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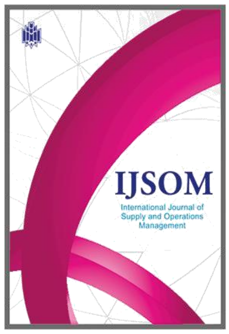

A Multi-Objective Optimization Model for the Resilience and Sustainable Supply Chain: A Case Study

Mohammad Reza Zamanian [a], Ehsan Sadeh [a,*], Zeinolabedin Amini Sabegh [a] and Reza Ehtesham Rasi [b]

[a] *Department of management, college of human science, Saveh Branch, Islamic Azad University, Saveh, Iran*
[b] *Department of Industrial Management, Qazvin Branch, Islamic Azad University, Qazvin, Iran*

Abstract
In this research, a real case study of the natural gas supply chain has been investigated. Using concepts related to natural gas industry and the relations among the components of gas and oil wells, refineries, storage tanks, dispatching, transmission and distribution network, a seven-level supply chain has been offered and presented schematically. The aim of this paper is to optimize the case study using a multi-objective and multi-period model to minimize the economic and environmental costs as well as the penalty per underutilized capacity and maximize the total revenue as well as the service level. A small-sized model is verified and solved using an improved augmented ε-constraint algorithm to generate Pareto optimal solutions and assessed trade-offs among objectives in order to help decision makers make an optimal decision. To the best of our knowledge, this is the first study that presents a multi-objective optimization model for the resilience and sustainable supply chain.

Keywords: Resilience; Sustainable; Supply Chain; Multi-Objective; Optimization.

1. Introduction

Nowadays, companies have indisputable effects on the economy of their countries (Doaei et al., 2017). Meanwhile, competition between companies has been replaced by competition between supply chains. In other words, if supply chain activities fail to resolve unforeseen disruptions appropriately, there will be potentially harmful consequences. It escalates the risk of business discontinuity, causing huge amounts of financial loss (Pfohl et al., 2010). Supply chain resilience can define the capacity of disruptions and retaining the basic, structural supply chain tasks in the face of stoppages (Pettit et al., 2010). On the other hand, Sustainable development has become a major jargon in the business terminology. Influenced by sustainability practices through the integration of economic, environmental and social goals, professions extensively gain a competitive edge when sustainable supply chains are projected. Most organizations pay attention to the strategic importance of sustainable investments. In this environment, the development and availability of analytical models and decision support tools can help organizations make more effective, informed decisions (Fahimnia and Jabbarzadeh, 2016). In response, academic research has been done on the design and management of sustainable supply chains over the past two decades (Brandenburg et al., 2014; Fahimnia et al., 2015a; Fahimnia et al., 2015b; Seuring, 2013). Most efforts in sustainable supply chain have been orchestrated to mitigate the supply chain's burden of environmental responsibility in measuring greenhouse gas emissions and consumption of resources (Fahimnia et al., 2015). In terms of social sustainability, the focus has mostly been shifted to damages to human community health (Boukherroub et al., 2015). An evaluation involving the dimensions of sustainability is different from an evaluation of traditional business-oriented performance. When dimensions of sustainability are considered, the scope of evaluation should be expanded. In addition to its economic dimension, sustainable development covers environmental and social dimensions (Cetinkaya et al., 2011). Despite the growing efforts at designing and managing sustainable supply chains, there is little known about the effects of sustainability dimensions on resilient supply chains. In a specific environment affected by frequent inevitable stoppages, sustainable supply chain management requires a sustainable modeling and analysis adaptable to its dynamic complexity. Static sustainability analysis is simple because the sustainable economic and non-economic performances of a supply chain can be influenced by interruptive events such as supply stoppage (Fahimnia and Jabbarzadeh, 2016). Natural gas is one of the most substantial sources of energy for many residential, power plant, industry and commercial consumers throughout the world. It has an enormous and complex supply chain which is in need of manifold investments in all the levels of exploration, extraction, production, refinement, transmission, storage and distribution. In recent years, economic and environmental problems in the supply chain engrossed so much attention of researches. In other words, the two dimensions of the sustainable development such as environment and economy in the natural gas supply chain are very significant.

Given that a number of researches conducted in recent years on the dimensions of sustainability and resilience in some levels of the supply chain, some dimensions of resilience such as the service level, or adequate inventory on the network and facilities and decreasing penalty per underutilized capacity, or recovery, and some dimensions of sustainability such as the environmental or social costs of greenhouse gas emissions, economic or supply chain costs, and total revenue earned in the consumption nodes at all levels and components of the natural gas supply chain are investigated in the present study and provided as the contribution of this research while considering the trade-offs among them.

The schematic representation of the natural gas supply chain under study in Iran is shown in Fig. 1. In this research, natural gas supply chain modeling was carried out at seven levels. At the first level, there are three types of suppliers, including gas collection wells, imports and storage tanks. The gas refineries, the compressor stations, the city-gate stations (CGS), the dispatching, the town bordering stations (TBS) are at the second, third, fourth, fifth, and sixth levels, respectively. The nine groups of customers including 1. injection into the oil wells, 2. the export of liquid and gas products, 3. liquid and gas products for domestic use, 4. natural gas exports, 5. major industries, 6. power plants, 7. small industries, 8. residential consumers, and 9. commercial consumers are at the seventh level. In the entire supply chain, gas is transmitted through pipelines of varying sizes and pressures. The main part of the sour gas extracted from the gas wells are transmitted to the gas refineries, but a part of it is devoted to the injection into the oil wells and feeding petrochemical units. As a result of the refining process, in addition to the sweetened gas, five types of equal liquid products are produced, two of which are exclusively for export and a part of the two other types is devoted to the domestic customers in addition to exports; and the fifth type includes water and impurities. The storage and sales nodes of all four types of products are at the front doors of refineries. Further, refineries send sweetened natural gas to compressor stations, a part of which is devoted to the injection into oil wells as the sweetened gas. Imported natural gas enters the network directly; and then, enters the compressor stations, along with the gas produced at the refineries.

Therefore, compressor stations receive gas from refineries, imports and other compressor stations, and deliver it to other compressor stations, exports, major industries, power plants, city-gate stations and storage tanks after pressure boosting. In warm seasons, when gas consumption volume is low, the storage tanks receive and save the gas and deliver it to the compressor stations during the cold seasons and peak consumption periods, or when it is necessary to maintain balance and resilience of the network. The city-gate stations deliver the gas to the town bordering stations and small industries after reducing the gas pressure; and finally, the town bordering stations provide gas for residential and commercial customers after reducing the gas pressure. Dispatching directorate through monitoring and using information from refineries, compressor stations and city-gate stations balances the volume and pressure of the gas transmission lines in order to maintain resilience, sustainability, and customer demand throughout the supply chain. It is important to note that the refineries output gas is reduced due to the production of five types of equal liquid products and the fuel consumed in the refineries; however, the compressor stations and city-gate stations output gas is reduced due to fuel consumption (Zamanian et al., 2019).

The rest of the paper is organized as follows: In Section 2, the theoretical background and literature review of resilience and sustainable supply chains. Section 3 presents a multi-objective model including sets and indices, variables, parameters, objective functions, constraints, mathematical model and problem solving approach. Some levels of the natural gas supply chain are real size, but some others are small size. In Section 4, the case study is presented. Finally, the discussions on the sensitivity analysis and conclusions are given in Sections 5 and 6, respectively.

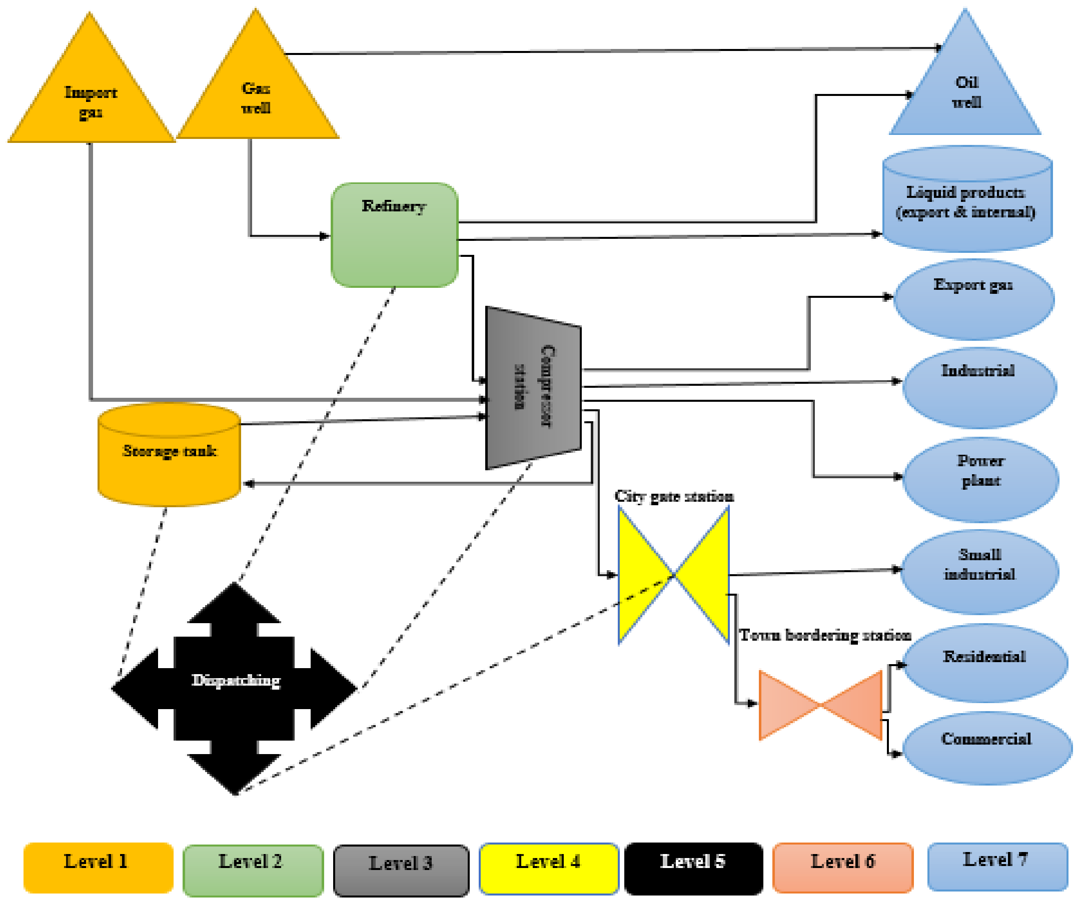

Figure1. Schematic representation of the natural gas supply chain

2. Theoretical Background and Literature Review

2.1. Resilience Supply Chains

The recent global financial crises and the frequent rise of human and natural catastrophes demonstrate why organizations need to deal with major supply chain disruptions (Esmaeilikia et al., 2014b). Today, supply chains require high flexibility and agility so as to quickly and regularly respond to fluctuations in demand, supply, current exchange rates and lag time. Such stoppages are usually managed at the technical design level through building flexibility in supply chains (Esmaeilikia et al., 2014a). As a well-known technique for resilient supply chain, expected value has been extensively adopted in making accurate mathematical decisions on investment and prioritization of resilience structure options by assigning weights to future events and calculating the expected values of various disruptive scenarios. Chen et al. (2011) expanded this model for decision-making on joint inventory under the assumption of equal independent probability for interruption and occurrence. The unequal interruption possibilities have been also studied by other scholars (Cui et al., 2010; Li et al., 2013; O'Hanley et al., 2013). Supply chain models have been explored for scenarios with dependent interruption probabilities by Jabbarzadeh et al. (2012) and Garcia-Herreros et al. (2014).

Certainly, Value at Risk (VAR) and Conditional Value at Risk (CVAR) have been two popular criteria for resilient supply chains. Sawik (2011) proposed the portfolio methods in order to pick suppliers alongside the risks of supply chain stoppages, VAR, and CVAR. Sawik (2013b) upgraded this approach to combine the selection and protection of suppliers and value allocation order. The protective decisions included choice of suppliers, protection against stoppages and pre-deployed emergency inventory allocation for protected suppliers so as to maintain continuous supply when stoppages occur. Adopting a similar method, Sawik (2013a, 2014a, 2014b, 2015) developed random mixed-integer planning models in order to integrate the selected suppliers and schedule customer orders under the threat of disruption. Moreover, CVAR was adopted by Madadi et al. (2014) to measure the risks of disruption in the design of pharmaceutical supply chains. The worst approaches and robust criteria were also employed in the optimization of models in designing resilient supply chains. Medal et al. (2014) experimented the integration of equipment location and difficult decisions in an attempt to minimize the maximum distance between the demand point and the closest equipment location at stoppages. A multi-objective optimization approach was proposed by Hernandez et al. (2014) seeking to balance the total displaced weight distance before and after stoppages. Without any need to remove potentially damaged equipment, the proposed approach allows a decision-maker to understand the effects of opened equipment on robust systems. Apart from the above studies generally intending to protect the network against stoppages, there have been a few efforts focusing on the network capability to discover previous malicious events. Pant et al. (2014) proposed a modeling paradigm for system resilience as a function of vulnerability (early undesired impact of stoppage) and recovery capability (system recovery speed). The study presented several accidental resilience criteria including the time to repair the entire system, time to service resilience of the entire system, and time to resilience percentage. Baroud et al. (2014b) studied the useful application of these criteria in the design of inland waterway network. An earlier study by Baroud et al. (2015) introduced a randomized approach to calculate three criteria of resilience cost namely cost of service, cost of network repair and cost of dependent effects. The same researchers also presented two approaches to measure the importance of resilient supply chain components as a function of accidental vulnerability and recovery capability (Baroud et al., 2014a). Furthermore, an optimization method was developed to determine a particular group of disruptive links to be recovered for resilience improvement. In this scope, Losada et al. (2012) proposed a new model to accelerate the recovery time after stoppages and protecting a type of installations network failing under the worst-case scenario. On the other hand, Sabouhi et al. (2018) presented an integrated hybrid approach based on data envelopment analysis (DEA) and mathematical programming method to design a resilient supply chain.

In recent years, several researches have surveyed the effects of technical parameters on the natural gas supply chain. In their research, Nikbakht et al. (2012) proposed a framework for integrating the operational parts of natural gas transmission. Pambour et al. (2016) presented a simulation motor for calculating the flow of gas in the supply chain and the network operations in case of gas crises in the future. Al-Sobhi and Elkamel (2015) provided a framework for analyzing and optimizing the natural gas network and showed the importance of using accurate modeling simulations in decision making. In their research, Ghaithan et al. (2017) developed a multi-objective integrated model for the medium-term tactical decision-making of the downstream oil and gas supply chain through an improved augmented ε-constraint algorithm. Gohari Bahabadi et al. (2017) found that the South Pars gas field has the optimal production rate when the technical parameters are optimized due to operational and economic constraints.

2.2. Sustainable Supply Chains

Numerous attempts have been made to model the environmental and green areas of sustainable supply chain, involving disruptions in sustainable environmental and economic calculations during the design and management of sustainable supply chain (Fahimnia et al., 2014a; Janatyan et al., 2018). Minimization of greenhouse gas emissions has so far been the most desirable environmental goal (Tang and Zhou, 2012). The optimal models for strategic supply chain design sought to balance the supply chain cost and CO2 emissions (Brandenburg, 2015; Elhedhli and Merrick, 2012; Wang et al., 2011), tactical and operational design tools for the emission-cost balance in supply chains (Fahimnia et al., 2013a; Fahimnia et al., 2015; Zakeri et al., 2015), design and planning of closed-loop supply chains with a concentration on emission-cost of forward and reverse networks (Chaabane et al., 2011; Chaabane et al., 2012; Fahimnia et al., 2013b), development and adoption of multiple performance criteria (beyond greenhouse gas emissions) for the management and design of green supply chains (Fahimnia et al., 2015; Pinto-Varela et al., 2011; Pishvaee and Razmi, 2012; Mahmoud Said, 2019), and introducing and reviewing environmental policy tools for optimization and design of supply chain planning (Diabat et al., 2013; Zakeri et al., 2015).

Apart from studies on the management and design of green supply chains, there have only been few attempts made to model the combined performance criteria in three dimensions of sustainability. In fact, there is no consensus on the measurement and reporting of supply chain social sustainability (Varsei et al., 2014), which is a primary explanation for insufficient research in this area. Zhang et al. (2014) conducted several studies on optimal design and cost planning in supply chains, greenhouse gas emissions, lead time, and social and environmental performance criteria. Boukherroub et al. (2015) studied supply chain planning problems from the perspective of employee distance to industrial sites and job stability as criteria for social performance. As evident in these studies, the selection of social and environmental criteria combined in supply chain models is a special technical problem.

In recent years, several researches have examined the economic and environmental effects and sustainable aspects of the natural gas supply chain (Azadeh et al., 2015; Azadeh et al., 2016; Hamedi et al., 2009; Sapkota et al., 2018). Vance et al. (2015) used the P-Graph framework for designing a supply chain. In a research, Rostamzadeh et al. (2018) provided a framework for assessing sustainable supply chain risk management. In their research, Zamanian et al. (2019) developed natural gas supply chain and presented a fuzzy goal-programming model for optimization of sustainable natural gas supply chain by focusing on the environmental and economic costs and total revenue of gas products.

2.3. Resilience and Sustainable Supply Chains

The relevant literature suggests that sustainability and resilience have been explored independently (Derissen et al., 2011; Redman, 2014). By the same token, the efforts made to model supply chains did not explicitly link the dimensions of resilience and sustainability. In fact, there are scenarios in which the dimensions and effects of sustainability in supply chain capacity are inconsistent with unforeseen stoppages. For instance, the majority of sustainability capabilities serve to enhance efficiency in utilization of resources and mitigation of redundant protections (similar to inventory points and fewer storage areas across the supply chain). Although such practices may be environmentally consistent and economically viable, supply chains may be more vulnerable to stoppages due to limited accessibility to safety inventory to cope with variations in supply and demand (Reyes Levalle and Nof, 2015).

Carvalho et al. (2011) presented a conceptual model based on four graphs indicating that synergy between lean, agile, resilient and green paradigms in a supply chain is correlated with the frequency of information and integration level. Divergence in a supply chain occurs due to other parameters such as capacity surplus, inventory level, and refilling process. Murino et al. (2011) proposed a supply chain model construction based on several factors including inventory level, number of suppliers and production rate through simulation software and promotion through analysis of critical outcomes and strengths in the supply chain. Moreover, they argued that supply chain sustainability could be achieved through the functional tasks of resilience. Hanke and Krumme (2012) presented a conceptual model while demonstrating the complex relationships between risk, resilience, and sustainability in the supply chain. In their research, Hawker and Edmonds (2015) showed that sustainability challenges the basic assumption of performance analysis seeking maximization of profits, not to mention that efficiency may serve as a trap for lower resilience in markets facing sudden changes. With an innovative approach in a case study, Azevedo et al. (2016) provided an integrated composite index known as lean, agile, resilient, and green (LARG) to evaluate the supply chain behavior in the automotive industry. Edgeman and Wu (2016) emphasized that strength, resilience, and sustainability of transcendental firms are crucial, desirable and complementary to various stakeholders. In their research, Papadopoulos et al. (2017) tested a theoretical framework, finding out that rapid trust, information sharing, and public-private partnerships are key empowerment factors for resilience in supply chains. They proposed a large-data analysis for a resilient supply chain framework capable of sustainability.

Fahimnia and Jabbarzadeh (2016) investigated the relationship between resilience and sustainability at the design level of supply chains. Providing a multi-objective optimal model developing a sustainability performance scoring method and probabilistic fuzzy ideal planning approach, they managed to design a sustainable, resilient supply chain through dynamic sustainable performance analysis. The approach could progress from static resilient supply chain toward dynamic analysis to deal with unpredictable disruptions in the supply chain. In an analytical study on the distribution of disruptions in the supply chain with regard to sustainability factors, Ivanov (2018) examined the interactions of resilience and sustainable supply chain. For that purpose, he designed a resilient supply chain structure given the mitigation of ripple effects and growth of sustainability. In his research, Ivanov simulated three hypotheses, thereby to identify factors increasing and decreasing sustainability in the supply chain. Zahiri et al. (2017) developed a linear multi-objective mixed-integer integrated resilient-sustainable planning model to design a supply chain under conditions of uncertainty. They developed new benchmarks and imported them into the model for resilience and sustainability. Their new model integrated strategic and tactical decisions. Razmi et al. (2018) proposed a mix-integer linear programming (MILP) model optimizing the hydrogen supply chain network. Karbassi Yazdi et al. (2019) presented a meta-heuristic Binary Particle Swarm Optimization (BPSO) algorithm to come up with an optimized solution for ship routing and scheduling of Liquefied Natural Gas (LNG) transportation. Furthermore, Pavlov et al. (2019) showed a problem of contingency plan optimization for seaport operations under supply and network structural dynamics. Their research methodology is based on a structural dynamics control approach solved by mathematical programming. Review of the literature shows that in the scope of the resilience and sustainable development in the natural gas supply chain, no significant research has been conducted. Therefore, presenting a multi-objective optimization model for the resilience and sustainable natural gas supply chain at their all levels would be very useful for gas industries management. Finally, the contributions of this research, compared to the former researches, are as follows: 1. Consideration of the sustainability aspect including the first, second and third objectives and the resilience aspect including the fourth and fifth objectives in the proposed model, and trade-offs among them and their Pareto optimal solution, 2. Application of improved augmented ε-constrained method of the proposed model, 3. A great compatibility of the proposed model and all its parameters with Iran's natural gas supply chain, 4. Considering the validity of the proposed model through the implementation and use of the actual parameters and the desired and optimal results of its outputs, 5. Considering the increase in the pressure of the oil wells and reservoirs through the injection of gas into them and, consequently, increasing their oil recovery while preserving the resilience and sustainability aspects of the natural gas supply chain. The key features of this model, along with previous studies, are presented in Table 1.

Table1. Classification and features of this study versus former studies

Reference articles	Level of supply chain			Objective		Sustainability			Resilience		Solution method
	Transport	Distribution	All	Single	Multi	Revenue	Economic	Environmental	Recovery	Service Level	
Tabkhi et al. (2009)	✓			✓			✓				Branch and bound
Hamedi et al. (2009)			✓	✓			✓				A hierarchic algorithm
Mahdavi et al. (2010)		✓		✓			✓				Minimum spanning tree
Dos Santos et al. (2011)		✓			✓		✓				Monte Carlo simulation
Santibanez-Gonzalez et al. (2011)	✓				✓		✓	✓			Genetic Algorithm
Jamshidi et al. (2012)	✓			✓			✓	✓			Hybrid genetic Taguchi algorithm
Azadeh et al. (2015)			✓		✓		✓	✓			An interactive method resolution
Azadeh et al. (2016)	✓				✓		✓	✓			ε-constraint algorithm
Ghaithan et al. (2017)			✓		✓	✓	✓			✓	ε-constraint algorithm
Sapkota et al. (2018)			✓		✓		✓	✓			A comparative assessment
Zamanian et al. (2019)			✓		✓	✓	✓	✓			Fuzzy goal programming
This study			✓		✓	✓	✓	✓	✓	✓	ε-constraint algorithm

3. Proposed Multi-Objective Model

This natural gas supply chain is formulated in terms of the dimensions of sustainability such as the environmental and economic costs and revenue and resilience such as the service level and penalty per underutilized capacity, or recovery. This study presents a multi-objective optimization model for the resilience and sustainable natural gas supply chain in the Iranian gas industry, including maximizing the total revenue and service level and minimizing the economic costs, environmental costs and penalty per underutilized capacity in the consumption nodes at all levels and components of the natural gas supply chain in a one-year time horizon, in order to assess trade-offs among them and advise decision makers on the natural gas supply chain management. The proposed model consists of sets and indices, decision variables, parameters, multi-objective functions, constraints, a mathematical model and a problem solving approach.

Sets and indices

w: Set of gas wells
a: Set of importations
r: Set of refineries
y: Set of compressor stations
s: Set of storage tanks
g: Set of city gate stations
b: Set of town bordering stations
o: Set of oil wells
e: Set of exportations
el: Set of equal liquid products
d: Set of industrial customers

p: Set of power plant customers
l: Set of residential customers
f: Set of commercial customers
m: Set of small industrial customers
t: Time period
i: Starting nodes $i \in \{w \cup a \cup r \cup y \cup g \cup b \cup s\}$
j: Finishing nodes $j \in \{r \cup y \cup g \cup o \cup e \cup d \cup p \cup s \cup b \cup l \cup f \cup m\}$

Decision variables in period t

xwr_{wrt}: Transported gas volume from gas well to the refinery
xwo_{wot}: Transported gas volume from gas well to the oil well
xry_{ryt}: Transported gas volume from refinery to the compressor station
xro_{rot}: Transported gas volume from refinery to the oil well
xay_{ayt}: Transported gas volume from importation to the compressor station
xys_{yst}: Transported gas volume from compressor station to the storage tank
xsy_{syt}: Transported gas volume from storage tank to the compressor station
xye_{yet}: Transported gas volume from compressor station to the exportation
xyd_{ydt}: Transported gas volume from compressor station to the industrial customer
xyp_{ypt}: Transported gas volume from compressor station to the power plant customer
$xyy'_{yy't}$: Transported gas volume from compressor station to the another compressor station
xyg_{ygt}: Transported gas volume from compressor station to the city gate station
xgm_{gmt}: Transported gas volume from city gate station to the small industrial customer
xgb_{gbt}: Transported gas volume from city gate station to the town bordering station
xbl_{blt}: Transported gas volume from town bordering station to the residential customer
xbf_{bft}: Transported gas volume from town bordering station to the commercial customer

Capacity parameters in period t

oc_{ot}: Delivery capacity of oil well
wc_{wt}: Capacity of gas well
ac_{at}: Capacity of importation
rc_{rt}: Capacity of refinery
yc_{yt}: Capacity of compressor station
gc_{gt}: Capacity of city gate station
bc_{bt}: Capacity of town bordering station

Fuel parameters

βr: Fuel consumption coefficient of refinery
βy: Fuel consumption coefficient of compressor station
βg: Fuel consumption coefficient of city gate station

Volume parameters

α_1: Decreased volume coefficient consequence of liquids analysis in the refinery as equal liquid product type one

α_2: Decreased volume coefficient consequence of liquids analysis in the refinery as equal liquid product type two

α_3: Decreased volume coefficient consequence of liquids analysis in the refinery as equal liquid product type three

α_4: Decreased volume coefficient consequence of liquids analysis in the refinery as equal liquid product type four

α_5: Decreased volume coefficient consequence of liquids analysis in the refinery as equal water product type five

α_{3i}: Percent of α_3 as equal liquid product type three for internal consumption $\alpha_{3i\%} + \alpha_{3e\%} = 1$
α_{3e}: Percent of α_3 as equal liquid product type three for exportation consumption
α_{4i}: Percent of α_4 as equal liquid product type four for internal consumption $\alpha_{4i\%} + \alpha_{4e\%} = 1$
α_{4e}: Percent of α_4 as equal liquid product type four for exportation consumption

Demand parameters in period t

od_{ot}: Demand volume of oil well

ed_{et}: Demand volume of exportation
dd_{dt}: Demand volume of industrial customer
pd_{pt}: Demand volume of power plant customer
ld_{lt}: Demand volume of residential customer
fd_{ft}: Demand volume of commercial customer
md_{mt}: Demand volume of small industrial customer
eld_{rt}: Demand volume of equal liquid products in the refinery

Route parameters

d_{ij}: length of the unique route between node *i* and node *j*
h_{ij}: Hardness coefficient of the unique route between node *i* and node *j*
ʎ_{ij}: If there is a unique route between node *i* and node *j*, *1* otherwise *0*
Q_{ij}^{Min} : Minimum flow unique route between node *i* and node *j*
Q_{ij}^{Max} : Maximum flow unique route between node *i* and node *j*

Greenhouse gas emissions parameters

gw: Average amount of greenhouse gas emissions produced by gas well per unit
gr: Average amount of greenhouse gas emissions produced by refinery per unit
gy: Average amount of greenhouse gas emissions produced by compressor station per unit
gg: Average amount of greenhouse gas emissions produced by city gate station per unit
gb: Average amount of greenhouse gas emissions produced by town bordering station per unit
go: Average amount of greenhouse gas emissions produced by oil well per unit
gd: Average amount of greenhouse gas emissions produced by industrial customer per unit
gp: Average amount of greenhouse gas emissions produced by power plant customer per unit
gl: Average amount of greenhouse gas emissions produced by residential customer per unit
gf: Average amount of greenhouse gas emissions produced by commercial customer per unit
gm: Average amount of greenhouse gas emissions produced by small industrial customer per unit
gs: Average amount of greenhouse gas emissions produced by storage tank per unit
$g\alpha_{3i}$: Average amount of greenhouse gas emissions produced by equal liquid product type three per unit
$g\alpha_{4i}$: Average amount of greenhouse gas emissions produced by equal liquid product type four per unit

Cost parameters in period t

cw_{wt}: Cost of supply by gas well per unit
ca_{at}: Cost of supply by importation per unit
cr_{rt}: Cost of production by refinery per unit
cy_{yt}: Operation cost of compressor station per unit
cg_{gt}: Operation cost of city gate station per unit
cb_{bt}: Operation cost of town bordering station per unit
cs_{st}: Operation cost of storage tank per unit
ct: Transportation cost per product unit per distance unit
sc: Social cost caused by per unit of greenhouse gas emissions (Convert parameter)

Penalty parameters

c_1: Penalty per underutilized capacity unit of gas well
c_2: Penalty per underutilized capacity unit of refinery
c_3: Penalty per underutilized capacity unit of compressor station
c_4: Penalty per underutilized capacity unit of city-gate station
c_5: Penalty per underutilized capacity unit of town bordering station

Price parameters in period t

Pwo_{wot}: Selling price of gas product by gas well for oil well per unit
Pro_{rot}: Selling price of gas product by refinery for oil well per unit
Pye_{yet}: Selling price of gas product by compressor station for exportation per unit
Pyd_{ydt}: Selling price of gas product by compressor station for industrial customer per unit
Pyp_{ypt}: Selling price of gas product by compressor station for power plant customer per unit
Pgm_{gmt}: Selling price of gas product by city gate station for small industrial customer per unit

Pbl_{blt}:	Selling price of gas product by town bordering station for residential customer per unit
Pbf_{bft}:	Selling price of gas product by town bordering station for commercial customer per unit
$P\alpha_{1t}$:	Selling price of equal liquid product as type one per unit
$P\alpha_{2t}$:	Selling price of equal liquid product as type two per unit
$P\alpha_{3it}$:	Selling price of equal liquid product as type three for internal consumption per unit
$P\alpha_{3et}$:	Selling price of equal liquid product as type three for exportation per unit
$P\alpha_{4it}$:	Selling price of equal liquid product as type four for internal consumption per unit
$P\alpha_{4et}$:	Selling price of equal liquid product as type four for exportation per unit

3.1. Mathematical Model

Multi-objective functions of the proposed model are presented as follows:

Z_1: Maximizing the total revenue of gas products

$$
\begin{aligned}
Max\ Z_1 = &\left(\sum_w\sum_o\sum_t xwo_{wot}\times Pwo_{wot}\right)+\left(\sum_r\sum_o\sum_t xro_{rot}\times pro_{rot}\right)+\\
&\left(\sum_y\sum_e\sum_t xye_{yet}\times Pye_{yet}\right)+\left(\sum_y\sum_d\sum_t xyd_{ydt}\times pyd_{ydt}\right)+\\
&\left(\sum_y\sum_p\sum_t xyp_{ypt}\times Pyp_{ypt}\right)+\left(\sum_g\sum_m\sum_t xgm_{gmt}\times pgm_{gmt}\right)+\\
&\left(\sum_b\sum_l\sum_t xbl_{blt}\times Pbl_{blt}\right)+\left(\sum_b\sum_f\sum_t xbf_{bft}\times pbf_{bft}\right)+\\
&\left(\sum_w\sum_r\sum_t xwr_{wrt}\times \alpha_1\times P\alpha_{1t}\right)+\left(\sum_W\sum_r\sum_t xwr_{wrt}\times \alpha_2\times P\alpha_{2t}\right)+\\
&\left(\sum_w\sum_r\sum_t xwr_{wrt}\times \alpha_{3e}\times P\alpha_{3et}\right)+\left(\sum_W\sum_r\sum_t xwr_{wrt}\times \alpha_{3i}\times P\alpha_{3it}\right)+\\
&\left(\sum_w\sum_r\sum_t xwr_{wrt}\times \alpha_{4e}\times P\alpha_{4et}\right)+\left(\sum_W\sum_r\sum_t xwr_{wrt}\times \alpha_{4i}\times P\alpha_{4it}\right)
\end{aligned}
\tag{1}
$$

Z_2: Minimizing the economic costs

$$
\begin{aligned}
Min\ Z_2 = &\sum_w\sum_r\sum_t xwr_{wrt}\left(cw_{wt}+d_{wr}h_{wr}ct\right)+\sum_w\sum_o\sum_t xwo_{wot}\left(cw_{wt}+d_{wo}h_{wo}ct\right)+\\
&\sum_r\sum_y\sum_t xry_{ryt}\left(cr_{rt}+d_{ry}h_{ry}ct\right)+\sum_r\sum_o\sum_t xro_{rot}\left(cr_{rt}+d_{ro}h_{ro}ct\right)+\\
&\sum_a\sum_y\sum_t xay_{ayt}\left(ca_{at}+d_{ay}h_{ay}ct\right)+\sum_y\sum_{\acute{y}}\sum_t xy\acute{y}_{y\acute{y}t}\left(cy_{yt}+d_{y\acute{y}}h_{y\acute{y}}ct\right)+\\
&\sum_y\sum_g\sum_t xyg_{ygt}\left(cy_{yt}+d_{yg}h_{yg}ct\right)+\sum_y\sum_s\sum_t xys_{yst}\left(cy_{yt}+d_{ys}h_{ys}ct\right)+\\
&\sum_s\sum_y\sum_t xsy_{syt}\left(cs_{st}+d_{sy}h_{sy}ct\right)+\sum_y\sum_e\sum_t xye_{yet}\left(cy_{yt}+d_{ye}h_{ye}ct\right)+\\
&\sum_y\sum_d\sum_t xyd_{ydt}\left(cy_{yt}+d_{yd}h_{yd}ct\right)+\sum_y\sum_p\sum_t xyp_{ypt}\left(cy_{yt}+d_{yp}h_{yp}ct\right)+\\
&\sum_g\sum_m\sum_t xgm_{gmt}\left(cg_{gt}+d_{gm}h_{gm}ct\right)+\sum_g\sum_b\sum_t xgb_{gbt}\left(cg_{gt}+d_{gb}h_{gb}ct\right)+\\
&\sum_b\sum_l\sum_t xbl_{blt}\left(cb_{bt}+d_{bl}h_{bl}ct\right)+\sum_b\sum_f\sum_t xbf_{bft}\left(cb_{bt}+d_{bf}h_{bf}ct\right)
\end{aligned}
\tag{2}
$$

Z_3: Minimizing the environmental costs

$$Min\ Z_3 = \mathrm{sc}\Bigg\{ gw\left[\sum_w\sum_r\sum_t xwr_{wrt} + \sum_w\sum_o\sum_t xwo_{wot}\right] + gr\left[\sum_r\sum_y\sum_t xry_{ryt} + \sum_r\sum_o\sum_t xro_{rot}\right] + gy\left[\sum_y\sum_{\acute{y}}\sum_t xy\acute{y}_{y\acute{y}t} + \sum_y\sum_g\sum_t xyg_{ygt} + \sum_y\sum_s\sum_t xys_{yst} + \sum_y\sum_e\sum_t xye_{yet} + \sum_y\sum_d\sum_t xyd_{ydt} + \sum_y\sum_p\sum_t xyp_{ypt}\right] + gs\left[\sum_s\sum_y\sum_t xsy_{syt}\right] + gg\left[\sum_g\sum_b\sum_t xgb_{gbt} + \sum_g\sum_m\sum_t xgm_{gmt}\right] + gb\left[\sum_b\sum_l\sum_t xbl_{blt} + \sum_b\sum_f\sum_t xbf_{bft}\right] + go\left[\sum_w\sum_o\sum_t xwo_{wot} + \sum_r\sum_o\sum_t xro_{rot}\right] + \left[gd\sum_y\sum_d\sum_t xyd_{ydt} + gp\sum_y\sum_p\sum_t xyp_{ypt} + gl\sum_b\sum_l\sum_t xbl_{blt} + gf\sum_b\sum_f\sum_t xbf_{bft} + gm\sum_g\sum_m\sum_t xgm_{gmt} + \left(g\alpha_{3i}\sum_w\sum_r\sum_t xwr_{wrt}\times\alpha_{3i}\right) + \left(g\alpha_{4i}\sum_W\sum_r\sum_t xwr_{wrt}\times\alpha_{4i}\right)\right]\Bigg\} \tag{3}$$

Z_4: Minimizing the penalty per underutilized capacity

$$Min\ Z_4 = \left(\sum_w\sum_r\sum_t xwr_{wrt} + \sum_w\sum_o\sum_t xwo_{wot} - \sum_w\sum_t wc_{wt}\right)C_1 + \left(\sum_r\sum_y\sum_t xry_{ryt} + \sum_r\sum_o\sum_t xro_{rot} + \sum_w\sum_r\sum_t xwr_{wrt}\times(\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5+\beta_r) - \sum_r\sum_t rc_{rt}\right)C_2 + \left(\left(\sum_y\sum_{\acute{y}}\sum_t xy\acute{y}_{y\acute{y}t} + \sum_y\sum_g\sum_t xyg_{ygt} + \sum_y\sum_s\sum_t xys_{yst} + \sum_y\sum_e\sum_t xye_{yet} + \sum_y\sum_d\sum_t xyd_{ydt} + \sum_y\sum_p\sum_t xyp_{ypt}\right) + \left(\sum_r\sum_y\sum_t xry_{ryt} + \sum_a\sum_y\sum_t xay_{ayt} + \sum_s\sum_y\sum_t xsy_{syt} + \sum_{\acute{y}}\sum_y\sum_t x\acute{y}y_{\acute{y}yt}\times\beta_y - \sum_y\sum_t yc_{yt}\right)\right)C_3 +$$

$$\left(\sum_{g}\sum_{m}\sum_{t} xgm_{gmt} + \sum_{g}\sum_{b}\sum_{t} xgb_{gbt} + \sum_{y}\sum_{g}\sum_{t} xyg_{ygt} \times \beta_g - \sum_{g}\sum_{t} gc_{gt}\right) C_4$$
$$+ \left(\sum_{b}\sum_{l}\sum_{t} xbl_{blt} + \sum_{b}\sum_{f}\sum_{t} xbf_{bft} - \sum_{b}\sum_{t} bc_{bt}\right) C_5 \quad (4)$$

Z_5: Maximizing the service level gas in period t

$$Max\ Z_5 = \quad SL \quad (5)$$

Equation (1) refers to the total revenue of gas products along the supply chain. This objective function is considered as the price of gas products and each section of it is as follows:
1-1: Selling price of gas product by gas wells for oil wells
1-2: Selling price of gas product by refineries for oil wells
1-3: Selling price of gas product by compressor stations for exportations, industrials, and Power plants
1-4: Selling price of gas product by city gate stations for small industrials
1-5: Selling price of gas product by town bordering stations for residential and commercial customers
1-6: Selling price of equal liquid products as type one and two for exportation
1-7: Selling price of equal liquid products as type three and four for internal consumption
1-8: Selling price of equal liquid products as type three and four for exportation
Equation (2) refers to the economic costs along the supply chain. This objective function is considered as the cost of supplying at each level and the cost of transmission to the next level and each section of it is as follows:
2-1: Supply cost by gas wells and transmission to the refineries
2-2: Supply cost by gas wells and transmission for sour gas injection to oil wells
2-3: Production cost by refinery and transmission to the compressor stations
2-4: Supply cost by importations and transmission to the compressor stations
2-5: Production cost by refinery and transmission for sweet gas injection to the oil wells
2-6: Operation cost of compressor station y and transmission to other compressor Stations ŷ
2-7: Operation cost of compressor station and transmission to city-gate stations, storage tanks, exportations, industrials and power plants
2-8: Operation cost of storage tank and transmission to compressor stations
2-9: Operation cost of city-gate station and transmission to town bordering station and small industrials
2-10: Operation cost of town bordering station and transmission to residential and commercial customers

Equation (3) refers to the costs of emission of greenhouse gases along the supply chain. This objective function is considered as the average amount of emission of greenhouse gases at all levels of the supply chain including supply and demand by gas wells, oil wells, refineries, equal liquid products type three and four, compressor stations, storage tanks, industrials, power plants, city-gate stations, town bordering stations, small industrials, residential customers and commercial customer.

Equation (4) refers to the penalty per underutilized capacity along the supply chain or recovery. This objective function is considered as the fines resulting from the use of low-capacity equipment or gas transmission at total levels, and each section of it is as follows:
4-1: The gas transmission or capacity of equipment form gas wells to oil wells and refineries and the associated shortage penalty
4-2: The gas transmission or capacity of equipment form refineries to oil wells and compressor stations and the associated shortage penalty
4-3: The gas transmission or capacity of equipment form compressor stations to another compressor stations, city gate stations, storage tanks, exportations, industrials and power plants and the associated shortage penalty
4-4: The gas transmission or capacity of equipment form city gate stations to town bordering stations and small industrials and the associated shortage penalty
4-5: The gas transmission or capacity of equipment form town bordering stations to residential and commercial customers and the associated shortage penalty

Equation (5) refers to the service level at consumption nodes along the supply chain.

Constraints of the proposed model are as follows:

$$\sum_{w} xwo_{wot} + \sum_{r} xro_{rot} \geq od_{ot} \qquad \forall o, t \tag{6}$$

$$\sum_{y} xye_{yet} \geq ed_{et} \qquad \forall e, t \tag{7}$$

$$\sum_{y} xyd_{ydt} \geq dd_{dt} \qquad \forall d, t \tag{8}$$

$$\sum_{y} xyp_{ypt} \geq Pd_{pt} \qquad \forall P, t \tag{9}$$

$$\sum_{b} xbl_{blt} \geq ld_{lt} \qquad \forall l, t \tag{10}$$

$$\sum_{b} xbf_{bft} \geq fd_{ft} \qquad \forall f, t \tag{11}$$

$$\sum_{g} xgm_{gmt} \geq md_{mt} \qquad \forall m, t \tag{12}$$

$$\sum_{w} xwr_{wrt} \times (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4) \geq eld_{rt} \quad \forall r, t \tag{13}$$

Constraints (6) – (13) guarantee demand satisfaction for each oil well, exportation, industrial, power plant, residential, commercial, small industrial and equal liquid products, respectively.

$$\sum_{r} xwr_{wrt} + \sum_{o} xwo_{wot} \leq wc_{wt} \qquad \forall w, t \tag{14}$$

$$\sum_{y} xay_{ayt} \leq ac_{at} \qquad \forall a, t \tag{15}$$

$$\sum_{y} xry_{ryt} + \sum_{o} xro_{rot} + \sum_{w} xwr_{wrt} \times (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5) \leq rc_{rt} \qquad \forall r, t \tag{16}$$

$$\sum_{g} xyg_{ygt} + \sum_{s} xys_{yst} + \sum_{e} xye_{yet} + \sum_{d} xyd_{ydt} + \sum_{p} xyp_{ypt} + \sum_{\acute{y}} xy\acute{y}_{y\acute{y}t} \leq yc_{yt} \quad \forall y, t \tag{17}$$

$$\sum_b xgb_{gbt} + \sum_m xgm_{gmt} \leq gc_{gt} \qquad \forall g, t \tag{18}$$

$$\sum_l xbl_{blt} + \sum_f xbf_{bft} \leq bc_{bt} \qquad \forall b, t \tag{19}$$

$$\sum_y \sum_{\acute{t}=1}^{t} xys_{ys\acute{t}} - \sum_y \sum_{\acute{t}=1}^{t} xsy_{sy\acute{t}} \geq o \quad \forall s, t \tag{20}$$

$$\sum_y \sum_{\acute{t}=1}^{t} xys_{ys\acute{t}} - \sum_y \sum_{\acute{t}=1}^{t} xsy_{sy\acute{t}} \leq sc_s \ \forall s, t \tag{21}$$

The importation, refinery, compressor station, city-gate station, town bordering station and storage tank capacity of each gas well are represented by constraints (14) – (21), respectively.

$$\sum_w xwr_{wrt} = \sum_y xry_{ryt} + \sum_o xro_{rot} + \sum_w xwr_{wrt} \times (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \beta_r) \quad \forall r, t \tag{22}$$

$$\left(\sum_{r} xry_{ryt} + \sum_{a} xay_{ayt} + \sum_{s} xsy_{syt} + \sum_{\acute{y}} x\acute{y}y_{\acute{y}yt} \right) =$$

$$\sum_g xyg_{ygt} + \sum_s xys_{yst} + \sum_e xye_{yet} + \sum_d xyd_{ydt} + \sum_p xyp_{ypt} + \sum_{\acute{y}} xy\acute{y}_{y\acute{y}t} + \left(\sum_r xry_{ryt} + \sum_a xay_{ayt} + \sum_s xsy_{syt} + \sum_{\acute{y}} x\acute{y}y_{\acute{y}yt}\right) \times \beta_y \qquad \forall y,t \tag{23}$$

$$\sum_y xyg_{ygt} = \sum_b xgb_{gbt} + \sum_m xgm_{gmt} + \sum_y xyg_{ygt} \times \beta_g \qquad \forall g,t \tag{24}$$

$$\sum_g xgb_{gbt} = \sum_l xbl_{blt} + \sum_f xbf_{bft} \qquad \forall b,t \tag{25}$$

Equations (22) – (25) represent the flow balance constraints in each refinery, compressor station, city gate station and town bordering station, respectively.

$$xwr_{wrt} \le M\lambda_{wr}, xwo_{wot} \le M\lambda_{wo}, xry_{ryt} \le M\lambda_{ry}, xay_{ayt} \le M\lambda_{ay} \tag{26}$$

$$xro_{rot} \le M\lambda_{ro}, xy\acute{y} \le M\lambda_{y\acute{y}}, xyg_{ygt} \le M\lambda_{yg}, xye_{yet} \le M\lambda_{ye} \tag{27}$$

$$xyd_{ydt} \le M\lambda_{yd}, xyp_{ypt} \le M\lambda_{yp}, xys_{yst} \le M\lambda_{ys}, xsy_{syt} \le M\lambda_{sy} \tag{28}$$

$$xgb_{gbt} \le M\lambda_{gb}, xgm_{gmt} \le M\lambda_{gm}, xbl_{blt} \le M\lambda_{bl}, xbf_{bft} \le M\lambda_{bf} \tag{29}$$

Equations (26) – (29) show the constraints on presence/absence of a path in the model. Parameter λ represents the presence or absence of a certain path. If this parameter accepts a value of 1, the corresponding decision variable can take a value, otherwise the corresponding decision variable is zero**.** (M is a big number).

$$\lambda_{wr}Q_{wr}^{min} \le xwr_{wrt} \le \lambda_{wr}Q_{wr}^{max} \qquad \forall w,r \tag{30}$$

$$\lambda_{wo}Q_{wo}^{min} \le xwo_{wot} \le \lambda_{wo}Q_{wo}^{max} \qquad \forall w,o \tag{31}$$

$$\lambda_{ro}Q_{ro}^{min} \le xro_{rot} \le \lambda_{ro}Q_{ro}^{max} \qquad \forall r,o \tag{32}$$

$$\lambda_{ry}Q_{ry}^{min} \le xry_{ryt} \le \lambda_{ry}Q_{ry}^{max} \qquad \forall r,y \tag{33}$$

$$\lambda_{ay}Q_{ay}^{min} \le xay_{ayt} \le \lambda_{ay}Q_{ay}^{max} \qquad \forall a,y \tag{34}$$

$$\lambda_{y\acute{y}}Q_{y\acute{y}}^{min} \le xy\acute{y}_{y\acute{y}t} \le \lambda_{y\acute{y}}Q_{y\acute{y}}^{max} \qquad \forall y,\acute{y} \tag{35}$$

$$\lambda_{yg}Q_{yg}^{min} \le xyg_{ygt} \le \lambda_{yg}Q_{yg}^{max} \qquad \forall y,g \tag{36}$$

$$\lambda_{ye}Q_{ye}^{min} \le xye_{yet} \le \lambda_{ye}Q_{ye}^{max} \qquad \forall y,e \tag{37}$$

$$\lambda_{yd}Q_{yd}^{min} \le xyd_{ydt} \le \lambda_{yd}Q_{yd}^{max} \qquad \forall y,d \tag{38}$$

$$\lambda_{yp}Q_{yp}^{min} \le xyp_{ypt} \le \lambda_{yp}Q_{yp}^{max} \qquad \forall y,p \tag{39}$$

$$\lambda_{ys}Q_{ys}^{min} \le xys_{yst} \le \lambda_{ys}Q_{ys}^{max} \qquad \forall y,s \tag{40}$$

$$\lambda_{sy}Q_{sy}^{min} \le xsy_{syt} \le \lambda_{sy}Q_{sy}^{max} \qquad \forall s,y \tag{41}$$

$$\lambda_{gb}Q_{gb}^{min} \le xgb_{gbt} \le \lambda_{gb}Q_{gb}^{max} \qquad \forall g,b \tag{42}$$

$$\lambda_{gm}Q_{gm}^{min} \le xgm_{gmt} \le \lambda_{gm}Q_{gm}^{max} \qquad \forall g,m \tag{43}$$

$$\lambda_{bl}Q_{bl}^{min} \le xbl_{blt} \le \lambda_{bl}Q_{bl}^{max} \qquad \forall b,l \tag{44}$$

$$\lambda_{bf}Q_{bf}^{min} \le xbf_{bft} \le \lambda_{bf}Q_{bf}^{max} \qquad \forall b,f \tag{45}$$

Equations (30) – (45) represent the guarantee continuing net flow constraints. This set of constraints represents the range of possible physical flows that are limited to certain lower and upper bounds. These bounds are determined based on pipeline diameters, and the primal and secondary gas pressure in the related nodes.

$$SLG_t = \frac{\sum_w\sum_o xwo+\sum_r\sum_o xro+\sum_y\sum_e xye+\sum_y\sum_d xyd+\sum_y\sum_p xyp+\sum_b\sum_l xbl+\sum_b\sum_f xbf+\sum_g\sum_m xgm+\sum_w\sum_r xwr\times(\alpha_1+\alpha_2+\alpha_3+\alpha_4)}{\sum_o od_{ot}+\sum_e ed_{et}+\sum_d dd_{dt}+\sum_p pd_{pt}+\sum_l ld_{lt}+\sum_f fd_{ft}+\sum_m md_{mt}+\sum_r eld_{elt}} \tag{46}$$

$$SL \le SLG_t \qquad \forall\, t \in T \tag{47}$$

Equation (46) shows the Service level gas constraint in period t that is defined for inventory or impacted gas line volume along supply chain and at consumption nodes, divided by the total demand. A new decision variable defined as a minimum target for the service level (SL), Equation (47), and the model then maximizes the minimum amount of the service level gas at any period t.

Xij_{ijt}, SLG_t, SL, t, ≥ 0 (48)

Equation (48) denotes that Xij_{ijt}, SLG_t, SL, and t are equal to or greater than 0.

3.2. Problem Solving Approach

Multi-objective problems solving methods are classified into three categories based on decision-makers' preferences. These categories are the priori, interactive, and posteriori approaches (Hwang and Masud, 2012). In the priori approach, the decision-maker is rolled before the problem is resolved. While in the interactive approach, it usually converges to the best after several iterations. The main defect of the first and second categories is that the decision-maker does not have a general view about the trade-off before getting the Pareto optimal set. To avoid the mentioned defect, in the posteriori approach, such as the ε-constraint approach, at first, the set of Pareto optimal points are generated, then the decision-maker selects among them. In the ε-constraint approach, the objective function with the highest priority is optimized by adding the other objectives as unbinding constraints. Then the set of Pareto optimal points, including the weakly efficient solutions, is generated. To eliminate the weakly efficient solutions, Mavrotas and Florios (2013) developed a new issue of the ε-constraint algorithm called an augmented ε-constrained to generate Pareto optimal solutions without the weakly efficient solutions by adding the other objectives as binding constraints. Therefore, the augmented ε -constraint algorithm avoids the generation of weakly Pareto optimal solutions and accelerates the whole process by avoiding redundant iterations. The multi-objective model in this paper has been solved using the Improved Augmented ε-Constraint algorithm.

3.2.1. Fuzzy goal programming (FGP) Method

Fuzzy goal programming approach has been a universal method for solving multi-objective supply chain problems. Several usages have been investigated in a supply chain network design (Fahimnia and Jabbarzadeh, 2016; Touil et al., 2019). Equations (49) – (53) formulate the degree of satisfaction of each goal (Fahimnia and Jabbarzadeh, 2016; Tiwari et al., 1987).

$$\text{Degree of satisfaction of goal } 1 = \mu_1 = \frac{\text{Obj}_1 - \varepsilon_1}{\text{AL}_1 - \varepsilon_1} \quad (49)$$

$$\text{Degree of satisfaction of goal } 2 = \mu_2 = \frac{\varepsilon_2 - \text{Obj}_2}{\varepsilon_2 - \text{AL}_2} \quad (50)$$

$$\text{Degree of satisfaction of goal } 3 = \mu_3 = \frac{\varepsilon_3 - \text{Obj}_3}{\varepsilon_3 - \text{AL}_3} \quad (51)$$

$$\text{Degree of satisfaction of goal } 4 = \mu_4 = \frac{\varepsilon_4 - \text{Obj}_4}{\varepsilon_4 - \text{AL}_4} \quad (52)$$

$$\text{Degree of satisfaction of goal } 5 = \mu_5 = \frac{\text{Obj}_5 - \varepsilon_5}{\text{AL}_5 - \varepsilon_5} \quad (53)$$

Where AL_1–AL_5 define the aspiration levels of the objectives 1–5, respectively, ε_1 and ε_5 represent the lower tolerance limits for the total revenue of gas products (AL_1) and total service level gas (AL_5) situations, respectively. ε_2, ε_3 and ε_4 define the upper tolerance limits for the economic costs (AL_2), the costs of emission of greenhouse gases (AL_3) and the penalty per underutilized capacity (AL_4) situations, respectively. Regarding the fuzzy goal programming approach, the obtained values of the absolute priorities method for the aspiration levels and the obtained values of the payoff results for the lower and upper tolerance limits for each aspiration level are presented in the Table 2. According to the definition by Tiwari et al. (1987), the objective function of the fuzzy goal programming model is as follows:

$$Maximize f(\mu) = \sum_{i=1}^{5} W_i \mu_i \quad (54)$$

The fuzzy goal programming model is subject to:

Constraints (6) – (53)

In the objective function of the obtained deterministic model that follows the Tiwari's method, it was aimed to maximize the total satisfaction levels of the goals, for which all the values of satisfaction membership degree were summed up. The point to be considered is the different importance of each of the goals for decision makers. Therefore, it is necessary to determine the weight of each goal by one of the common methods of determining weights by decision-makers (Tiwari et al., 1987). Then each of these weights is multiplied by the degree of satisfaction of the corresponding goal; and finally, the results of each value are summed up, and the objective function will seek to maximize the obtained equation. In this paper, the fuzzy goal programming (FGP) model has been solved using GAMS 24.1.2 software in order to compare its results with the results of the proposed ε-constraint approach.

Table2. Aspiration levels values and tolerance limits

AL_1	7.9E+09	lower	7.889604E+9
AL_2	3.45E+08	upper	3.735181E+8
AL_3	1787535	upper	1925681.020
AL_4	94100.92	upper	266407.409
AL_5	1.083891	lower	1.020

4. Case study

Any process that takes place requires the use of a series of data and resources (Esfandiar et al., 2018). In this research, the multi-objective model has been solved using the improved augmented ε-constraint algorithm. The improved augmented ε-constraint is accorded and practiced in the GAMS 24.1.2–64 bit to solve the presented multi-objective model using the CPLEX solver. The specifications of the PC used to run the software are as follows: Intel Corei5 3.4 GHz processor with 4 GB of RAM. For verifying and validating the proposed model, a small-sized problem with real data has been solved. The natural gas supply chain of the problem includes forty-one gas wells, six oil wells, eight refineries, nine compressor stations, two storage tanks, ten city-gate stations, dispatching, twenty town bordering stations, two origin of importation, five exportation customers, two industrial customers, three power plant customers, twenty residential customers, three commercial customers, and four small industrial customers. The model statistics and a small-size of the natural gas supply chain are shown in the Table 3 and Fig. 2, respectively.

Table3. Model Statistics

Blocks of Equations	77	Single Equations	63,862
Blocks of Variables	21	Single Variables	20,531
Non Zero Elements	219,128		

5. Discussions

In this section, the obtained payoff table and Pareto optimal solutions and the mentioned real case study are analyzed. Table 4 epitomizes the payoff results obtained by the lexicographic optimization of the five objectives, as follows: Firstly, the problem is optimized as a single objective problem, including maximizing the total revenue Obj_1 (9.097676E+9). Then, the economic costs Obj_2 (3.735181E+8) are optimized by adding the obtained total revenue value as a constraint. In the following, the environmental costs of emission of greenhouse gases Obj_3 (1925681.020) are optimized by adding the obtained total revenue and economic costs as a constraint. After that, the penalty per underutilized capacity Obj_4 (266407.409) is optimized by adding the obtained total revenue value, economic costs and environmental costs as a constraint. Eventually, the service level Obj_5 (1.078) is optimized by adding the obtained total revenue value, economic costs, environmental costs, and penalty per underutilized capacity, as a constraint. The same procedure is repeated considering the economic costs, environmental costs, penalty per underutilized capacity and service level shown in the second, third, fourth and fifth rows, respectively.

Table4. Payoff results of the five objectives for 12 months.

	Obj_1	Obj_2	Obj_3	Obj_4	Obj_5
Max Obj_1	9.097676E+9	3.735181E+8	1925681.020	266407.409	1.078
Min Obj_2	7.978580E+9	3.222105E+8	1792972.364	95158.187	1.021
Min Obj_3	7.891647E+9	3.425925E+8	1769560.560	83154.650	1.020
Min Obj_4	7.889604E+9	3.427223E+8	1782140.178	83154.650	1.020
Max Obj_5	9.092699E+9	3.671147E+8	1887791.744	231342.576	1.084

In the following, the Pareto optimal solutions consisting of 28 categories for 5 objective functions are generated. The decision makers have to select the preferred scheme based on their selected criteria. The best scheme for the first and fifth objectives gives a high total revenue of 9.085000E+9 /12 months and a high service level of 1.084, but with high total cost of economic, environmental and penalty per underutilized capacity /12 months. Therefore, a high total revenue and a low total cost cannot be achieved. The worst scheme for the first and fifth objectives gives low values for total revenue of 7.900000E+9 /12 months and a service level of 1.019, and a low total cost of economic, environmental and penalty per underutilized capacity /12 months. Consequently, there are big trade-offs among the five objective functions. It is obvious that as the total revenue increases, total economic cost increases. Accordingly, decision makers have to select the preferred scheme. Results of the Pareto optimal solutions are shown in Table 5. On the other hand, objectives values of the fuzzy goal programming method are shown in the Table 6 and Fig.3 in order to be compared with the payoff results.

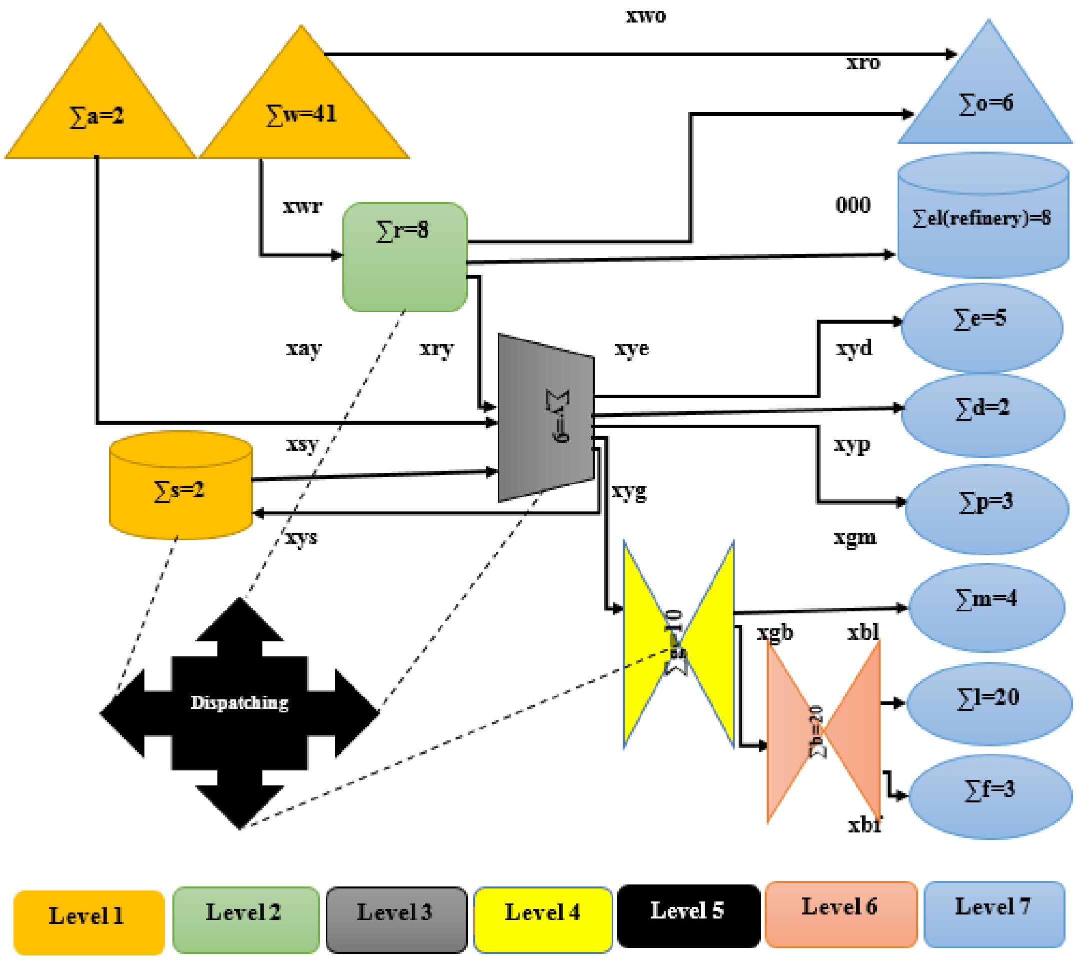

Figure 2. A small-size of the natural gas supply chain

Table5. Results of the Pareto Optimal Solutions for 12 months.

	Obj_1	Obj_2	Obj_3	Obj_4	Obj_5
1	7.900000E+9	3.415500E+8	1769659.650	82808.810	1.019
2	7.900000E+9	3.415500E+8	1769659.650	84690.828	1.019
3	7.900000E+9	3.415500E+8	1787535.000	82808.810	1.019
4	8.137000E+9	3.208500E+8	1805410.350	117626.150	1.051
5	8.137000E+9	3.208500E+8	1823285.700	117626.150	1.051
6	8.216000E+9	3.208500E+8	1805410.350	117626.150	1.030
7	8.216000E+9	3.208500E+8	1823285.700	117626.150	1.030
8	8.532000E+9	3.553500E+8	1876911.750	175027.711	1.073
9	8.532000E+9	3.588000E+8	1876911.750	175027.711	1.084
10	8.690000E+9	3.484500E+8	1841161.050	175027.711	1.030
11	8.690000E+9	3.484500E+8	1841161.050	175027.711	1.051
12	8.690000E+9	3.484500E+8	1841161.050	175027.711	1.084
13	8.690000E+9	3.484500E+8	1859036.400	175027.711	1.030
14	8.690000E+9	3.484500E+8	1859036.400	175027.711	1.051
15	8.690000E+9	3.484500E+8	1859036.400	175027.711	1.084
16	8.690000E+9	3.588000E+8	1841161.050	175027.711	1.051
17	8.690000E+9	3.588000E+8	1841161.050	175027.711	1.084
18	8.769000E+9	3.553500E+8	1841161.050	175027.711	1.030
19	8.848000E+9	3.484500E+8	1841161.050	190083.858	1.084
20	8.848000E+9	3.588000E+8	1841161.050	189142.849	1.084
21	8.927000E+9	3.484500E+8	1841161.050	195729.914	1.051
22	8.927000E+9	3.484500E+8	1841161.050	198552.941	1.030
23	8.927000E+9	3.622500E+8	1841161.050	194788.904	1.051

Table5. Continued

	Obj_1	Obj_2	Obj_3	Obj_4	Obj_5
24	8.927000E+9	3.622500E+8	1841161.050	197611.932	1.030
25	9.006000E+9	3.484500E+8	1930537.800	262541.567	1.062
26	9.085000E+9	3.484500E+8	1894787.100	234311.291	1.084
27	9.085000E+9	3.726000E+8	1930537.800	266305.604	1.062
28	9.085000E+9	3.726000E+8	1930537.800	266305.604	1.084

Table6. Objectives values and objective function of the fuzzy goal programming method

Obj_1	Obj_2	Obj_3	Obj_4	Obj_5	$f(\mu)$
7.9E+09	3.45E+08	1809853.031645	94906.147294	1.083891	0.967738

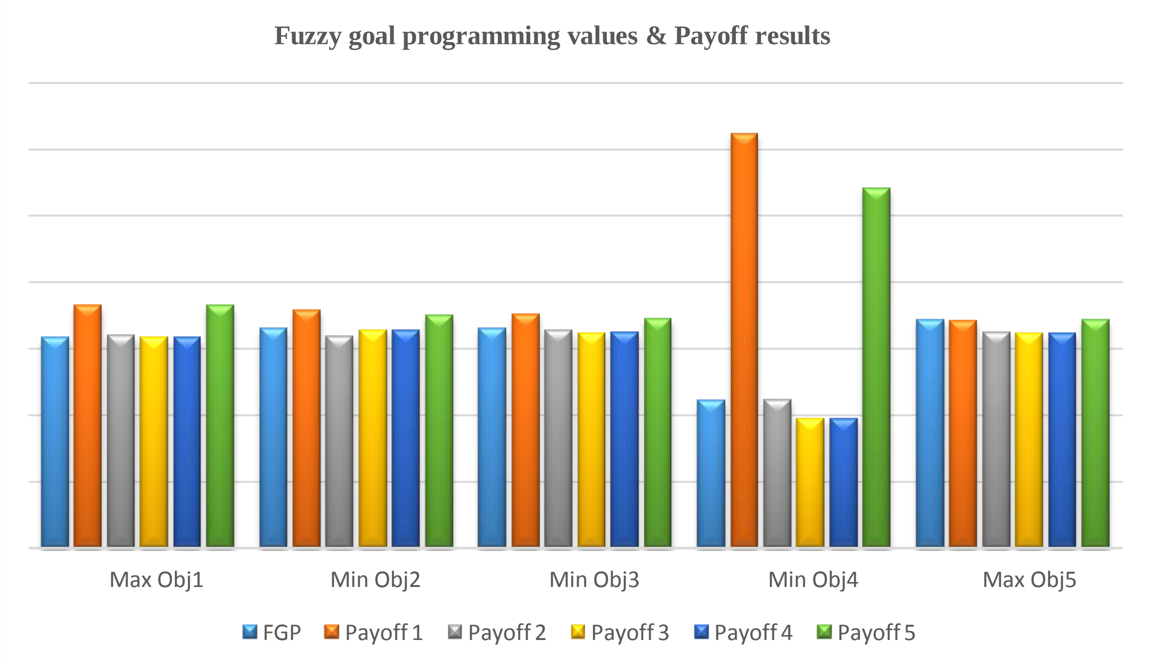

Figure3. Fuzzy goal programming values compared with the Payoff results

5.1. Sensitivity Analysis

The results of the analysis of the model sensitivity to the changes made in the parameters α, β and γ show that the multi-objective model can provide a variety of Pareto optimal solutions. The proposed model demonstrates appropriate changes to the manipulation of the parameters and consequently one of the most substantial outputs of this model, i.e. maintaining the resilience and sustainability aspects of the supply chain, is adhered to. Changes in the α parameter of the production capacity of gas wells lead to different amounts in the objective functions, i.e., by decreasing the α parameter from 0.99 to 0.97, the total revenue, environmental costs and service level are decreased while the economic costs and penalty per underutilized capacity in the objective functions are increased. Accordingly, the decreased gas production leads to decreased greenhouse gas emissions and adequate inventory on the network and facilities while increased penalty per underutilized capacity is due to the underutilization of facilities. Despite the decrease in gas production, the economic costs are increased because of the increase in import to overcome the shortage. However, it is obvious that as the total revenue decreases, economic costs decrease. Storage tanks are other strategic important constraints on the resilience and sustainability of the natural gas supply chain, i.e., applying the β parameters 0.45 and 0.50 of the storage tanks and, consequently, creating changes in the volume of storage capacity of the storage tanks, leading to increase of the service level from 1.082 to 1.084, respectively. Changes in the γ parameter of the demand for gas from oil wells lead to different amounts in the objective functions, that is, by increasing the γ parameter by 1.5, 2 and 3.5 times, the total revenue and service level are reduced while the economic and environmental costs and penalty per underutilized capacity in the objective functions are increased. Accordingly, the increase of demand for gas from oil wells leads to the underutilization of facilities or the increase in the penalty per underutilized capacity. The economic costs are increased due to an increase in imported gas to overcome the shortage. Consequently, manipulating and making changes to the γ parameter that relates to the demand for gas from oil wells or, in other words, the increase of gas injection into the oil wells, suggests that the increased demand augments the pressure inside oil wells and reservoirs and, as a result, increases oil recovery rates, with respect to the sustainability and resilience aspects of the natural gas supply chain. Sensitivity analysis of various α, β and γ values and the effect of simultaneous change in the parameters on the amount of the objectives and charts related are reported in the Tables 7, 8, 9, 10, and Figs. 4,5, 6 and 7, respectively. Information, features, and conditions of the proposed model which, based on consulting with experts, are similar to the real model, can help decision makers make an optimal decision in terms of production, refinement, injection into oil reservoirs, storage, transmission and distribution of natural gas in warm and cold seasons of the year, and optimally allocate gas to each customer while taking into account the resilience and sustainability aspects of the supply chain. The multi-objective model includes the total revenue, economic and environmental costs, as well as penalty per underutilized capacity of equipment and facilities and service levels of the gas throughout the supply chain and trade-offs among them and their Pareto optimal solution lead to integrated strategic and the medium-term tactical decisions making of the natural gas supply chain through an improved augmented ε-constraint algorithm. A managerial insight is that variety of demands in each period lead to different scenarios, which influence the decision. Thus, different scenarios of demand may accrue in the planning horizon. On the other, managerial and practical applications of this research are dispatching directorate through monitoring and using information from variety of nodes, balances the volume and pressure of the gas transmission and distribution lines in order to consider and maintain the integrated resilience, sustainability and customer demands throughout the supply chain with prioritizing the dimensions of resilience in cold seasons and sustainability in the warm seasons. The research findings are similar to the results of the interviews with experts in the oil and gas industry and review of the existing documents; actual parameters and data are implemented and used in this research. It is important to notice that the amounts obtained for some objectives are close to the amounts considered in the documentation.

Table7. Results of sensitivity analysis of the parameters of the production capacity of gas wells

	Obj_1	Obj_2	Obj_3	Obj_4	Obj_5
α=0.99	9.074145E+9	3.194253E+8	1791745.470	86396.598	1.082
α=0.98	9.050264E+9	3.231407E+8	1770541.992	89638.547	1.080
α=0.97	9.021444E+9	3.234224E+8	1769968.020	92880.495	1.078

Table8. Results of sensitivity analysis of the parameters of storage tanks

	Obj_1	Obj_2	Obj_3	Obj_4	Obj_5
β =0.45	9.074655E+9	3.221503E+8	1769025.796	83154.650	1.082
β =0.50	9.094253E+9	3.222676E+8	1769270.514	83154.650	1.084

Table9. Results of sensitivity analysis of the parameters of demand volume of oil wells

	Obj_1	Obj_2	Obj_3	Obj_4	Obj_5
γ =1.50	9.097550E+9	3.231601E+8	1797176.254	86549.150	1.077
γ =2	9.097516E+9	3.237424E+8	1815426.219	89943.650	1.071
γ =3.50	9.060768E+9	3.276220E+8	1829461.611	100375.346	1.052

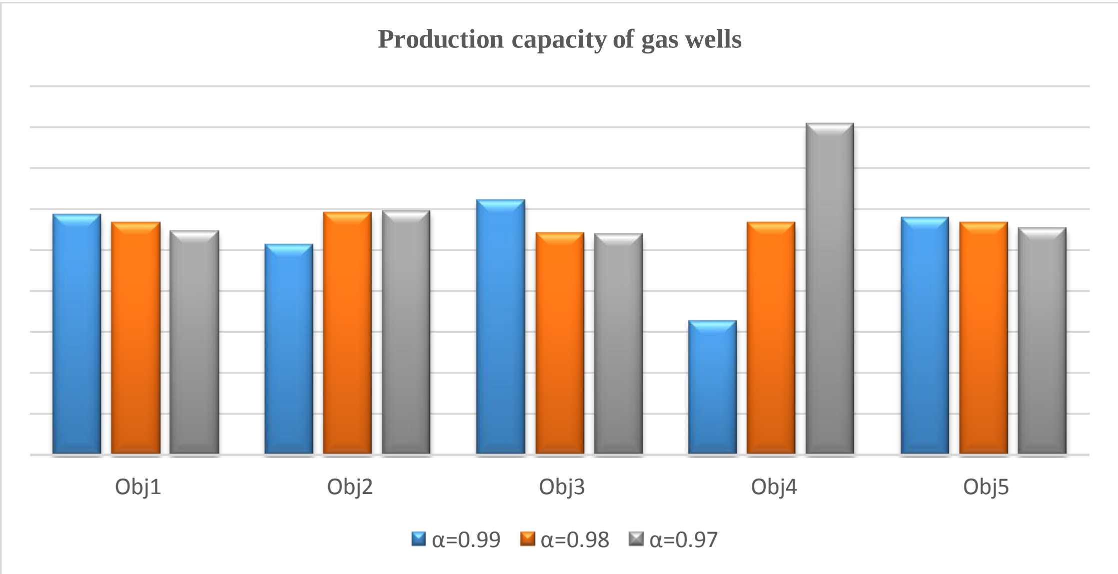

Figure4. The chart of sensitivity analysis of the parameters of the production capacity of gas wells

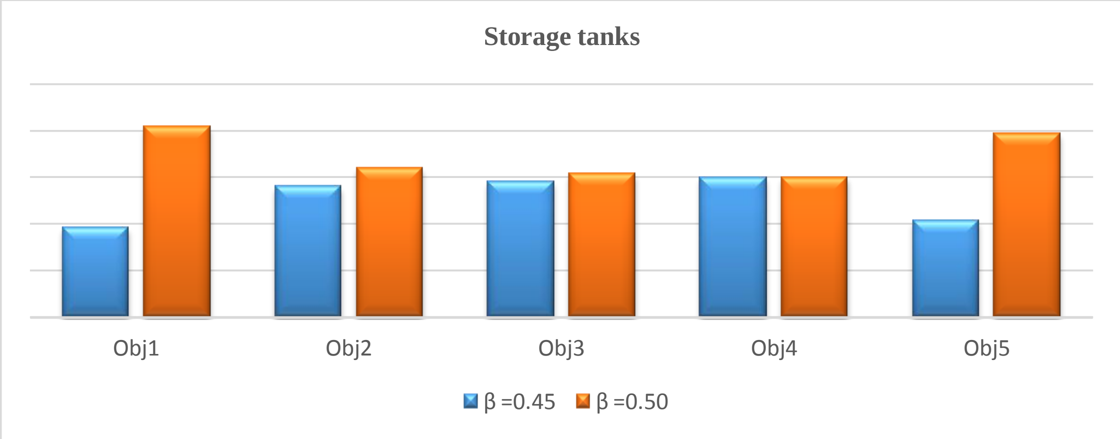

Figure5. The chart of sensitivity analysis of the parameters of the storage tanks

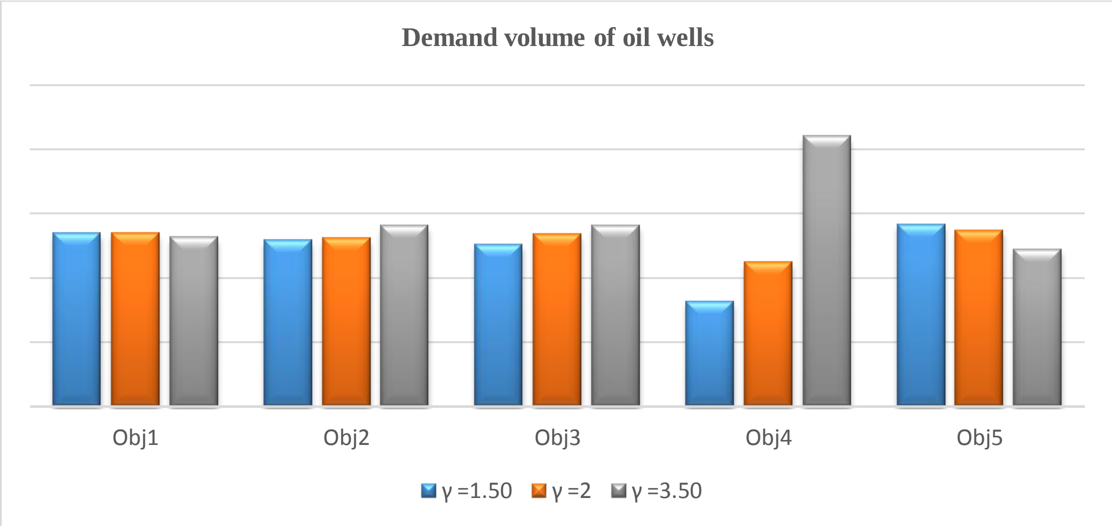

Figure6. The chart of sensitivity analysis of the parameters of demand volume of oil wells

Table10. Results of simultaneous changes of sensitivity analysis of the parameters of the production capacity of gas wells, storage tanks & demand volume of oil wells.

	Obj_1	Obj_2	Obj_3	Obj_4	Obj_5
α=0.99, β =0.45, γ =1.50	9.070896E+9	3.211631E+8	1797012.134	89791.098	1.073
α=0.98, β =0.50, γ =2	9.053863E+9	3.216877E+8	1796281.032	96427.547	1.067
α=0.97, β =1, γ =3	9.011377E+9	3.228950E+8	1794826.499	106466.121	1.052

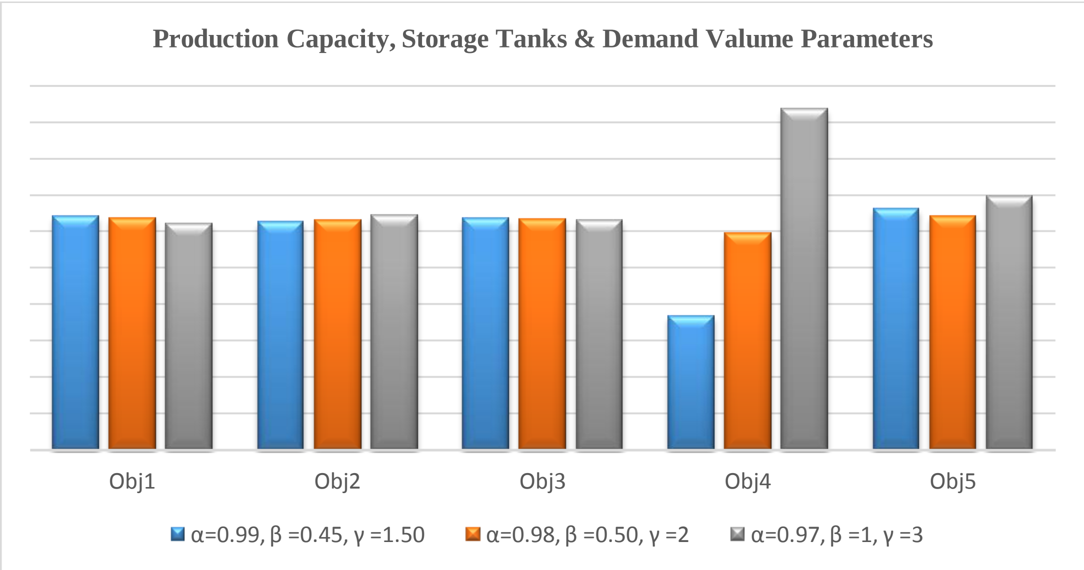

Figure7. The chart of sensitivity analysis of the parameters of the production capacity of gas wells, storage tanks & demand volume of oil wells

6. Conclusions

The main purpose of this research was the mathematical modelling of the natural gas supply chain and its development with the optimized model approach of the multi objective with conflicting objectives by trade-offs among them. In this paper, based on the general structure of the Iranian gas industry and the relationship among its components, seven levels were introduced for the natural gas supply chain and a multi-objective model was developed to optimize the resilience and sustainability aspects at all its levels. Objective functions of the proposed model included the total revenue, economic and environmental costs, as well as the penalty per underutilized capacity of equipment and service level for the natural gas, and all four products derived from natural gas in multiple time periods (12 months). The multi-objective model in this research with real data and parameters were resolved using the improved augmented ε-constraint method by Gams 23.1.2−64-bit software, using the CPLEX solver. Sensitivity analysis of the key parameters of α, β and γ and their manipulation made appropriate changes and provided various optimal solutions. Changes in the α parameter of the production capacity of gas wells led to the generation of different values in the objective functions. Changes in the β parameter related to storage tanks leading to different amounts and results of objective functions showed the strategic importance of storage tanks in increasing the resilience and sustainability of the natural gas supply chain. The sensitivity analysis and changes in the γ parameter associated with the demand for gas for injection into the oil wells also showed that the amount of oil recovery from the oil fields could be augmented by increasing the pressure inside the oil wells and reservoirs through maintaining the resilience and sustainability aspects of the natural gas supply chain.

As the proposed model solution is the improved augmented ε-constraint approach, changes in the key parameters generate different values of the Pareto optimal solutions and the payoff tables for objective functions. As a result, the resilience and sustainability in the supply chain with optimality and trade-offs among the objectives are also met, and decision makers also have the Pareto optimal solutions.

For future studies, the model in the actual size of the supply chain nodes can be solved through other methods as Differential Evolutionary, Genetic Algorithm, Tabu Search, PSO and various heuristic and metaheuristic methods, and the results may be compared with the proposed model. Another suggestion for further research is considering some objective functions and constraints and adding them to the model.

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