi-objective and multi-period model to optimize sustainable-resilience NGSC by considering the environmental and economic costs, total revenue of gas products and the penalty per underutilized capacity as well as the service level. [28] investigated the resiliency of the European Union NG network using a linear programming model under an unexpected increase in demand. LNG and NG storage were considered as resilience strategies.

Some research papers such as [31] , [8] , [12] , [35] and [29] investigated the resiliency of NGSC via qualitative methods. [31] studied the practical solutions for building resilience NG and oil supply chain against exogenous security threats. They concluded that a combination of some resilience strategies, including portfolio diversification, flexible contracts, and transport capacity planning and safety stock is needed to appropriately deal with disruption. [8] proposed a new index to measure the performance of the gas distribution network, which is a function of pipeline length and flow rate. The restoration phase also is attended to assess the developed index. They simulated different failure modes of pipeline and concluded that installing the emergency shutoff valves along pipelines is the most effective strategy to enhance the resiliency of NGSC. [12] introduced a systematic procedure for evaluating the reliability in the supply network of natural gas pipelines that significantly can be enhanced by standby units in compressor stations and capacity dispatch based on the topological structure. [29] developed a systematic method based on stochastic processes, graph theory and thermal-hydraulic simulation to analyze the reliability of NG pipeline networks considering uncertainty, complexity, and physical constraints. They stated that components situation and the network structure affect the supply capacity of a pipeline network. [35] proposed a methodology to assess NG supply reliability of pipeline network due to supply capacity and market demand uncertainties.

Gap analysis

Since natural gas accounts for one of the most consumed energy sources in daily activities, the main mission of the NGTN is to meet the consumer demand, which can only be met appropriately by a resilient NG network. However, none of the aforementioned works addresses the resiliency of NGTN design under possible disruptions. Also, most of the papers did not provide quantitative measures and models for the resiliency of NGTN to assess the effects of the proactive resiliency strategies on NGTN planning decisions. Only a handful of studies have considered some proactive resilience strategies such as parallel pipeline as back up pipeline, fortification of a pipeline, keeping standby turbo compressor in compressor station to withstand against disruption. Most of the existing works do not study the NGTN with both disruption and operation risk. Eventually, few papers have considered the different failure modes of the pipeline such as partial or complete disruption because of small leakage or shear failure. Despite the importance of the risk of each pipeline route before installation in NGTN design, only a few articles have addressed this issue.

To fill the literature gap, this paper presents a two-stage approach to optimize the design of resilient NGTN under operational and disruption risks. In the first stage, the risk of each pipeline route due to leakage accident is evaluated. In the second stage, an MINLP model is developed to design a resilient NGTN under disruption and operational risks. In order to find a global optimal solution due to the nonlinearity of the developed model, the piecewise linear approximation is employed. To reduce the computational complexity, the compressor stations arcs are considered as nodes. The proposed model utilizes proactive strategies in the design phase such as the route risk for installing the pipeline, parallel or back-up pipeline, fortification of the pipeline, keeping standby turbo compressor in the compressor station to enhance the resiliency of NGTN in the operational phase. Furthermore, the model can appropriately cope with seasonal changes as uncertainty in NG demand and provides information about the effects of each strategy on two conflict objective functions. These features enable the model to enhance the resiliency of the NG transmission network against different types of risk and different modes of pipeline failure.

Problem description

As illustrated in Fig. 2, the studied NGTN consists of refinery nodes, import nodes, compressor station nodes, Transmission nodes and demand nodes that are connected by pipelines. Refinery nodes start the flow in the network and send the processed NG to the receiving and sending nodes that are known as the transmission and demand node. NG loses its pressure due to friction with the wall of pipelines through the network. Therefore, compressor stations with a number of turbo compressors are required to install between pipelines to ensure the smooth flow. It is assumed that NGTN operates in a steady state and an isothermal situation. The direction of positive flow which is influenced by pressure difference, diameter and length of the pipe and gas properties can change from one period to another due to a varying demand. Each of network nodes must receive NG flow with the appropriate pressure, which is restricted to the minimum and maximum permissible pressure value. The outlet pressure of compressor stations is assumed to boost the pressure at most 60% more than the inlet pressure. The location of pipelines affects the surrounding communities due to different failure modes that cause explosion and fires. For this purpose, a safety distance is set up to prohibit possible damages from pipelines to adjacent points. Natural gas pipeline privacy rules approved 250 meters for this maximum limit. Hence, Transmission Company intends to evaluate the risk of each pipeline route before installing, and then decide to install the lowest risk value.

The performance of the NGTN can be disrupted by pipelines challenges and sudden increase in consumption. Pipelines are vulnerable to different disruptions. the disruption risks are handled based on independent and discrete scenarios with a pre-defined probability of incident that exclusively can lead to one kind of pipeline failure mechanism as small leakage or shear failure in which influence the capacity of pipelines partially or completely, respectively. Also, with decreasing the temperature in cold season, the volume of NG flow increases in the network. so, each of compressor stations need to standby more turbo compressor as a backup to deal with emergency situations. In order to withstand these challenges, NG Transmission Company can apply some resilience strategies as follows:

- ❖ Fortifying of the pipeline at different levels which have different cost and impact on the capacity.
- ❖ Using parallel pipelines as a back-up pipelines which could be used after any disruption of the main pipeline.
- ❖ Standby one or two turbo compressor stations as spare in each compressor station, which will be used in an emergency situation.
- ❖ Considering different modes of failure pipeline which impose on the capacity of pipeline partially or completely.
- ❖ Coping with consumer challenges as uncertainty in natural gas demand.

Fortified pipelines are more robust to disruptions under different scale which lose their capacities less than unfortified pipelines. It is assumed that backup pipeline is installed when a primary pipeline located. To consider a realistic situation, backup pipeline also disrupts by disruption risks. This problem aims to determine decisions before occurring the scenario such as the location of main and backup pipeline, the fortification level of each installed pipeline, the location and number of turbo compressor in compressor station, and after happening the scenario such as the direction of flow in pipeline, the amount of NG flow transferred between two nodes and inlet and outlet pressure of each node in a way that the NG transmission network stays resilient to disruptions at the lowest cost.

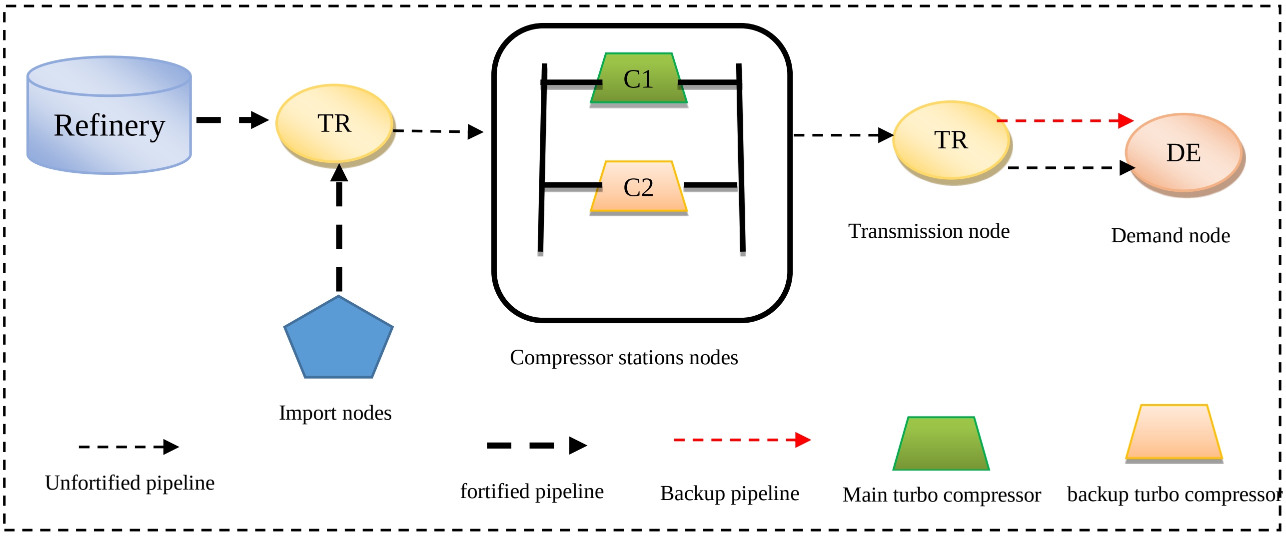

Fig. 2. The structure of the studied NG transmission network

The proposed two-stage methodology

To address the above-mentioned problem, a two-stages methodology is proposed that aims to minimize the total cost and vulnerability under different scale scenarios. Fig. 3 demonstrate the phases of the two-stage approach. The first stage evaluates the risk of the potential pipeline routes according to the diffusion concentrations of NG based on distance. Using Aloha software, the risk coefficient of potential pipelines is achieved. More diffusion distance, the higher risk coefficient of that pipeline. In the second stage, a stochastic, multi-objective, multi-period model is proposed in which the pipeline's risk coefficient obtained from the first stage are inserted as input parameters. Each stage is described in the following section.

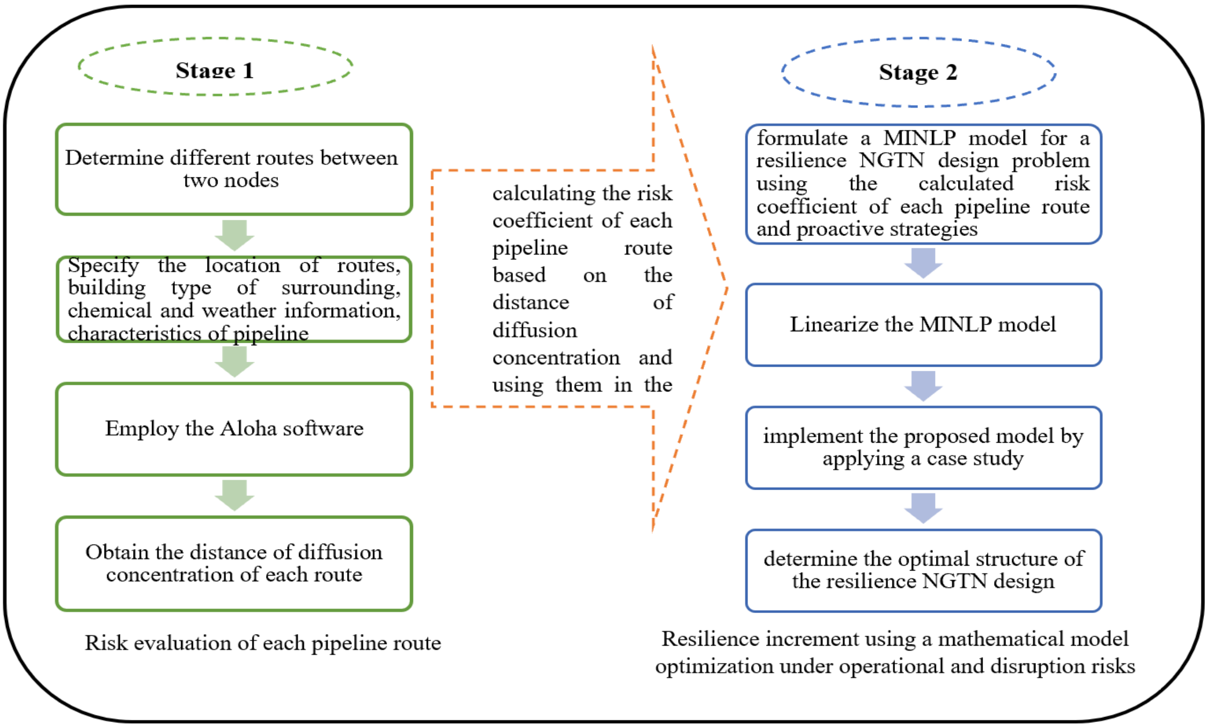

Fig. 3. Stages of the proposed methodology used for the design of concerned NGTN.

Risk evaluation

Now considerable numbers of NG transmission pipelines are located in the densely populated areas of cities that create dangers for the people living in these areas. Therefore, one solution is to evaluate the risk of each pipeline route before installing and then choose among them with the least risk. For this purpose, ALOHA software is used to simulate the diffusion statuses after NG leakage in each region ([33]). It provides the diffusion concentrations of NG based on distance. Aloha evaluates risks such as toxicity, flammability, thermal radiation, and explosion related to chemical releases. This software uses some criteria such as location, building type, building surroundings, chemical information (e.g., methane), weather information (wind speed, ground roughness), type of source (e.g., direct, gas pipeline and tank) and pipeline's characteristics (diameter, pipe length, pipe roughness, pipe pressure, pipe temperature, hole size) to determine the hazardous chemical concentration at any location in the local community from the source of the release. The damage distances for NG pipelines leakage are divided into three categories threat zone based on ALOHA software output. The red threat zone shows highest exposure level (15%), and the orange threat zone predicts medium exposure level (5%-15%). Finally, the yellow threat zone displays a low exposure level (5%). Noteworthy, the amount of NG in the air should reach 5% to 15% its volume fraction, then explosion occur.

Assuming Mazandaran province as the north part of Iran country should be installed NG pipeline. The diameter of the gas pipeline is 30in, and the operating pressure of gas pipeline 1050 psi. Weather condition is that east wind is 5 m/s, the temperature is 15 centigrade, ground roughness is Urban or forest, hole size is 1200 mm, the grade of atmospheric stability is c, and no temperature inversion when the NG leaks. The simulation result about the distances of diffusion concentrations based on three threat zone is explained in Section 5.1.

The proposed mathematical model

In this phase, the mathematical model of NGTN design is formulated as a two-stage scenario-based stochastic programming in which the obtained risk coefficient of potential pipelines from the Aloha software are insert as input parameters. In the following, the sets, parameters and decision variables used in the proposed mathematical model are presented.

Sets	
NR	Set of refineries
NI	Set of imports
ND	Set of demands
NC	Set of compressor stations
N	Indexes of Nr, NI, Nd,Nc
U	Set of turbo compressor in each compressor stations
$E, \acute{E}$	Set of Fortification levels
T	set of periods
S	Set of disruption scenarios
parameters	
f_{et}^{p}	Fixed cost of locating a pipeline with fortification level e in period t
f_{t}^{c}	Fixed cost of locating one turbo compressor in a compressor station in period t
o_{t}^{p}	Operating cost of one km of a pipeline arc in period t
o_{t}^{c}	Operating cost of one turbo compressor in a compressor station in period t
c_t	Transportation cost in period t
h_{it}	Purchased cost of natural gas by refineries $i \epsilon NR$ in period t
hi_{it}	Supply cost by imports $i \epsilon NI$ in period t
AP_{ij}	1 if a connection is allowed between nodes $i \in N, j \in N$, otherwise 0
l_{ij}	Distance between nodes $i \in N, j \in N$
$\widetilde{De}_{jt}$	Demand of customers $j \in ND$in period t
cap_{ijt}	Capacity of the total possible flow between nodes $i \in N, j \in N$in period t
ca_i	Capacity of supply nodes $i \in NR \cup NI$
ϑ_{ijes}	Percentage of lost capacity a pipeline with fortification level e between nodes $i \in N, j \in N$ under scenario s
ν	Capacity of one turbo compressor in compressor station
wp	the weight coefficient of each part of the second objective function
P_{max}	Maximum permissible gas pressure in the network
P_{min}	Minimum permissible gas pressure at a demand node
ω	Maximum pressure rise multiplier at a compressor
τ_{ij}	Risk coefficient resulting pipeline construction between nodes $i \in N, j \in N$
π_s	Probability of occurrence of scenario $s \in S$
α_{ijtsk}	Lower bound of flow in interval k between nodes $i \in N, j \in N$ in period t under scenario s
β_{ijtsk}	Upper bound of flow in interval k between nodes $i \in N, j \in N$ in period t under scenario s
A_{ijtsk}	The square of lower bound of flow in interval k between nodes $i \in N, j \in N$ in period t under scenario s
B_{ijtsk}	The square of upper bound of flow in interval k between nodes $i \in N, j \in N$ in period t under scenario s
$simaxrisk$	Maximum possible value of risk related to pipeline installation
$siminrisk$	Minimum possible value of risk related to pipeline installation
Binary variables	
Y_{ijet}	1 if a new pipeline is located between nodes $i \in N$ and $j \in N$, $i < j$, with fortification level e in period t, 0 otherwise

V_{ijet}	1 if a backup pipeline is located between nodes $i \in N$ and $j \in N$, $i < j$, with fortification level e in period t, 0 otherwise
CS_{iut}	1 if a compressor station $i \in NC$with type u is locatedin period t, 0 otherwise
W_{ijet}	1 if NG flows in a pipeline with fortification level e from $i \in N$ to $j \in N$ in period t, 0 otherwise
G_{ijet}	1 if NG flows in a backup pipeline with fortification level e from $i \in N$ to $j \in N$ in period t, 0 otherwise
Continues variables	
x_{ijst}	Mass flow rate in pipeline between nodes $i \in N$ and $j \in N$ under scenario $s$in period t
Q_{ijst}	Mass flow rate in backup pipeline between nodes $i \in N$ and $j \in N$ under scenario $s$in period t
p_{ist}^{in}	Inlet pressure of nodes$i \in N$under scenario $s$in period t
p_{ist}^{out}	Outlet pressure of nodes $i \in N$under scenario sin period t

$$\begin{aligned} minZ_1 = &\sum_{i\epsilon N}\sum_{j\epsilon N}\sum_{e}\sum_{t}\left(Y_{ijet}-Y_{ijet-1}\right)f_{et}^{p}l_{ij} + \sum_{i\epsilon N}\sum_{j\epsilon N}\sum_{e}\sum_{t} Y_{ijet_{ijet}} l_{ij} o_t^p \\ &+ \sum_{i\epsilon N}\sum_{j\epsilon N}\sum_{e}\sum_{t}\left(V_{ijet}-V_{ijet-1}\right)f_{et}^{p}l_{ij} + \sum_{i\epsilon N}\sum_{j\epsilon N}\sum_{e}\sum_{t} V_{ijet} l_{ij} o_t^p \\ &+ \sum_{i\in NC}\sum_{u\in U}\sum_{t\epsilon T} U(CS_{iut}-CS_{iut-1})f_t^c + \sum_{i\epsilon NC}\sum_{u\in U}\sum_{t} UCS_{iut}o_t^c \\ &+ \sum_{i\epsilon N}\sum_{j\epsilon N}\sum_{s}\sum_{t}(x_{ijst}+Q_{ijst})c_t \\ &+ \sum_{i\epsilon NR}\sum_{j\in N}\sum_{s}\sum_{t}(x_{ijst}+Q_{ijst})\, h_{it} + \sum_{i\epsilon NI}\sum_{j\epsilon N}\sum_{s}\sum_{t}(x_{ijst}+Q_{ijst})\, hi_{it} \end{aligned} \quad (1)$$

$$minz2 = (wp)res_s + (1-wp)risk_t \quad (2)$$

$$res_s \geq \left[\frac{\sum_j \sum_t (\widetilde{De}_{jt} - \sum_{i\epsilon N} x_{ijst} - \sum_{i\epsilon N} Q_{ijst} + \sum_{i\epsilon N} x_{jist} + \sum_{i\epsilon N} Q_{jist})}{\sum_j \sum_t \widetilde{De}_{jst}}\right] \quad \forall s \in S \quad (3)$$

$$risk_t \geq \frac{simaxrisk - \sum_{i\epsilon N}\sum_{j\epsilon N}\sum_{e} \tau_{ij}\left(Y_{ijet}+V_{ijet}\right)}{simaxrisk - siminrisk} \quad \forall t\epsilon T \quad (4)$$

$$p_{ist}^{out} = P_{max} \quad \forall i\epsilon NR, s \in S, t\epsilon T \quad (5)$$

$$p_{ist}^{in} \geq P_{min} \quad \forall i\epsilon Nd, s \in S, t\epsilon T \quad (6)$$

$$p_{ist}^{out} \leq P_{max} \quad \forall i\epsilon Nd, s \in S, t\epsilon T \quad (7)$$

$$\sum_{e} Y_{ijet} \leq AP_{ij} \quad \forall i,j\epsilon N, t\epsilon T \quad (8)$$

$$Y_{ijet} \geq Y_{ijet-1} \quad \forall i,j \in N, i<j, e \in E, 1<t\leq T \quad (9)$$

$$V_{ijet} \geq V_{ijet-1} \quad \forall i,j \in N, i<j, e \in E, 1<t\leq T \quad (10)$$

$$V_{ij\acute{e}t} \leq \sum_{e} Y_{ijet} \quad \forall i,j \in N, i<j, \acute{e} \in E, t\epsilon T \quad (11)$$

$$W_{ijet} + W_{jiet} \leq Y_{ijet} \quad \forall i,j\epsilon N, i<j, e \in E, t\epsilon T \quad (12)$$

$$G_{ijet} + G_{jiet} \leq V_{ijet} \quad \forall i,j \in N, i<j, e \in E, t\epsilon T \quad (13)$$

$$\sum_{e}(W_{ijet} + W_{jiet}) \leq 1 \quad \forall i,j \in N, i<j, t\epsilon T \quad (14)$$

$$\sum_{e}(G_{ijet} + G_{jiet}) \leq 1 \quad \forall i,j \in N, i<j, t\epsilon T \quad (15)$$

$$x_{ijst} \leq cap_{ijt} \sum_{e} W_{ijet}(1-\vartheta_{ijes}) \quad \forall i,j \in N, s \in S, t\epsilon T \quad (16)$$

$$Q_{ijst} \leq cap_{ijt} \sum_{e} G_{ijet}(1 - \vartheta_{ijes}) \qquad \forall i,j \in N, s \in S, t\epsilon T \qquad (17)$$

$$\left(\sum_{i\epsilon N \nexists (NR,NI)} x_{ijst} + \sum_{i\epsilon N \nexists (NR,NI)} Q_{ijst} \right) - \left(\sum_{i\epsilon N \nexists (NR,NI)} x_{jist} + \sum_{i\epsilon N \nexists (NR,NI)} Q_{ijst} \right) \geq \widetilde{De}_{jt} \qquad \forall j \in Nd, s \in S, t \in T \qquad (18)$$

$$\left(\sum_{j \in N} x_{ijst} + \sum_{j \in N} Q_{ijst} \right) \leq ca_i \qquad \forall i \in Nr, s \in S, t \in T \qquad (19)$$

$$\left({p_{ist}^{out}}^2 - {p_{jst}^{in}}^2 \right) - \delta_{ij}\left(x_{ijst}\right)^2 \geq M_1\left(\sum_{e} W_{ijet} - 1\right) \qquad \forall i,j \in N, s \in S, t\epsilon T \qquad (20)$$

$$\left({p_{ist}^{out}}^2 - {p_{jst}^{in}}^2 \right) - \delta_{ij}\left(x_{ijst}\right)^2 \leq M_1\left(\sum_{e} W_{ijet} - 1\right) \qquad \forall i,j \in N, s \in S, t\epsilon T \qquad (21)$$

$$\left({p_{ist}^{out}}^2 - {p_{jst}^{in}}^2 \right) - \delta_{ij}\left(Q_{ijst}\right)^2 \geq M_1\left(\sum_{e} G_{ijet} - 1\right) \qquad \forall i,j \in N, s \in S, t\epsilon T \qquad (22)$$

$$\left({p_{ist}^{out}}^2 - {p_{jst}^{in}}^2 \right) - \delta_{ij}\left(Q_{ijst}\right)^2 \leq M_1\left(\sum_{e} G_{ijet} - 1\right) \qquad \forall i,j \in N, s \in S, t\epsilon T \qquad (23)$$

$$\sum_{u \in U} CS_{iut} \leq 1 \qquad \forall i \in NC, t\epsilon T \qquad (24)$$

$$CS_{iut-1} \leq CS_{iut} \qquad \forall i \in NC, u \in U, t\epsilon T \qquad (25)$$

$$p_{ist}^{out} \leq (1+\omega) p_{ist}^{in} + M_2\left(1 - \sum_{u} CS_{iut}\right) \qquad \forall i \in NC, s \in S, t\epsilon T \qquad (26)$$

$$p_{ist}^{out} \leq p_{ist}^{in} + M_2\left(\sum_{u} CS_{iut}\right) \qquad \forall i \in NC, s \in S, t\epsilon T \qquad (27)$$

$$p_{ist}^{out} \geq p_{ist}^{in} \qquad \forall i \in NC, s \in S, t\epsilon T \qquad (28)$$

$$\sum_{i \in N} x_{ijst} \leq \nu \sum_{u\epsilon U} U.CS_{jut} \qquad \forall j \in Nc, t\epsilon T \qquad (29)$$

$$p_{ist}^{out} = P_{max} \qquad \forall i\epsilon NI, s \in S, t\epsilon T \qquad (30)$$

$$\left(\sum_{j \in N} x_{ijst} + \sum_{j \in N} Q_{ijst} \right) \leq ca_i \qquad \forall i \in NI, s \in S, t \in T \qquad (31)$$

$$p_{ist}^{in}, p_{ist}^{out}, x_{ijst}, Q_{ijst} \geq 0 \qquad (32)$$

$$W_{ijet}, G_{ijet}, CS_{iut}, Y_{ijet}, V_{ijet} \epsilon \{0,1\} \qquad (33)$$

The objective function (1) aims to minimize the entire expenses of NGTN design under different scenarios. The first term expresses the installation cost of the main pipeline, which is a function of the pipe length and fortification level. The second term represents the operating cost of the main pipeline, like maintenance, utility, and transmission. The third and fourth terms state the installation and operating costs of the back-up pipeline, respectively. The fifth term expresses the construction cost of the compressor station, which depends on the installed power and number of turbo compressors. The sixth term accounts for the operating cost of compressor station, which is related to electricity and maintenance costs. The seventh term states the NG transportation cost through a section of pipeline. The eighth term indicates the NG purchased cost by the refinery. The last term expresses the NG supply cost by importation. The objective function (2) describes the vulnerability of NGTN design through minimizing the maximum ratio of the NG shortage to the total demand in each scenario and total risk due to pipeline installation in each period that is defined in Eqs. 3 and 4, respectively. wp is the weight coefficient of the service continuity (first part of the second objective function) and $(1 - wp)$ related with the risk pipeline installation (the second part of the second objective function) which is determined by decision-makers (DMs) opinions. It is obvious that the higher the weight coefficient wp, the service continuity part has more important. Parameter $siminrisk$ is the minimum possible value of risk related to pipeline installation and it is calculated by solving the model only with the second part of the second objective function i.e., the total risk. Also, $simaxrisk$ is the maximum possible value of risk related to pipeline installation and it is calculated by the sum of the total allowed pipeline routes along with their risk coefficient.

Eq. 5 ensures that the outlet pressure at the refinery node should be the maximum permitted value. Eqs. 6 and 7 indicates that the input and output pressure of demand node should be more than minimum and less than maximum allowable pressure, respectively. Eq. 8 shows that the pipeline between two nodes can be installed if a connection is allowed. Eqs. 9 and 10 state that when a main or backup pipeline is installed in a period, it is accessible the rest of the planning horizon. Eq. 11 guarantees that a back-up pipeline can be installed parallel to the main pipeline, if the main pipeline is located. Installation of main and backup pipelines are the prerequisite for the existence of flow direction in the main and back-up pipelines that is defined by Eqs. 12 and 13, respectively. Eqs. 14 and 15 indicate that the flow runs only in one direction in a main and back-up pipeline, respectively. The remaining capacity of pipelines (both main and back-up) in order to flow NG in the disruption phase is showed through Eqs. 16 and 17. Eq. 18 explains the flow balance in the demand node. Eq. 19 shows the capacity limit of the refinery node. Eqs. 20 to 23 calculate the pressure drop of the main and back-up pipeline according to the NG flow rate and pipeline resistance, respectively. The pipeline resistance δ_{ij} is computed using formulation $\delta_{ij} = \left({}^{1}/{}_{c_1}\right)^2 \frac{GT_f l_{ij} Zf}{dia_{ij}^5} \left({}^{P_b}/{}_{T_b}\right)^2$, that depends on friction factor f, base pressureP_b, base temperatureT_b, gas gravity G, average gas flowing temperature T_f and gas compressibility factor Z, pipe length L_{ij} and pipe diameter dia_{ij} ([20]). The parameters c_1, f, P_b,T_b, G, T_f and Z are presumed to be set equal to 1.1494×10^{-3}, 0.01, 100 KPA, 288 K, 0.66, 283 K, and 0.805 in our computational study**.** Notably, Eqs. 20 and 21 together calculate the pressure drop between nodes. Specifically, when there is flow from i to j ($W_{ijet} = 1$), the left-hand side of these constraints must be equal to zero. However, when X_{ijst} is zero, Eqs. 20 and 21 can get any value, positive or negative, and since it cannot be any more than the square of the maximum pressure difference, so, we set "M1" equal to $(P_{max})^2$. This issue is also valid for Eqs. 22 and 23. Eq. 24 expresses that a compressor station will be built just by one kind of turbo compressor. Eq. 25 states that when a compressor station is installed in a period, it is accessible for the rest of the planning horizon. Eq. 26 makes clear that if a compressor station is installed, the output pressure should not exceed ω times the input pressure. Also, Eqs. 27 and 28 guarantee that output pressure is equal to input pressure if the compressor station not installed. Eq. 29 states that a compressor station can compress the flow rate to its maximum capacity. Eq. 30 guarantees that the outlet pressure at the import node should be the maximum permitted value. Eq. 31 shows the capacity limit of the import node.

This MINLP formulation cannot be resulted in a global optimal solution due to the nonlinearity of the proposed model. The source of nonlinearity is due to the presence of the squared pressure and flow variables in Eqs. 20 to 23. At the first stage, the problem can be partially linearized by removing the squared pressure variables. For this purpose, new variables ps_{ist}^{in} and ps_{ist}^{out} are defined instead of ${p_{ist}^{in}}^2$ and ${p_{ist}^{out}}^2$, respectively. To update the relevant constraints, the left-hand-side and right-hand-side of Eqs. 5 to 7 and 26 to 28 and 30 should be squared as follows.

$$ps_{ist}^{out} = (P_{max})^2 \qquad \forall i \epsilon NR, s \in S, t \epsilon T \qquad (34)$$

$$ps_{ist}^{in} \geq (P_{min})^2 \qquad \forall i \epsilon Nd, s \in S, t \epsilon T \qquad (35)$$

$$ps_{ist}^{out} \leq (P_{max})^2 \qquad \forall i \epsilon Nd, s \in S, t \epsilon T \qquad (36)$$

$$ps_{ist}^{out} \leq (1+\omega)^2 ps_{ist}^{in} + (M_2)^2 (1 - \sum_u CS_{iut}) \qquad \forall i \in NC, s \in S, t \epsilon T \qquad (37)$$

$$ps_{ist}^{out} \leq ps_{ist}^{in} + (M_2)^2(\sum_u CS_{iut}) \quad \forall i \in NC, s \in S, t\epsilon T \quad (38)$$

$$ps_{ist}^{out} \geq ps_{ist}^{in} \quad \forall i \in NC, s \in S, t\epsilon T \quad (39)$$

$$(ps_{ist}^{out} - ps_{ist}^{in}) - \delta_{ij}(x_{ijst})^2 \geq M_1(\sum_e W_{ijet} - 1) \quad \forall i,j \in N, s \in S, t\epsilon T \quad (40)$$

$$(ps_{ist}^{out} - ps_{ist}^{in}) - \delta_{ij}(x_{ijst})^2 \leq M_1(\sum_e W_{ijet} - 1) \quad \forall i,j \in N, s \in S, t\epsilon T \quad (41)$$

$$ps_{ist}^{out} = (P_{max})^2 \quad \forall i\epsilon NI, s \in S, t\epsilon T \quad (42)$$

At the second stage, in order to linearize the model completely, it also needed to eliminate the squared flow variables in the Eqs. 20 to 23. Hence, the piece-wise linear approximation is employed that described in 3 steps as follows:

1- Determine the variation range of flow variable (minimum and maximum value of flow variable):

$$x_{ijst}^{min} = 0 \qquad x_{ijst}^{max} = \sum_{j\in ND} De_{jt}$$

2- Divide the range of flow into some intervals. For this purpose, the lower bound and upper bound of each interval are calculated as follows:

$$lower\ bound\ of\ each\ interval: \quad \alpha_{ijstk} = x_{ijst}^{min} + (k-1) * \left[(x_{ijst}^{max} - x_{ijst}^{min}) / |k| \right]$$

$$upper\ bound\ of\ each\ interval: \quad B_{ijstk} = x_{ijst}^{min} + k * \left[(x_{ijst}^{max} - x_{ijst}^{min}) / |k| \right]$$

The more intervals are made, the more accurate approximate value of flow. k is the number of intervals.

3- In each interval, the value of flow is equal to the linear combination of the lower bound and upper bound of the interval.

$$x_{l-ijst} = \sum_k \lambda_{ijstk}\, \alpha_{ijstk} + \mu_{ijstk}\beta_{ijstk} \quad \forall i,j,s,t \quad (43)$$

Because the flow variable is squared in the formulation, the value of squared flow should be equal to a linear combination of the square of the lower bound and upper bound of the interval. Also, λ_{ijstk} and μ_{ijstk} get values only if the flow value falls in the interval formed by the lower and upper bounds ($\sum_k \Upsilon_{ijstk} = 1$).

$$A_{ijstk} = \alpha_{ijstk}{}^2$$

$$B_{ijstk} = \beta_{ijstk}{}^2$$

$$x_{l-ijst}{}^2 = \sum_k \lambda_{ijstk}\, A_{ijstk} + \mu_{ijstk}B_{ijstk} \quad \forall i,j,s,t \quad (44)$$

$$\lambda_{ijstk} + \mu_{ijstk} \leq \Upsilon_{ijstk} \quad \forall i,j,s,t,k \quad (45)$$

$$\sum_k \Upsilon_{ijstk} = 1 \quad \forall i,j,s,t \quad (46)$$

$$\Upsilon_{ijstk} \in \{0,1\}$$

$$0 \leq \lambda_{ijstk}, \mu_{ijstk} \leq 1 \quad (47)$$

Finally, the linearized equation of Eq. 20 in the main model is equal to:

$$(ps_{ist}^{out} - ps_{ist}^{in}) - \delta_{ij}(\sum_k \lambda_{ijstk}\, A_{ijstk} + \mu_{ijstk}B_{ijstk}) \geq M_1(\sum_e W_{ijet} - 1) \quad \forall i,j,s,t \quad (48)$$

This issue is valid for the Q_{ijst} variable.

Dealing with operational risk

The complex and dynamic nature of supply chains and the long-term horizon of strategic-level planning, such as network design, exert a high degree of uncertainty as a result of decisions on this network. The existence of diverse uncertainties in different parts of the NGTN, such as supply, demand, production, transportation, operation and NG price, significantly affect the performance of the entire network. Uncertainty in the mathematical models categorized into flexibility in the constraints and aspiration levels of objective functions and uncertainty in input parameters. Randomness, epistemic and deep uncertainty are three categories of uncertainty in input parameters. Randomness uncertainty occurs if historical data about the input parameter is available, sufficient and reliable in which can be extracted from its probability distribution. Generally, Stochastic programming is utilized for handling randomness uncertainty. On the other hand, epistemic uncertainty is accomplished when the input parameter suffers from a lack of knowledge in which can be extracted from expert's subjective data to express the possibility distribution of the uncertain parameter. For dealing with epistemic uncertainty in input parameter, a possibilistic programming approach is applied. Finally, Deep uncertainty is a type of uncertainty in which the objective or subjective probability/possibility of plausible future conditions cannot be estimated due to lack of information about imprecise input parameter and Robust optimization approach is used to cope with this kind of uncertainty ([3]). NG demand is an inherently uncertain parameter according to the different factors such as growth economic, electricity generation and weather conditions. This uncertain parameter is known as epistemic uncertainty because accurate information and sufficient historical data are not available. Therefore, we take advantage of domain expert’s subjective data based on their contemplative opinions and professional experiences. Hence, this parameter was presented as triangular or trapezoidal fuzzy numbers. To deal with an inaccurate parameter, the possibilistic chance constrained programming approach, which is a subset of fuzzy mathematical programming has been devised ([25]). This method employs the expected value of fuzzy numbers and the possibility (Pos) and necessity (Nec) measures, and the DM determines the confidence level of constraint satisfaction. This method is successfully applied in the area of supply chain design and planning (see e.g., [26]). For more explanation, we consider the compact form of the proposed model (excluding the second objective function) as follows:

$$
\begin{aligned}
& Min\ z_1 = Cy + Fx \\
& s.t. \\
& res \geq \frac{\tilde{d} - x}{\tilde{d}} = \tilde{d} \times res \geq \tilde{d} - x \\
& Ay \leq 0 \\
& Hx \leq 0 \\
& Bx \leq Ty \\
& Gx \leq Ky \\
& Lx \geq \tilde{d} \\
& x \geq \tau y \\
& Py \leq 1 \\
& y \in \{0,1\}, x \geq 0 \qquad (49)
\end{aligned}
$$

Where vectors C, F, d represent the fixed cost, variable cost, and demand parameter. Also, A, H, B, T, G, K, L, τ, and P correspond to the coefficient matrices, and x and y denote the continuous and binary variables, respectively. In the model (49), parameter $\tilde{d}$ is imprecise and the perception about it is fuzzy triangular numbers $d_i = (d_i^1, d_i^2, d_i^3)$ in which the prominent points of corresponding triangular fuzzy numbers are considered as follows: $\widetilde{d_\iota} = (0.25d_i, 0.8d_i, 1.2d_i)$. Assume r is a real number, the valid interval for necessity (*NEC*) of $r \geq \widetilde{d_J}$, according to [14] would be:

$$Nec(r \geq \widetilde{d_J}) \geq \theta \leftrightarrow r \geq (1-\theta)d_j^2 + \theta d_j^3 \;\; \forall j \in J \tag{50}$$

In order to establish a possibilistic chance-constrained (PCC) programming model, necessity measure (NEC) is taken to deal with the possibilistic chance constraints, respectively. Now, consider the following crisp equivalent of the formulation (49):

$$\begin{aligned}
&Min\ z_1 = Cy + Fx \\
&s.t. \\
&x \geq \frac{(1-\theta)d_2 + \theta d_3 - x}{(1-\theta)d_2 + \theta d_3} = (1-\theta)d_2 + \theta d_3 \times x \geq (1-\theta)d_2 + \theta d_3 - x \\
&Ay \leq 0 \\
&Hx \leq 0 \\
&Bx \leq Ty \\
&Gx \leq Ky \\
&Lx \geq (1-\theta)d_2 + \alpha d_3 \\
&x \geq \tau y \\
&Py \leq 1 \\
&y \in \{0,1\}, x \geq 0
\end{aligned} \tag{51}$$

θ is the confidence level of chance constraints in which determine Regarding DM's ideas in the lowest satisfaction degree of PCC.

Case study

National Iranian Gas Company (NIGC) was established in 1965 in Iran, and now it operates as one of the largest NG producer company in the world. The main task of NIGC involves receiving NG from refineries and import stations and transferring it to export stations and distribution areas. This paper considered the northern part of the transmission operational area that yearly experiences the shortage of NG due to their long distances with the refineries. Table 1 represents the considered locations with nodes number in the case study from origin to destination. This operational region covers Guilan, Golestan and Mazandaran provinces. Demand quantities are 780 million cubic meter (mm3), 210 mm3 and 840 mm3 in one month, respectively. Five potential compressor stations are considered in this region, namely Rasht, Ramsar, Noor, Neka, and Mino Dasht, in order to compensate the missing pressure. The maximum and minimum permissible gas pressure values in the network are 90 and 75 bar, respectively. This region is fed from Assaluyeh and Hashemi Nejad refineries and import is by Turkmenistan. Based on the information we obtained from NIGC, the capacity of Assaluyeh, Hashemi Nejad and import is 2700 mm3, 1500 mm3 and 1110 mm3 in one month, respectively.

Table 1. The considered locations in the case study from origin to destination

Location (number of node)	Demand of Province (number of node)	Number of Transmission nodes
Hashemi Nejad refinery (1) /Mino Dasht (5)	Razavi Khorasan (3)	(2), (4)
Mino Dasht (5) Qaleh jiq (8)	Golestan (7)	(6)

Qaleh jiq (8) / Neka (12)	Part of Mazandaran (11)	(9), (10)
Neka (12) / Noor (18)	Part of Mazandaran (15)	(13), (14), (16), (17)
Noor (18) / Ramsar (24)	Part of Mazandaran (21)	(19), (20), (22), (23)
Ramsar (24) / Rasht (31)	Part of Guilan (25)	(26), (27)
Assaluyeh refinery (28) / Rasht (31)	Central of Iran (30)	(29)
Rasht (31) / Chelavand (34)	Part of Guilan (33)	(32)
Chelavand (34) / Ardabil (36)	Part of Ardabil (36)	(35)

The Substantial impact of pipelines on the life and death of people who are surrounding the pipelines makes it necessary to carefully get decisions before installing them. For this purpose, the evaluation of risks such as toxicity, flammability, thermal radiation and explosion related to NG leakage in each region is one the most important strategic goals of the company. To do so, the company uses Aloha software to simulate the diffusion concentrations of NG based on distance in each region and then, according to the obtained results and comparison with the approved legal distance (250m), decides on installing and fortification level of pipelines.

Highly vulnerability of pipelines to seismic hazards has forced the transmission company to employ the best fortification strategies to reduce explosion and wildfire risks against earthquakes and corrosion. Steel pipes are commonly used in the NG pipeline which has less strength and resistance against corrosion. So, the company enforces fortification in two classes: class A and class B. Class A places in low fortification level and entails cheap and unreliable coating. However, Class B refers to modern covering which utilizes the most expensive and resistant technologies and decreases the waste of NG in coating operation (e.g., Fiber Reinforced Polymer (FRP)). In addition to the coating pipeline, the company tries to install back-up pipelines in parallel to the main pipeline, that continue NG flow in the network after disruption of the main pipeline or decreases pressure drop with increasing the flow. On the other hand, to cope with increasing NG consumption in cold seasons, the company considers uncertainty in NG demand parameter and hold one or two turbo compressor in each compressor stations on standby to decrease pressure drop or increase the flow rate. The disruption risks in the case study are handled based on three independent scenarios, small, medium and large scale. The small-scale scenario recognizes the least severe and the large-scale scenario recognizes the most severe case. As a result, each scenario has a different impact on the capacity of pipelines due to fortification levels and meeting the NG demand. Table 2 explains a summary of the disruption risks in the NGTN as well as the relevant factors, the amount of importance and the location of occurrence.

Table 2. different kinds of disruption risks in NGTN.

Disruption risk	**Disruption modeling**		**factors**	**The amount of importance**	**The Affected area**
pipeline failure (ϑ_{ijes})	Small leakage = partial	Shear failure =Complete	Corrosion, Collision, Terrorist attacks, the lack of safety issues, earthquake.	Lead to casualties and extensive economic damage due to explosion and fire	transmission pipeline
	scenario-based stochastic programming				
network pressure drops or sudden increase in NG consumption	uncertain demand parameter		High consumption Sudden outage of compressor stations, workforce error, earthquake.	NG consumers experience the NG shortage	transmission pipeline
	possibilistic programming				

Implementation and solution results

As mentioned, the transmission company searches to have pipeline routes with low risk. We first calculate the risk of each pipeline routes based on the distances of diffusion concentrations by the Aloha software. If the distance of diffusion concentrations is less than 250m, show low risk (e.g., the numerical risk is equal to one), 250m-500moffer medium risk (e.g., risk=2) and more than 500m display high risk. It should be noted that all mathematical models and their experiments are executed using GMAS 24.1.3 software (with Cplex solver) on a laptop with the Intel Core i7 processor running at 1.8GHz up to 1.99GH and with 16 GB of RAM. In addition, all the monetary data is considered in Iranian currency (i.e., *Toman*). Fig. 4 displays the simulation result about the distances of diffusion concentrations based on three threat zones for the case study cities.

It can be seen that the maximum distance of NG release is 219 meters from the source. Therefore, the risk of this route is equal to one because the rate of expansion of NG has not exceeded 250 meters. This result is correct for other cities of the case study, and all of them take the least number of risks. The result of risk calculations for each potential pipeline route is a critical parameter in the proposed mathematical model aiming to select the safest pipeline routes, design a resilient NGSC, and determine flow directions.

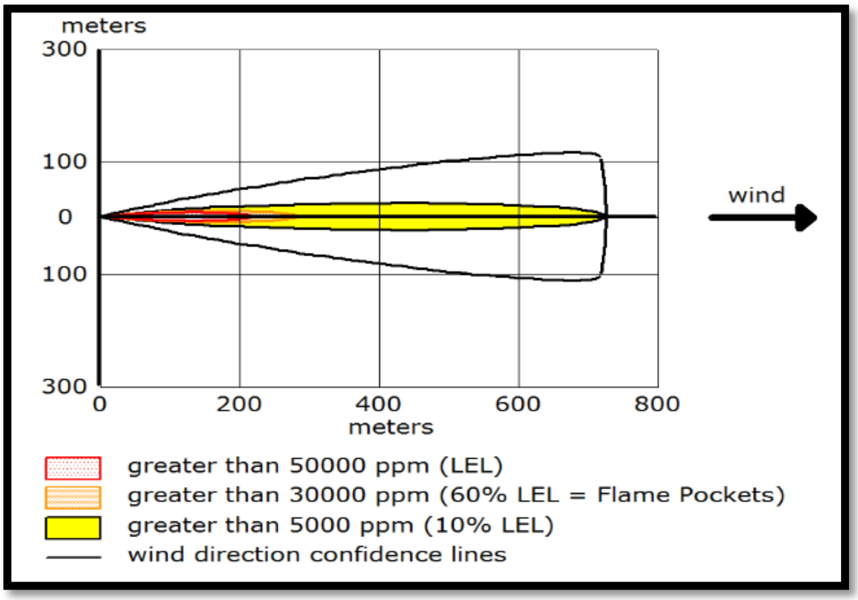

Fig. 4. the distances of diffusion concentrations based on three threat zone

After running the model at the confidence level of 0.7, compressor stations Mino Dasht, Neka, Ramsar and, Rasht with two turbo compressors have been installed, in which one of them is used under normal condition and another one employed as spare parts in the abnormal state. The entire pipeline fortified with the first fortification level, but pipelines between nodes (1-2), (2-3), (8-9) and (24-25) installed with the second fortification level or class B. because the pipelines that begin from refineries (1-2) and imports (8-9) or locate in bottleneck paths (24-25), are the primary and constituent routes of the flow in the network. So, they must be constructed with higher resistance in which can utilize their maximum remaining capacity against disruption risk. According to the flow direction, it is clear that Hashemi Nejad refinery only can feed one consumer node (node 3) due to its capacity, so, the main supplier of this network is the import station (node 8) that cover the rest of the consumers (Golestan and Mazandaran provinces) up to node (25). Finally, Guilan and Ardabil consumers are supplied by the Assaluyeh refinery. The parallel pipelines are installed between nodes (8-9), (12-13) and

(28-29) to increase the flow rate, or keep flow if one of the parallel pipelines is disturbed. Fig. 5 demonstrates the optimal structure of the NGTN design after solving the model.

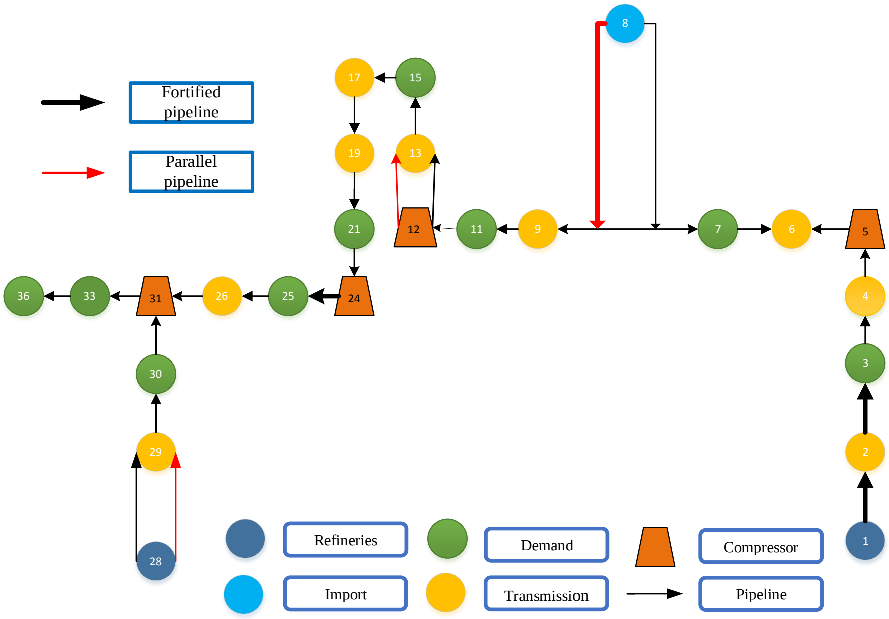

Fig. 5. The optimal structure of NGTN design after solving the model.

Model validation

In order to validate the Possibilistic programming model, we need to generate 10 random realizations of an uncertain parameter $(\tilde{d})$. Each random realization is done by generating a random number regarding the two extreme points of the relevant triangular fuzzy numbers *(i.e.,* $d_{real} \sim [d_i^1, d_i^3]$).Then the results that were achieved by the PCCP model based in nominal data $[x^*, y^*]$ will be substituted in the model. The brief form of this model is as follows:

$$\begin{aligned}
&Minz_1 = C_{real} y^* + F_{real} x^* + \delta_1 R \\
&S.t. \\
&z_2 \leq \varepsilon \\
&x^* + R \geq \frac{d_{real} - x^*}{d_{real}} = (d_{real} \times x) + R \geq d_{real} - x^* \\
&Ay^* \leq 0, \\
&Hx^* \leq 0 \\
&Bx^* \leq Ty^*, \\
&Gx^* \leq Ky^* \\
&Lx^* + R \geq d_{real} \\
&x \geq \tau y^* \\
&Py^* \leq 1, \\
&R \geq 0.
\end{aligned} \qquad (53)$$

In this realization model, the decision variable of model R specify the deviations from the chance constraint under different realization and the parameters δ_i is the penalty value. Fig. 6 describes the results of these experiments with the standard deviation of objective functions values under 10 random realizations at 0.9, 0.8, and 0.7 confidence levels under three penalty levels. As it is clear, with the increase in the confidence level of possibilistic chance-constrained, the standard deviation of objective functions decreases. Therefore, it can be concluded that when the amount of penalty value is great, it is necessary to use a higher confidence level to reduce the risk and standard deviation in the network.

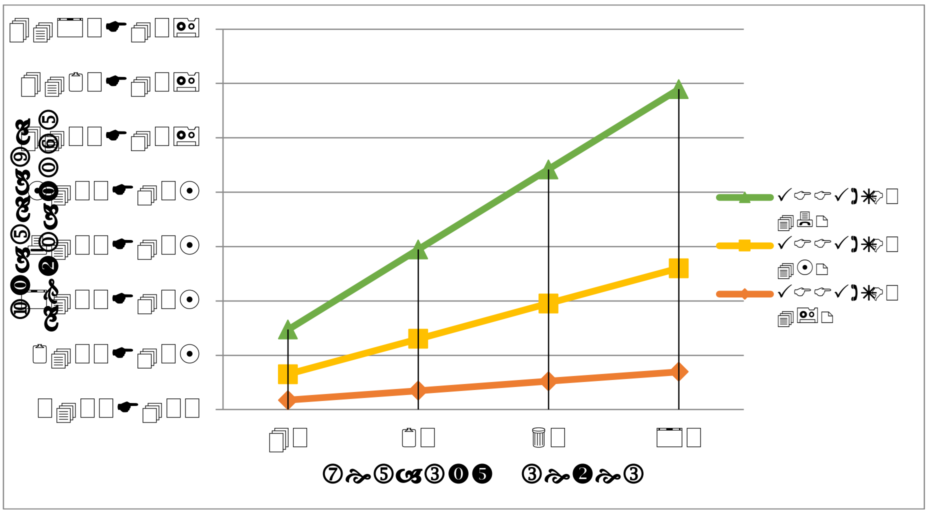

Fig. 6. standard deviation of objective function against penalty levels

Sensitivity analysis

In this section, various sensitive analysis tests are accomplished to assess the effects of key parameters on the proposed model.

Impact of sudden increase in NG consumption

Unexpected increase in NG consumption is considered as a challenge that can affect the performance of the studied NGTN. Since reduction of temperature in winter occurs simultaneously throughout the whole country, NG consumption of all consumers increased. Fig. 7 illustrates how the network vulnerability is affected by sudden increase in the NG consumption. A general observation shows that, with an increase in the percentage of NG consumption (demand parameter), the network pressure is reduced and more consumption regions experience the lack of NG such that when the amount of increase of consumption reaches to 8%, the vulnerability of network reaches the peak.

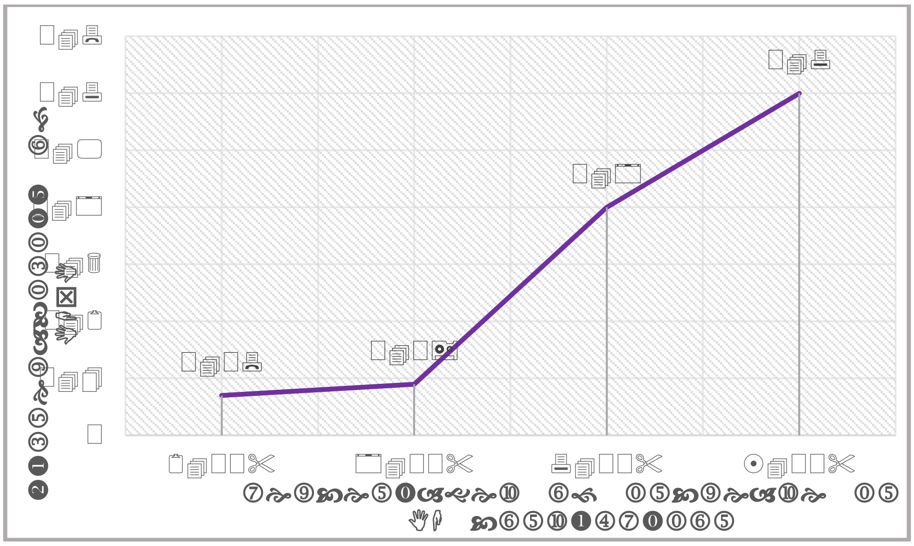

Fig.7. Impact of sudden increase in NG consumption on vulnerability.

Impact of various resilience strategy on vulnerability

how the resiliency of the network is affected by utilizing each of resilience strategies under different disruption scales investigated. Based on results, with an increase scale disruption, the vulnerability of NGTN increase. the reason is that the lost capacity of pipeline in the post-disruption increase with the scale disruption. So, more consumers experience NG shortages. It is obvious that in the small disruption scale, the NGTN has been shown good resistance even without using resilience strategies. However, as the scale of disruption increases, the impact of resilience strategies on the network is very tangible such that with using three resilience strategies even in large scale scenarios, the vulnerability of NGTN gets its lowest value, so the resilience of the network is more. The reason is that, by applying the fortification level strategy, the remaining capacity of pipeline increases after the disruption and in case of complete failure of the pipeline, the back-up pipeline will be replaced. Also, as demonstrated in Fig. 8, both back-up pipeline and fortification level have more impact in the resiliency of network, respectively, and back-up turbo compressor almost does not affect just in investment cost of compressor stations.

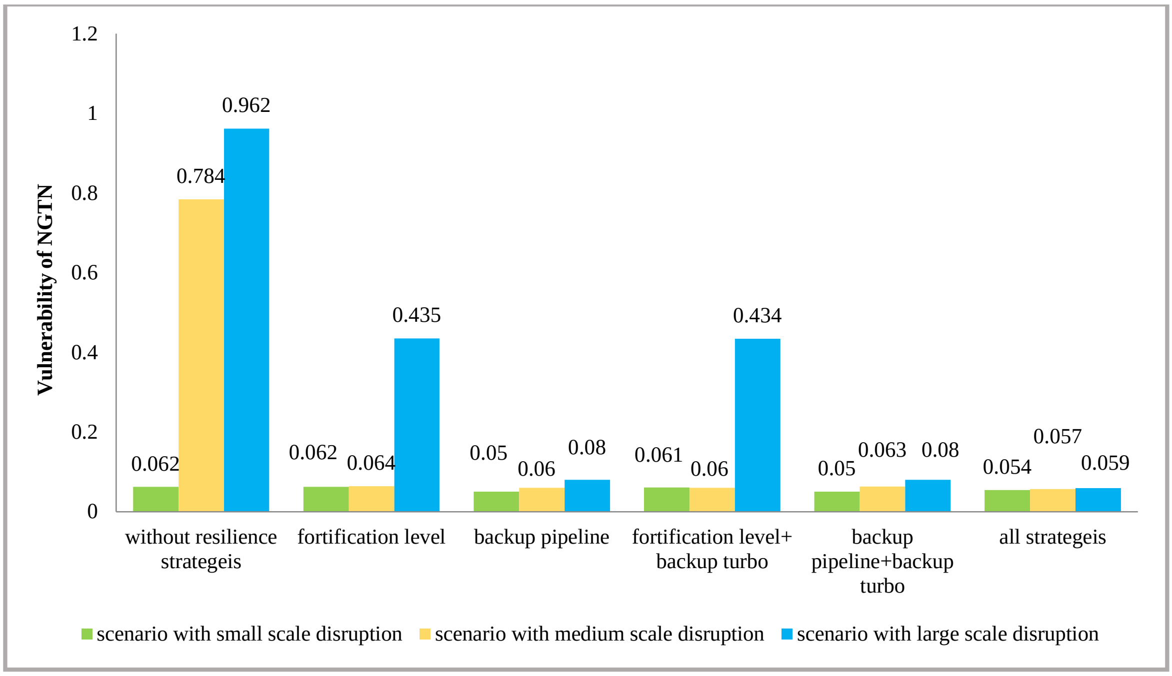

Fig. 8. Impact of various resilience strategies on vulnerability.

Managerial insights

Generally, three significant challenges threaten the northern part of the national gas transmission network that need to be addressed:

- Failure of pipelines: failure of the Assaluyeh-Rasht pipeline has a major impact on the resilience of the national gas transmission network. The reason is that the Rasht and Ardabil consumers are feed from this pipeline.
- Sudden increase in natural gas consumption: sudden increase in the NG consumption results in drop temperature across the NG network. Therefore, the northern part of the country experiences the lack of NG.

Hence, in order to increase the resiliency of NG network against disruptions, some managerial insights are provided as follows:

- ✓ Use of parallel pipeline and increase of fortification level: parallel pipeline can be used to continue NG supply when the main pipeline is disrupted. In our case study, results show that in the main routes (i.e., the pipelines that are started from import and Assaluyeh refinery as important suppliers) parallel pipeline is installed and the fortification level is enhanced.

- ✓ Installation of spare turbo compressor in compressor stations: currently, most of the compressor station in this region should arrange with the 1+1 layout. The reason is that in this arrangement, one turbo compressor is used under normal condition and another one is employed as spare parts in the abnormal state or when the NG consumption increased suddenly specially in cold season. Therefore, the completion and installation of additional units in these facilities can be considered as a redundancy strategy.

Conclusions

This paper developed a two-stage method that can be evaluating the risk of each pipeline route and design resilience NG transmission network. In the first stage, the risk of each pipeline route between two nodes based on the distance of diffusion concentrations is evaluated and used as a pipeline installation risk coefficient in the next stage. In the second stage, the resilience NG transmission network design problem is formulated via a multi-objective, two-stage possibilistic-stochastic programming model under operational and disruption risk. This paper considers proactive resiliency strategies such as parallel pipeline, standby compressor stations and pipeline fortification to withstand against disruption risk. Also, the proposed model is able to consider different failure modes of the pipeline such as partial or complete disruption.

Finally, the validation of the proposed model is done by the use by the data of north NG transmission network of Iran. The proposed approach is employed to investigate the impact of proactive resiliency strategies on the cost and vulnerability objectives. Ten realizations are executed to indicate the effect of different confidence levels and penalty values on the performance of proposed possibilistic programming model using standard deviation and average of objective functions performance measures. The numerical results show that utilizing the back-up pipeline and pipeline fortification together can enhance the resiliency of NGTN more 93 percent under large scale disruption scenario. Also, we show that how sudden increase in NG consumption can affect the resiliency of NGTN. Although we gained important insights from the implementation of the proposed model and our study has some limitations which can be resolved in future research. In the future, the proposed model can be developed by considering the disruption risks in the other parts of NGTN such as refineries and NG storages. Research can also investigate the recovery phase of disrupted network facilities and measure its effects on the network resilience. Another research topic is to consider robust optimization or fuzzy-stochastic programming to deal with uncertain input parameters. Finally, to solve the resilient NG network design problem in large, meta-heuristics and exact methods such as decomposition algorithms can be developed.

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