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A Fuzzy Goal-Programming Model for Optimization of Sustainable Supply Chain by Focusing on the Environmental and Economic Costs and Revenue: A Case Study

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ABSTRACT

Sustainable supply chain has become an integral part of the corporate strategy. In this paper, 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 introduced and presented schematically. The aim of this paper is to optimize a case study using a fuzzy goal-programming multi-period model considering environmental and economic costs and revenue as fuzzy goals and maximize the total degree of satisfaction of goals as objective function. A small-sized problem was solved using GAMS 23.2.1 software and sensitivity analysis was conducted on its parameters. To the best of our knowledge, this is the first study that presents a fuzzy goal programming model for the optimization of sustainable natural gas supply chain by focusing on the environmental and economic costs and total revenue of gas products and the other main contribution of this research is focused to the developing of the mentioned model.

1 Introduction

Nowadays, firms have undeniable effect on the economy of their countries [7]. gas industries, have an important role in the world economy because they supply the necessary products to sustain the world energy supply. Hence, improving gas supply chain planning schemes has been investigated. Natural gas is an important source of energy for many countries. According to a report released by the British Petroleum Corporation in 2015, Iran holds about 18 percent of the world's natural gas reserves and is still considered as the top holder of gas reserves. After being extracted from oil and gas resources, rich gas is delivered to gas factories, gas refineries and dehydration units. Part of the produced gas is also sent to oil fields and petrochemical plants. Injection of gas and water into oil reservoirs is one of the most important factors in protecting oil reserves, and one of the sustainable produc-

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tion strategies in which both sweet and sour gas are continuously injected into the oil reservoirs. On the other hand, the development of natural gas consumption as a clean and safe fuel has made the issue of its constant transmission and distribution in the gas network to be one of the main challenges facing the industry. The aim of natural gas storage is also to supply gas at the peak of gas consumption during winter and in the emergency situations and to make the gas transmission systems more resilient. The refined gas is transmitted by the gas compressor stations through high-pressure gas pipelines, and supplied to the consumers after several pressure reductions by the pressure reducing stations in proportion to the type and amount of demand. Natural gas is the cleanest fuel and has the least pollution, compared to other fossil fuels. However, due to the high consumption rate, 61% of the total carbon dioxide emissions are from natural gas, which is significant in terms of the climate change issues. Therefore, through the management of consumption, improving the quality of fuels, changing the composition of energy carriers, optimizing energy consumption, and establishing an effective and continuous management and monitoring system, it is possible to stabilize or even reduce the emissions of gases [15]. Therefore, the increasing importance of using natural gas has led to a large amount of funding for the exploration, extraction, production, transmission, storage and distribution of gas, with a share of about 30% for the gas transmission cost [3, 14]. Currently, there is a growing concern among strategists and decision makers around the world about the negative social and environmental impacts of rapid economic growth. Hence, the international community emphasizes the acceptance of sustainable modes of production and consumption for emerging and developed markets [27]. Given that a number of studies have been conducted in recent years on the dimensions of sustainability in some levels of the supply chain, some dimensions of sustainability such as the environmental or social costs of greenhouse gas emissions, economic costs and total revenue earned in the consumption nodes in all components and at all levels of the natural gas supply chain, are investigated in the present research and provided as the contribution of this study while considering the trade-offs among them. This paper presents a fuzzy goal-programming model to optimize the sustainable supply chain of natural gas in the Iranian gas industry.

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 in 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, the dispatching, the town bordering stations 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. This natural gas supply chain is formulated in terms of the dimensions of sustainability such as the environmental and economic costs and revenue with the aim of providing a fuzzy goal-programming model to optimize it in a one-year time horizon. 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.

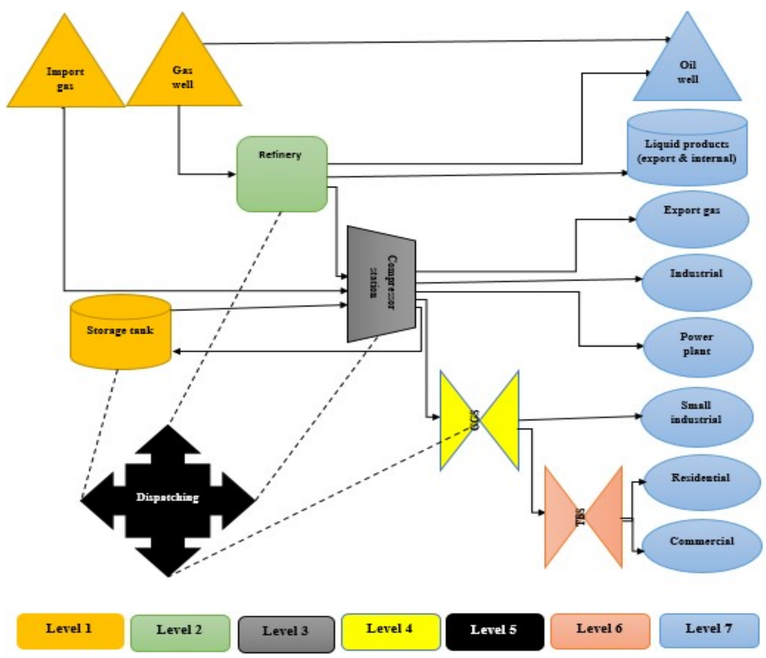

Fig. 1: Schematic representation of the natural gas supply chain

The rest of the article is organized as follows: In Section 2, the literature review. Section 3 presents the mathematical model including sets and indices, variables, parameters, objective function, goals and constraints. Some levels of the natural gas supply chain are real size, but some others are small size. In Section 4, the problem solving approach with case study are presented. Finally, the discussions and conclusions are given in Sections 5 and 6, respectively.

2 Literature Review

The literature review considers the mathematical optimization models, few of which consider all levels of the gas supply chain and most of which focused only on one or some parts of the supply chain in their mathematical models. The first researches in this area were presented by Duffuaa et al. [10], who developed a linear programming model for the oil and gas supply chain. Contesse et al. [6] considered three main agents including producers, transportation companies, and local distribution companies and presented a mixed-integer programming model for the gas supply chain. Several studies have surveyed the environmental and economic effects of the gas supply chain. In a study, Hamedi et al. [14] studied the supply chain of natural gas and its transmission and distribution components in six levels of the supply chain and formulated a single-objective multi-period and single-product model as a mixed integer non-linear programming model aimed at minimizing direct and indirect gas distribution costs. Nikbakht et al. [24] studied three levels of the natural gas supply chain including gas gathering, transmission and distribution systems. They proposed a framework for integrating of the operational parts of natural gas transmission systems through pipelines and better coordination for the flow of natural gas and information in the system.

Pishvaee and Razmi [26] developed a multi-objective fuzzy mathematical programming model for designing an environmental supply chain under inherent uncertainty of input data in such problem. They considered the minimization of multiple environmental impacts beside the traditional cost minimization objective to make a fair balance between them. In their research, Al-Sobhi and Elkamel [2] showed the importance of using accurate modeling simulations in decision making by providing a framework for analyzing and optimizing the natural gas network. Vance et al. [36] used the P-Graph framework for designing a supply chain of energy called financial constraints and sustainability considerations. On the other hand, in a research, Azadeh et al. [3] optimized and assessed the natural gas supply chain at five levels using a multi-objective multi-period fuzzy linear programming model while considering economic and environmental objectives. In order to deal with uncertainty, they considered demand, capacity and cost parameters as the fuzzy parameters. Azadeh et al. [4] introduced, for the first time, a new concept of macro-ergonomic analysis and design methodology in the form of a multi-objective mathematical model for the supply chain, which included targets for reducing transport and operational costs, environmental costs, and late payment costs, as well as increasing the value of purchases from importers. The results of their research led to a 10% reduction in the unit operating costs. In a research, Dovi and Meshalkin [9] showed how simple models could be obtained while identifying generic models and algorithms that can provide a complete decision support tool for the gas supply chain. In their research, Ghaithan et al. [13] developed a multi-objective integrated model for the medium-term tactical decision-making of the downstream oil and gas supply chain. They solved the objectives associated with downstream activities, such as minimizing total costs, maximizing total revenue, and maximizing service levels through an improved augmented ε-constraint algorithm.

Rostamzadeh et al. [28] provided a framework for assessing sustainable supply chain risk management. They assessed the seven main criteria and the fourteen sub-criteria for the mentioned framework based on an integrated approach to fuzzy multi-criteria decision making using the Topsis technique. In a research, Sapkota et al. [30] conducted a comparative study on the delivery costs and life cycle of greenhouse gas of the natural gas supply chain emitted from Canadian manufacturing sites to the north and southwest of Europe through the development of technical-economic analytical models and life cycles. Review of literature shows that in the field of the sustainable development in the natural gas supply chain, no significant research has been conducted. Therefore, presenting a mathematical model for the optimization of the sustainable natural gas supply chain in their all levels by focusing on the environmental and economic costs and total revenue, would be very helpful for gas industries management.

3 Proposed Mathematical Programing Approach

In this paper, the fuzzy goal-programming model consists of three goals formulated in a fuzzy manner.

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
sc_{s}: Capacity of storage tank(constant)

Fuel parameters

β_r: Fuel consumption coefficient of refinery
β_y: Fuel consumption coefficient of compressor station
β_g: 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*
Λ_{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)

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

Aspiration level, lower and upper tolerance parameters for goals

AL_1: Aspiration level for the environmental or social costs
AL_2: Aspiration level for the economic costs
AL_3: Aspiration level for the total revenue of gas products
ε_1: The upper tolerance limit for the environmental or social costs
ε_2: The upper tolerance limit for the economic costs
ε_3: The lower tolerance limit for the total revenue of gas products

3.1 Mathematical Model

Goals and constraints of the proposed model are presented as follows:

G_1: Minimizing the environmental costs of emission of greenhouse gases (Goal 1)

$$G_1 = sc\left\{ gw\left[\sum_w\sum_r\sum_t xwr_{wrt} + \sum_w\sum_o\sum_t xwo_{wot}\right] + gr\left[\sum_r\sum_y\sum_t xry_{ryt} + \sum_r\sum_o\sum_t xro_{rot}\right] + \right.$$

$$gy\left[\sum_y\sum_{\acute{y}}\sum_t xy\acute{y}_{y\acute{y}t} + \sum_y\sum_g\sum_t xyg_{ygt} + \sum_y\sum_s\sum_t xys_{yst}\right.$$

$$\left. + \sum_y\sum_e\sum_t xye_{yet} + \sum_y\sum_d\sum_t xyd_{ydt} + \sum_y\sum_p\sum_t xyp_{ypt}\right] +$$

$$gs\left[\sum_s\sum_y\sum_t xsy_{syt}\right] + gg\left[\sum_g\sum_b\sum_t xgb_{gbt} + \sum_g\sum_m\sum_t xgm_{gmt}\right] +$$

$$gb\left[\sum_b\sum_l\sum_t xbl_{blt} + \sum_b\sum_f\sum_t xbf_{bft}\right] + go\left[\sum_w\sum_o\sum_t xwo_{wot} + \sum_r\sum_o\sum_t xro_{rot}\right] +$$

$$\left[gd \sum_{y}\sum_{d}\sum_{t} xyd_{ydt} + gp \sum_{y}\sum_{p}\sum_{t} xyp_{ypt} + gl \sum_{b}\sum_{l}\sum_{t} xbl_{blt} + gf \sum_{b}\sum_{f}\sum_{t} xbf_{bft} + gm \sum_{g}\sum_{m}\sum_{t} xgm_{gmt} + \left(g\alpha_{3i} \sum_{w}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{3i}\right) + \left(g\alpha_{4i} \sum_{W}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{4i}\right)\right] \quad (1)$$

G_2: Minimizing the economic costs (Goal 2)

$$G_2 = \sum_{w}\sum_{r}\sum_{t} xwr_{wrt}\left(cw_{wt} + d_{wr}h_{wr}ct\right) + \sum_{w}\sum_{o}\sum_{t} xwo_{wot}\left(cw_{wt} + d_{wo}h_{wo}ct\right) + \sum_{r}\sum_{y}\sum_{t} xry_{ryt}\left(cr_{rt} + d_{ry}h_{ry}ct\right) + \sum_{r}\sum_{o}\sum_{t} xro_{rot}\left(cr_{rt} + d_{ro}h_{ro}ct\right) + \sum_{a}\sum_{y}\sum_{t} xay_{ayt}\left(ca_{at} + d_{ay}h_{ay}ct\right) + \sum_{y}\sum_{\acute{y}}\sum_{t} xy\acute{y}_{y\acute{y}t}\left(cy_{yt} + d_{y\acute{y}}h_{y\acute{y}}ct\right) + \sum_{y}\sum_{g}\sum_{t} xyg_{ygt}\left(cy_{yt} + d_{yg}h_{yg}ct\right) + \sum_{y}\sum_{s}\sum_{t} xys_{yst}\left(cy_{yt} + d_{ys}h_{ys}ct\right) + \sum_{s}\sum_{y}\sum_{t} xsy_{syt}\left(cs_{st} + d_{sy}h_{sy}ct\right) + \sum_{y}\sum_{e}\sum_{t} xye_{yet}\left(cy_{yt} + d_{ye}h_{ye}ct\right) + \sum_{y}\sum_{d}\sum_{t} xyd_{ydt}\left(cy_{yt} + d_{yd}h_{yd}ct\right) + \sum_{y}\sum_{p}\sum_{t} xyp_{ypt}\left(cy_{yt} + d_{yp}h_{yp}ct\right) + \sum_{g}\sum_{m}\sum_{t} xgm_{gmt}\left(cg_{gt} + d_{gm}h_{gm}ct\right) + \sum_{g}\sum_{b}\sum_{t} xgb_{gbt}\left(cg_{gt} + d_{gb}h_{gb}ct\right) + \sum_{b}\sum_{l}\sum_{t} xbl_{blt}\left(cb_{bt} + d_{bl}h_{bl}ct\right) + \sum_{b}\sum_{f}\sum_{t} xbf_{bft}\left(cb_{bt} + d_{bf}h_{bf}ct\right) \quad (2)$$

G_3: Maximizing the total revenue of gas products (Goal 3)

$$G_3 = \left(\sum_{w}\sum_{o}\sum_{t} xwo_{wot} \times Pwo_{wot}\right) + \left(\sum_{r}\sum_{o}\sum_{t} xro_{rot} \times pro_{rot}\right) + \left(\sum_{y}\sum_{e}\sum_{t} xye_{yet} \times Pye_{yet}\right) + \left(\sum_{y}\sum_{d}\sum_{t} xyd_{ydt} \times pyd_{ydt}\right) + \left(\sum_{y}\sum_{p}\sum_{t} xyp_{ypt} \times Pyp_{ypt}\right) + \left(\sum_{g}\sum_{m}\sum_{t} xgm_{gmt} \times pgm_{gmt}\right) +$$

$$\left(\sum_{b}\sum_{l}\sum_{t} xbl_{blt} \times Pbl_{blt}\right) + \left(\sum_{b}\sum_{f}\sum_{t} xbf_{bft} \times pbf_{bft}\right) +$$
$$\left(\sum_{w}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_1 \times P\alpha_{1t}\right) + \left(\sum_{W}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_2 \times P\alpha_{2t}\right) +$$
$$\left(\sum_{w}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{3e} \times P\alpha_{3et}\right) + \left(\sum_{W}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{3i} \times P\alpha_{3it}\right) +$$
$$\left(\sum_{w}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{4e} \times P\alpha_{4et}\right) + \left(\sum_{W}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{4i} \times P\alpha_{4it}\right) \quad (3)$$

The first goal (1) is related to the costs of emission of greenhouse gases across the supply chain. This goal has been considered as the amount of emission of greenhouse gases at all levels of the supply chain including supply and demand. The terms of this goal are the amount of greenhouse gas emissions produced 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 customers.

The second goal (2) is related to the economic costs in the entire supply chain. This goal has been considered as the cost of supplying at each level and the cost of transmission to the next level. In addition, each term presents some parts of this goal that respectively are as follows:

2-1: The cost of producing in gas wells and transmission to the refineries
2-2: The cost of producing in gas wells and transmission for sour gas injection to oil wells
2-3: The cost of refining and transmission to the compressor stations
2-4: The cost of importations and transmission to the compressor stations
2-5: The cost of refining and transmission for sweet gas injection to the oil wells
2-6: The operation cost of compressor stations y and transmission to other compressor Stations ŷ
2-7: The operation cost of compressor stations and transmission to city-gate stations, storage tanks, exportations, industrials and power plants
2-8: The operation cost of storage tanks and transmission to compressor stations
2-9: The operation cost of city-gate stations and transmission to town bordering Station and small industrials
2-10: The operation cost of town bordering stations and transmission to residential and commercial customers

The third goal (3) is also related to the total revenue of gas products in the entire supply chain. This goal has been considered as the selling price of gas products and each term presents some parts of this goal that respectively are as follows:

3-1: Selling price of gas product by gas wells for oil wells
3-2: Selling price of gas product by refineries for oil wells
3-3: Selling price of gas product by compressor stations for exportations, industrials, and power plants
3-4: Selling price of gas product by city-gate stations for small industrials
3-5: Selling price of gas product by town bordering stations for residential and commercial customers

3-6: Selling price of equal liquid products as type one and two for exportation
3-7: Selling price of equal liquid products as type three and four for internal consumption
3-8: Selling price of equal liquid products as type three and four for exportation

$$\sum_{w} xwo_{wot} + \sum_{r} xro_{rot} \geq od_{ot} \qquad \forall o,t \tag{4}$$

$$\sum_{y} xye_{yet} \geq ed_{et} \qquad \forall e,t \tag{5}$$

$$\sum_{y} xyd_{ydt} \geq dd_{dt} \qquad \forall d,t \tag{6}$$

$$\sum_{y} xyp_{ypt} \geq Pd_{pt} \qquad \forall P,t \tag{7}$$

$$\sum_{b} xbl_{blt} \geq ld_{lt} \qquad \forall l,t \tag{8}$$

$$\sum_{b} xbf_{bft} \geq fd_{ft} \qquad \forall f,t \tag{9}$$

$$\sum_{g} xgm_{gmt} \geq md_{mt} \qquad \forall m,t \tag{10}$$

$$\sum_{w} xwr_{wrt} \times (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4) \geq eld_{rt} \quad \forall r,t \tag{11}$$

Constraints (4) – (11) guarantee demand satisfaction for each oil well, exportation, industrial, power plant, residential, commercial, small industrial and equal liquid products, respectively.

$$\sum_{r} xwr_{wrt} + \sum_{o} xwo_{wot} \leq wc_{wt} \qquad \forall w,t \tag{12}$$

$$\sum_{y} xay_{ayt} \leq ac_{at} \qquad \forall a,t \tag{13}$$

$$\sum_{y} xry_{ryt} + \sum_{o} xro_{rot} + \sum_{w} xwr_{wrt} \times (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5) \quad \leq rc_{rt} \qquad \forall r,t \tag{14}$$

$$\sum_{g} xyg_{ygt} + \sum_{s} xys_{yst} + \sum_{e} xye_{yet} + \sum_{d} xyd_{ydt} + \sum_{p} xyp_{ypt} + \sum_{\acute{y}} xy\acute{y}_{y\acute{y}t} \leq yc_{yt} \quad \forall y,t \tag{15}$$

$$\sum_{b} xgb_{gbt} + \sum_{m} xgm_{gmt} \leq gc_{gt} \qquad \forall g,t \tag{16}$$

$$\sum_{l} xbl_{blt} + \sum_{f} xbf_{bft} \leq bc_{bt} \qquad \forall b,t \tag{17}$$

$$\sum_{y} \sum_{\acute{t}=1}^{t} xys_{ys\acute{t}} - \sum_{y} \sum_{\acute{t}=1}^{t} xsy_{sy\acute{t}} \geq o \quad \forall s,t \tag{18}$$

$$\sum_{y}\sum_{\acute{t}=1}^{t} xys_{ys\acute{t}} - \sum_{y}\sum_{\acute{t}=1}^{t} xsy_{sy\acute{t}} \leq sc_s \;\; \forall s,t \tag{19}$$

Each gas well, importation, refinery, compressor station, city-gate station, town bordering station and storage tank capacity are represented by constraints (12) – (19), respectively.

$$\sum_{w} xwr_{wrt} = \sum_{y} xry_{ryt} + \sum_{o} xro_{rot} + \sum_{w} xwr_{wrt} \times (\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5+\beta_r) \qquad \forall r,t \tag{20}$$

$$\begin{aligned}&\left(\sum_{r} xry_{ryt} + \sum_{a} xay_{ayt} + \sum_{s} xsy_{syt} + \sum_{\acute{y}} x\acute{y}y_{\acute{y}yt}\right) = \\ &\sum_{g} xyg_{ygt} + \sum_{s} xys_{yst} + \sum_{e} xye_{yet} + \sum_{d} xyd_{ydt} + \sum_{p} xyp_{ypt} + \sum_{\acute{y}} xy\acute{y}_{y\acute{y}t} + \\ &\qquad\left(\sum_{r} xry_{ryt} + \sum_{a} xay_{ayt} + \sum_{s} xsy_{syt} + \sum_{\acute{y}} x\acute{y}y_{\acute{y}yt}\right) \times \beta_y \qquad \forall y,t\end{aligned} \tag{21}$$

$$\sum_{y} xyg_{ygt} = \sum_{b} xgb_{gbt} + \sum_{m} xgm_{gmt} + \sum_{y} xyg_{ygt} \times \beta_g \qquad \forall g,t \tag{22}$$

$$\sum_{g} xgb_{gbt} = \sum_{l} xbl_{blt} + \sum_{f} xbf_{bft} \qquad \forall b,t \tag{23}$$

Equations (20) – (23) represent the flow balance constraints in each refinery, compressor station, city-gate station and town bordering station, respectively.

$$xwr_{wrt} \leq M\lambda_{wr}\, , xwo_{wot} \leq M\lambda_{wo}\, ,\; xry_{ryt} \leq M\lambda_{ry}\, , xay_{ayt} \leq M\lambda_{ay} \tag{24}$$

$$xro_{rot} \leq M\lambda_{ro}\, , xy\acute{y} \leq M\lambda_{y\acute{y}}\, ,\;\; xyg_{ygt} \leq M\lambda_{yg}\, ,\;\; xye_{yet} \leq M\lambda_{ye} \tag{25}$$

$$xyd_{ydt} \leq M\lambda_{yd}\, , xyp_{ypt} \leq M\lambda_{yp}\, ,\; xys_{yst} \leq M\lambda_{ys}\, ,\; xsy_{syt} \leq M\lambda_{sy} \tag{26}$$

$$xgb_{gbt} \leq M\lambda_{gb}\, ,\; xgm_{gmt} \leq M\lambda_{gm}\, ,\; xbl_{blt} \leq M\lambda_{bl}\, ,\; xbf_{bft} \leq M\lambda_{bf} \tag{27}$$

Equations (24) - (27) represent the constraints on the existence/ lack of path in the model. The parameter λ shows the presence or absence of a specific path. If this parameter takes 1, the decision variable can take a value; otherwise, the corresponding decision variable is zero.

$$\lambda_{wr}Q_{wr}^{min} \leq xwr_{wrt} \leq \lambda_{wr}Q_{wr}^{max} \quad \forall w, r \tag{28}$$

$$\lambda_{wo}Q_{wo}^{min} \leq xwo_{wot} \leq \lambda_{wo}Q_{wo}^{max} \quad \forall w, o \tag{29}$$

$$\lambda_{ro}Q_{ro}^{min} \leq xro_{rot} \leq \lambda_{ro}Q_{ro}^{max} \quad \forall r, o \tag{30}$$

$$\lambda_{ry}Q_{ry}^{min} \leq xry_{ryt} \leq \lambda_{ry}Q_{ry}^{max} \quad \forall r, y \tag{31}$$

$$\lambda_{ay}Q_{ay}^{min} \leq xay_{ayt} \leq \lambda_{ay}Q_{ay}^{max} \quad \forall a, y \tag{32}$$

$$\lambda_{y\acute{y}}Q_{y\acute{y}}^{min} \leq xy\acute{y}_{y\acute{y}t} \leq \lambda_{y\acute{y}}Q_{y\acute{y}}^{max} \quad \forall y, \acute{y} \tag{33}$$

$$\lambda_{yg}Q_{yg}^{min} \leq xyg_{ygt} \leq \lambda_{yg}Q_{yg}^{max} \quad \forall y, g \tag{34}$$

$$\lambda_{ye}Q_{ye}^{min} \leq xye_{yet} \leq \lambda_{ye}Q_{ye}^{max} \quad \forall y, e \tag{35}$$

$$\lambda_{yd}Q_{yd}^{min} \leq xyd_{ydt} \leq \lambda_{yd}Q_{yd}^{max} \quad \forall y, d \tag{36}$$

$$\lambda_{yp}Q_{yp}^{min} \leq xyp_{ypt} \leq \lambda_{yp}Q_{yp}^{max} \quad \forall y, p \tag{37}$$

$$\lambda_{ys}Q_{ys}^{min} \leq xys_{yst} \leq \lambda_{ys}Q_{ys}^{max} \quad \forall y, s \tag{38}$$

$$\lambda_{sy}Q_{sy}^{min} \leq xsy_{syt} \leq \lambda_{sy}Q_{sy}^{max} \quad \forall s, y \tag{39}$$

$$\lambda_{gb}Q_{gb}^{min} \leq xgb_{gbt} \leq \lambda_{gb}Q_{gb}^{max} \quad \forall g, b \tag{40}$$

$$\lambda_{gm}Q_{gm}^{min} \leq xgm_{gmt} \leq \lambda_{gm}Q_{gm}^{max} \quad \forall g, m \tag{41}$$

$$\lambda_{bl}Q_{bl}^{min} \leq xbl_{blt} \leq \lambda_{bl}Q_{bl}^{max} \quad \forall b, l \tag{42}$$

$$\lambda_{bf}Q_{bf}^{min} \leq xbf_{bft} \leq \lambda_{bf}Q_{bf}^{max} \quad \forall b, f \tag{43}$$

Equations (28) - (43) show the gas flow constraints. These constraints set, represent a range of volumes of gas that are limited to some of the lower and upper boundaries. These ranges are determined by the diameter of the pipeline and the primary and secondary gas pressure in the associated nodes.

$$Xij_{ijt},\ t, \geq 0 \tag{44}$$

$$\begin{aligned} \mu_i &\leq 1 \quad i = 1,2,\dots,3 \\ \mu_i &\geq 0 \quad i = 1,2,\dots,3 \end{aligned} \tag{45}$$

Equations (44) and (45) represent that Xij_{ijt} and t are equal or greater than 0 and μ_i is equal or less than 1 and equal or greater than 0, respectively.

3.2 Problem Solving Approach

Fuzzy goal-programming approach has been a universal method to solving multi-objective supply chain problems. Several of usages have been investigated in a supply chain planning [20, 31, 35], supply chain network design [12, 25, 32] and performance [19]. Equations (46)– (48) formulate the degree of satisfaction of each goal [1, 5, 12, 23, 34]. Corresponding graph of degree of satisfaction for first and second fuzzy goals and third fuzzy goal are shown in the Figs. 2 and 3, respectively.

$$\text{Degree of satisfaction of goal 1} = \mu_1 = \frac{\varepsilon_1 - G_1}{\varepsilon_1 - AL_1} \tag{46}$$

$$\text{Degree of satisfaction of goal 2} = \mu_2 = \frac{\varepsilon_2 - G_2}{\varepsilon_2 - AL_2} \tag{47}$$

$$\text{Degree of satisfaction of goal 3} = \mu_3 = \frac{G_3 - \varepsilon_3}{AL_3 - \varepsilon_3} \tag{48}$$

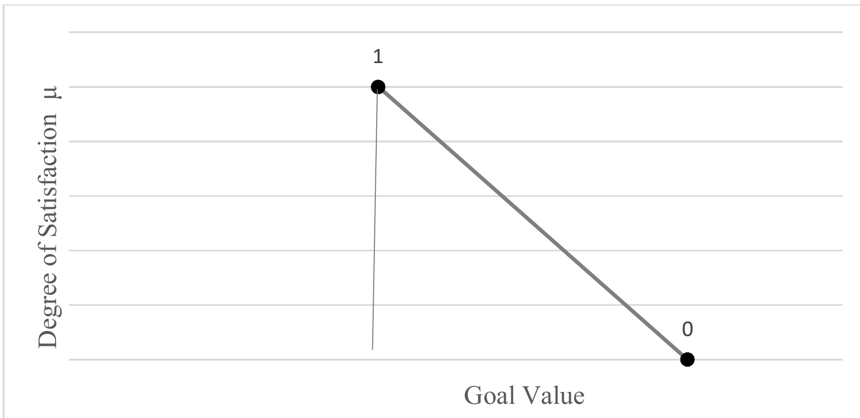

Fig. 2: Degree of satisfaction for first and second fuzzy goals

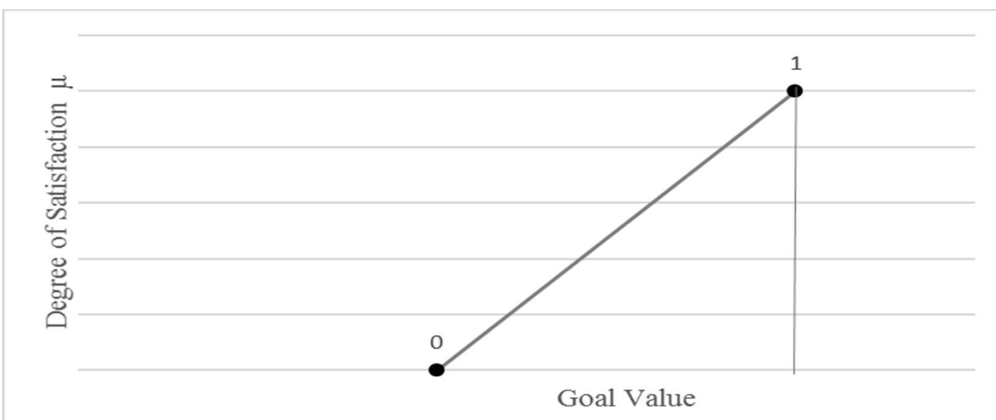

Fig. 3: Degree of satisfaction for third fuzzy goal

Where AL_1–AL_3 define the aspiration levels of the goals 1–3, respectively. ε_1 and ε_2 represent the upper tolerance limits for the environmental or social costs (Goal 1) and the economic costs (Goal 2) situations, respectively. ε_3 define the lower tolerance limits for the total revenue of gas products (Goal 3). Regarding the fuzzy goal-programming approach, the obtained values of the payoff results for the aspiration levels of goals and the upper and lower tolerance limits for each aspiration level are presented in the Table 1. According to the definition of Tiwari et al. [34], the objective function of the deterministic model of the present research is as follows:

$$\text{Maximize} f(\mu) = \sum_{i=1}^{3} W_i \mu_i \tag{49}$$

The proposed model is subject to:
Constraints (4)–(48)

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 [34]. 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.

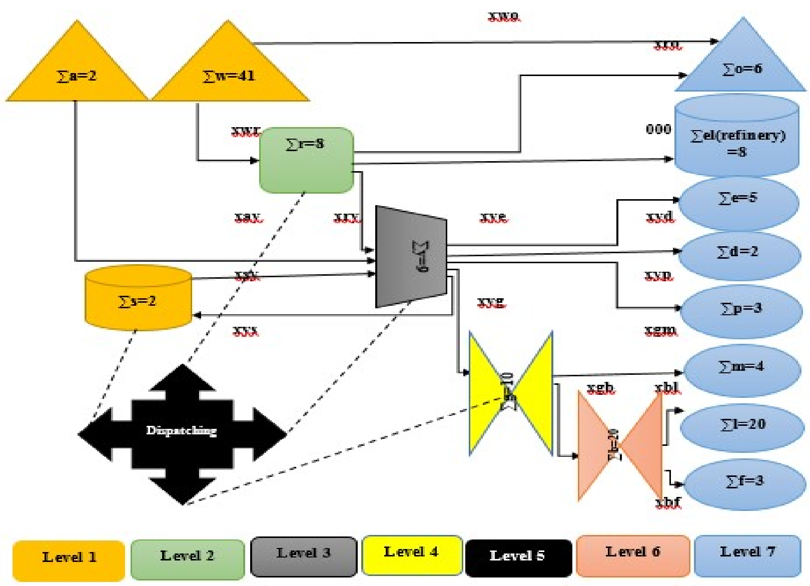

Fig. 4: A small-sized of the natural gas supply chain

4 Case Study

Any process that takes place requires the use of a series of data and resources [11]. For verifying and validating the proposed model, a small-sized problem with real data has been solved using GAMS 24.2.1 software. 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. A small-size of the natural gas supply chain is shown in the Fig. 4.

Table 1: Payoff results for the aspiration levels of goals and tolerance limits

AL1	1769560.560	ε_1	upper	1900729.129
AL2	322210500	ε_2	upper	369150600
AL3	9097109000	ε_3	lower	7908254000

Sensitivity analysis of various w, α and β values and the amount of the goals and objective function are shown in the Table 2, 3 and 4, respectively.

Table 2: Results of sensitivity analysis on parameters of *w*

∑_(*Wi*)	*G1*	*G2*	*G3*	*f(μ)*
0.4,0.3,0.3	1792174.756	322210500	8209237238.693	0.706
0.3,0.4,0.3	1792174.756	322210500	8209237238.693	0.724
0.3,0.3,0.4	1849061.501	335305740.854	8951133636.176	0.685
0.5,0.25,0.25	1778977.704	322210500	8047339042.086	0.743
0.25,0.50,0.25	1792174.756	322210500	8209237238.693	0.770
0.25,0.25,0.50	1855239.615	336483254.709	8997371371.183	0.718
0.60,0.20,0.20	1777224.850	322210500	7997162271.250	0.779
0.20,0.60,0.20	1792174.756	322210500	8209237238.693	0.816
0.20,0.20,0.60	1855667.362	336564780.707	9000572673.199	0.758
0.70,0.15,0.15	1776642.441	322210500	7980490357.841	0.821
0.15,0.70,0.15	1792174.756	322210500	8209237238.693	0.862
0.15,0.15,0.70	1855667.362	336564780.707	9000572673.199	0.798

Table 3: Results of sensitivity analysis on parameters of Storage tanks

SC	*G1*	*G2*	*G3*	*f(μ)*
α=0.2	1778446.571	338866411.687	7955435985.081	0.576
α=0.5	1782139.269	322210500	8086137317.291	0.706
α=1	1792174.756	322210500	8209237238.693	0.706
α=1.5	1792174.756	322210500	8209237238.693	0.706

Table 4: Results of sensitivity analysis on parameters of demand volume of oil wells

Od	*G1*	*G2*	*G3*	*f(μ)*
β= 0.6	1789992.377	322210500	8223211146.421	0.717
β= 0.8	1791067.398	322210500	8216535617.223	0.712
β= 1	1792174.756	322210500	8209237238.693	0.706
β= 1.5	1794946.072	322210500	8190935025.646	0.693
β= 2	1798004.215	322210500	8167108109.303	0.678

5 Discussions

The results of the analysis of the model sensitivity to the changes made in the parameters w, α and β show that the fuzzy goal-programming can provide a variety of solutions. The proposed model demonstrates appropriate changes to the manipulation of the parameters. Changes in the parameter w representing the importance of the degree of satisfaction of the goals based on the preferences of the decision makers, lead to different degree of satisfaction in the objective function. Storage tanks are other important constraints on the sustainability of the natural gas supply chain. Manipulating and changing the α parameter of the storage tanks and, consequently, creating changes in the volume of storage capacity of the storage tanks, and consequently change in goals and objective function, show different values and results that highlight the strategic importance of storage tanks in increasing the degree of satisfaction in the objective function and sustainability of the natural gas supply chains. Manipulating and making changes to the β 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 increases the pressure inside oil wells and reservoirs and, as a result, increases oil recovery rates, with respect to the sustainability aspects of the natural gas supply chain, even though it reduces the degree of satisfaction in the objective function. As the goals of the proposed model are fuzzy, changes in the parameters w, α and β make the values obtained by the goals to be between the aspiration levels and authorized low or high tolerances, and consequently one of the most important outputs of the model, i.e. maintaining the sustainability aspects of the supply chain, is adhered to. Therefore, the sensitivity analysis assists in detecting the effect of the above mentioned parameters on valuable performance measures such as environmental and economic costs and total revenue. 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 optimal gas allocation to each customer while taking into account the sustainability aspects of the supply chain. Fuzzy goals of the model include environmental and economic costs, as well as sales revenue of the gas throughout the supply chain; and the objective function is to maximize the total satisfaction level of the goals.

Finally, the contributions of this research, compared to the previous researches, are as follows: 1. Development of the model and consideration of seven natural gas supply chain levels integrated into it, 2. Consideration of the sustainability aspects in the proposed model, and trade-offs among them and their optimization, 3. Application of Fuzzy goal programming approach and fuzzification of three goals of the proposed model, 4. A great compatibility of the proposed model and all its parameters with Iran's natural gas supply chain, 5. Considering and modeling the quadruple products produced from refining operations in the refineries, in addition to the natural gas, 6. Considering and modeling fuel consumed in the refineries, compressor stations, and city-gate stations,7. 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, 8. 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 sustainability aspects of the natural gas supply chain. The key features of this model, along with previous studies, are presented in Table 5.

Table 5: Classification and features of this study versus previous studies

Reference articles	Level of supply chain			Objective		Sustainability		Develop	Solution method
	Trans	Dist	All	Single	Multi	Econo	Enviro		
Mahlke et al. [22]	✓			✓		✓			Simulated annealing algorithm
Kabirian and Hemmati [18]	✓			✓		✓			A heuristic random search
Wu et al. [37]		✓		✓		✓			Primal-relaxed dual decomposition
Tabkhi et al. [33]	✓			✓		✓			Branch and bound
Hamedi et al. [14]			✓	✓		✓			A hierarchic algorithm
Mahdavi et al. [21]		✓		✓		✓			Minimum spanning tree
Dos Santos et al. [8]		✓			✓	✓			Monte Carlo simulation
Santibanez-Gonzalez et al. [29]	✓				✓	✓	✓		Genetic Algorithm
Jamshidi et al. [16]	✓			✓		✓	✓		Hybrid genetic Taguchi algorithm
Azadeh et al. [3]			✓		✓	✓	✓		An interactive method resolution
Azadeh et al. [4]	✓				✓	✓	✓		ε-constraint algorithm
Ghaithan et al. [13]			✓		✓	✓			ε-constraint algorithm
Sapkota et al. [30]			✓		✓	✓	✓		A comparative assessment
Jayaraman et al. [17]					✓	✓	✓		Fuzzy goal programming (Resource allocation)
This study			✓		✓	✓	✓	✓	Fuzzy goal programming

6 Conclusions

The main purpose of this research was the mathematical modeling of the natural gas supply chain and its development with the optimized model approach of the fuzzy goal programming with conflicting objectives by focusing on the environmental and economic costs and total revenue**.** 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 an appropriate fuzzy goal programming model was developed to optimize the sustainability aspects at all its levels. Fuzzy goals of the proposed model included the environmental and economic costs, as well as total revenue for the natural gas, and all four products derived from natural gas in multiple time periods (12 months) with the objective function of maximizing the total satisfaction degree of the goals. In this research, for verifying and validating the solution approach, a small size of it with real data and parameters were resolved by Gams 23.2.1 software. Sensitivity analysis on the key parameters of w, α, and β, and their manipulation, made appropriate changes and provided various solutions. Changes in the parameter w representing the importance of the degree of satisfaction of the goals based on the preferences of the decision makers led to the generation of a different total degree of satisfaction in the objective function and the values of the goals. Changes in the parameter α associated with storage tanks leading to different values and results of goals and objective function showed the strategic importance of storage tanks in increasing the sustainability of the natural gas supply chain. The sensitivity analysis and changes in the β parameter related to the demand for gas for injection into the oil wells, also showed that the amount of oil recovery from the oil fields could be increased by increasing the pressure inside the oil wells and reservoirs through maintaining the sustainability aspects of the natural gas supply chain. As the proposed model's goals are fuzzy, changes in the key parameters cause the values of the achieved goals to be between the aspiration and low or high tolerance levels. As a result, the sustainability in the supply chain with optimality and trade-offs among the goals are also met, and decision makers also have the optimal solutions. Using meta-heuristic methods to solve the proposed model in the actual size of the supply chain nodes, and comparing its results with the proposed model as well as using ε-constraint algorithm are recommended for further research.

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