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Multi-Objective Optimization Model for the Sustainable Natural Gas Supply Chain

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Abstract

Sustainable supply chain has become an accurate part of the corporate strategy. 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-echelon supply chain has been offered and presented schematically. The aim of this paper is to optimize a case study using a multi-objective and multi-period model. A small-sized model was 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. Sensitivity analysis was conducted on its parameters. To the best of our knowledge, this is the first study that presents a multi-objective optimization model for the sustainable natural gas supply chain.

Keywords: Multi-objective, ε-constraint, Natural gas supply chain, Sustainability, Optimization.

1- Introduction

Nowadays, supply chain sustainability is a fairly recent and highly influential topic widely discussed by SCM researchers [1]. 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 [2]. In response, academic research has been developed on the design and management of sustainable supply chains over the past two decades [3-6]. 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 [7]. In terms of social sustainability, the focus has mostly been shifted on damages to human community health [8]. Any success in the modern business environment requires continuous supply chain improvement. To this end, it is critical to evaluate supply chains and extract the performance indicators [9]. 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 [10].

On the other hand, 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 echelons 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 have been conducted in recent years on the dimensions of sustainability in some echelons of the supply chain, 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 echelons 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. This study presents a multi-objective optimization model for the sustainable natural gas supply chain in the Iranian gas industry, including maximizing the total revenue and minimizing the economic costs and environmental costs in order to assess trade-offs among them and advise decision makers for the natural gas supply chain management.

Therefore, the rest of the paper is organized as follows: In Section 2, the literature review of sustainable supply chains. In Section 3, natural gas supply chain modeling in seven echelons as problem description is discussed. Section 4 (Mathematical Modelling) presents a multi-objective model including sets and indices, variables, parameters, objective functions and constraints. Some echelons of the natural gas supply chain are real size, but some others are small size. In Section 5 the problem solving approach is presented. Finally, the findings including case study and sensitivity analysis and Discussion and conclusions are given in Sections 6 and 7, respectively.

1-1-Literature Review

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 [11]. Minimization of greenhouse gas emissions has so far been the most desirable environmental goal [12]. The efforts made to model a green supply chain expanded in six directions. The optimal models for strategic supply chain design sought to balance the supply chain cost and CO_2 emissions [13-15]. Tactical and operational design tools for the emission-cost balance in supply chains [7, 16-17]. Design and planning of closed-loop supply chains with a concentration on emission-cost of forward and reverse networks [18-20]. Integration of life-cycle evaluation practices for assessment of environmental effects left by a sustainable supply chain [21]. Development and adoption of multiple performance criteria (beyond greenhouse gas emissions) for the management and design of green supply chains [7, 22-24]. And introducing and reviewing environmental policy tools for optimization and design of supply chain planning [17], [25].

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 [26], which is a primary explanation for insufficient research in this area. On the other hand, Zhang et al. conducted several studies on optimal design and cost planning in supply chains, greenhouse gas emissions, lead time, and social and environmental performance criteria [27]. Boukherroub et al. studied supply chain planning problems from the perspective of employee distance to industrial sites and job stability as criteria for social performance [8]. 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 surveyed the economic and environmental effects and sustainable aspects of the natural gas supply chain [24, 28-32]. In a research, Rostamzadeh et al. provided a framework for assessing sustainable supply chain risk management [33]. In their research, Ghaithan et al. 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 [34]. Another research, Zamanian et al. developed a fuzzy goal programming model for optimization of sustainable natural gas supply chain [32].

Review of literature shows that in the scope of the sustainable development in the natural gas supply chain, no significant research has been conducted. Therefore, presenting a multi-objective optimization model for the sustainable natural gas supply chain in their all echelons, would be very useful for gas industries management.

2- Problem Description

In this research, natural gas supply chain modeling was carried out in seven echelons. At the first echelon, there are three types of suppliers, including gas wells, storage tanks and imports. 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 echelons, respectively. The nine groups of customers including: 1. Residential consumers 2. Commercial consumers 3. Small industries 4. Natural gas exports 5. Major industries 6. Power Plants 7. Liquid and gas products for domestic use 8. The export of liquid and gas products and 9. Injection into the oil wells are at the seventh echelon. This natural gas supply chain is formulated in terms of the sustainability aspects with the aim of providing a multi-objective 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, 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. The schematic representation of the natural gas supply chain under study in Iran is shown in Figure 1: [32].

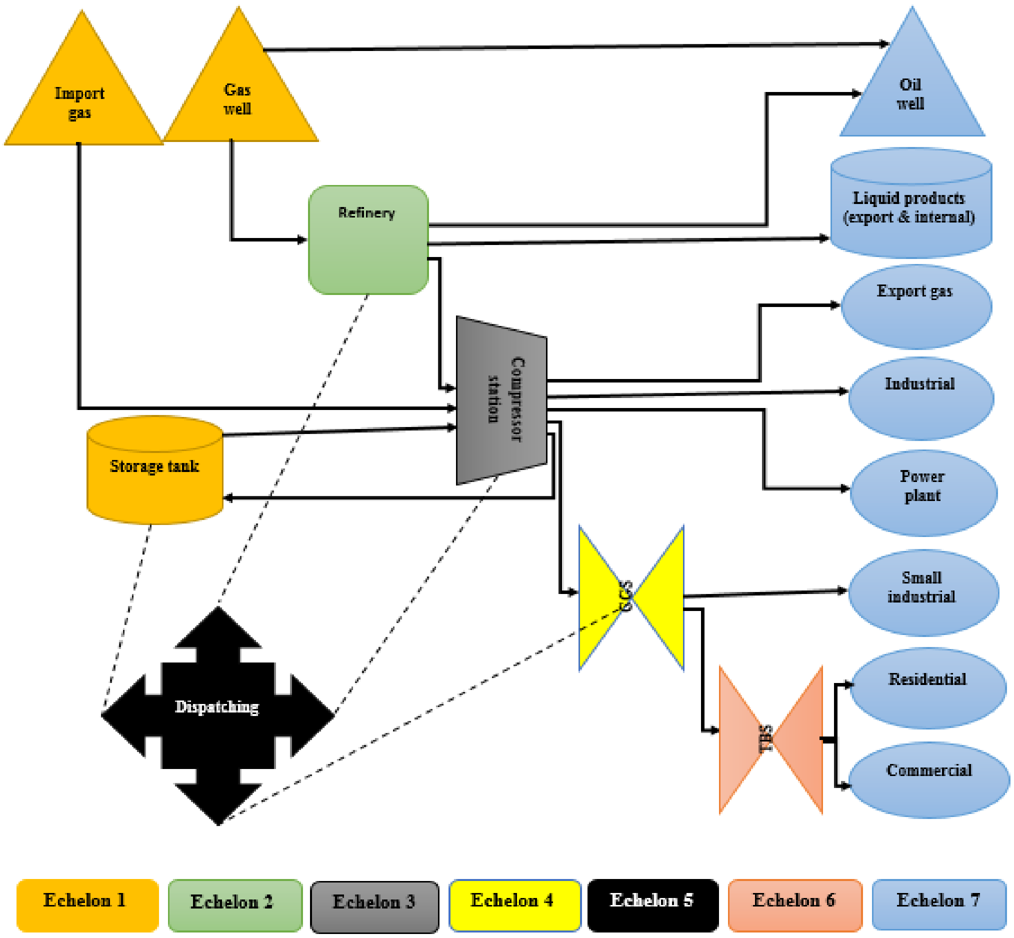

Figure 1-Schematic representation of the natural gas supply chain

3- Mathematical Modelling

This multi-objective model consists of sets and indices, decision variables, parameters, multi-objective functions and constraints.

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

Decision variables in period

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 $j \in \{r \cup y \cup g \cup o \cup e \cup d \cup p \cup s \cup b \cup l \cup f \cup m\}$
xwr_{wrt}: Gas volume transmitted from gas well to the refinery
xwo_{wot}: Gas volume transmitted from gas well to the oil well
xry_{ryt}: Gas volume transmitted from refinery to the compressor station
xro_{rot}: Gas volume transmitted from refinery to the oil well
xay_{ayt}: Gas volume transmitted from importation to the compressor station
xys_{yst}: Gas volume transmitted from compressor station to the storage tank
xsy_{syt}: Gas volume transmitted from storage tank to the compressor station
xye_{yet}: Gas volume transmitted from compressor station to the exportation
xyd_{ydt}: Gas volume transmitted from compressor station to the industrial customer
xyp_{ypt}: Gas volume transmitted from compressor station to the power plant customer
$xyy'_{yy't}$: Gas volume transmitted from compressor station to the another compressor station
xyg_{ygt}: Gas volume transmitted from compressor station to the city-gate station
xgm_{gmt}: Gas volume transmitted from city-gate station to the small industrial customer
xgb_{gbt}: Gas volume transmitted from city-gate station to the town bordering station
xbl_{blt}: Gas volume transmitted from town bordering station to the residential customer
xbf_{bft}: Gas volume transmitted from town bordering station to the commercial customer

Capacity parameters in period t

oc_{ot}: Oil well delivery capacity
wc_{wt}: Gas well capacity
ac_{at}: Importation capacity
rc_{rt}: Refinery capacity
yc_{yt}: Compressor station capacity
gc_{gt}: City-gate station capacity
bc_{bt}: Town bordering station capacity
sc_{s}: Storage tank capacity

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 path between node i and node j
h_{ij}: Hardness coefficient of the unique path between node i and node j
Λ_{ij}: If there is a unique path between node i and node j 1 otherwise 0
Q_{ij}^{Min}: Minimum flow unique path between node i and node j
Q_{ij}^{Max}: Maximum flow unique path between node i and node j

Average amount of greenhouse gas emissions parameters per unit

gw: Gas well
gr: Refinery
gy: Compressor station
gg: City-gate station
gb: Town bordering station
go: Oil well
gd: Industrial customer
gp: Power plant customer
gl: Residential customer
gf: Commercial customer
gm: Small industrial customer
gs: Storage tank
$g\alpha_{3i}$: Equal liquid product type three
$g\alpha_{4i}$: Equal liquid product type four

Cost parameters per unit in period t

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

Price parameters per unit in period t

Pwo_{wot}: Selling price of gas product by gas well for oil well
Pro_{rot}: Selling price of gas product by refinery for oil well
Pye_{yet}: Selling price of gas product by compressor station for exportation
Pyd_{ydt}: Selling price of gas product by compressor station for industrial customer

Pyp_{ypt}:	Selling price of gas product by compressor station for power plant customer
Pgm_{gmt}:	Selling price of gas product by city-gate station for small industrial customer
Pbl_{blt}:	Selling price of gas product by town bordering station for residential customer
Pbf_{bft}:	Selling price of gas product by town bordering station for commercial customer
$P\alpha_{1t}$:	Selling price of equal liquid product as type one
$P\alpha_{2t}$:	Selling price of equal liquid product as type two
$P\alpha_{3it}$:	Selling price of equal liquid product as type three for internal consumption
$P\alpha_{3et}$:	Selling price of equal liquid product as type three for exportation
$P\alpha_{4it}$:	Selling price of equal liquid product as type four for internal consumption
$P\alpha_{4et}$:	Selling price of equal liquid product as type four for exportation

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

Maximizing the total revenue of gas products $= Z_1$:

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

Minimizing the economic costs $= Z_2$:

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

Minimizing the environmental costs $=Z_3$:

$$sc\left\{ gw\left[\sum_{w}\sum_{r}\sum_{t} xwr_{wrt} + \sum_{w}\sum_{o}\sum_{t} xwo_{wot}\right] + gr\left[\sum_{r}\sum_{y}\sum_{t} xry_{ryt} + \sum_{r}\sum_{o}\sum_{t} xro_{rot}\right] + \right.$$
$$gy\left[\sum_{y}\sum_{\acute{y}}\sum_{t} xy\acute{y}_{y\acute{y}t} + \sum_{y}\sum_{g}\sum_{t} xyg_{ygt} + \sum_{y}\sum_{s}\sum_{t} xys_{yst} \right.$$
$$\left. + \sum_{y}\sum_{e}\sum_{t} xye_{yet} + \sum_{y}\sum_{d}\sum_{t} xyd_{ydt} + \sum_{y}\sum_{p}\sum_{t} xyp_{ypt}\right] +$$
$$gs\left[\sum_{s}\sum_{y}\sum_{t} xsy_{syt}\right] + gg\left[\sum_{g}\sum_{b}\sum_{t} xgb_{gbt} + \sum_{g}\sum_{m}\sum_{t} xgm_{gmt}\right] + \tag{3}$$
$$gb\left[\sum_{b}\sum_{l}\sum_{t} xbl_{blt} + \sum_{b}\sum_{f}\sum_{t} xbf_{bft}\right] + go\left[\sum_{w}\sum_{o}\sum_{t} xwo_{wot} + \sum_{r}\sum_{o}\sum_{t} xro_{rot}\right] +$$
$$\left[gd\sum_{y}\sum_{d}\sum_{t} xyd_{ydt} \right.$$
$$+ gp\sum_{y}\sum_{p}\sum_{t} xyp_{ypt}$$
$$+ gl\sum_{b}\sum_{l}\sum_{t} xbl_{blt} + gf\sum_{b}\sum_{f}\sum_{t} xbf_{bft} + gm\sum_{g}\sum_{m}\sum_{t} xgm_{gmt}$$
$$\left.\left. + \left(g\alpha_{3i}\sum_{w}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{3i}\right) + \left(g\alpha_{4i}\sum_{W}\sum_{r}\sum_{t} xwr_{wrt} \times \alpha_{4i}\right)\right]\right\}$$

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 echelon and the cost of transmission to the next echelon 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 echelons 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.

Constraints of the proposed model are presented as follows:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

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

Equation (44) represent that Xij_{ijt}, and t are equal or greater than 0.

4- 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 [35]. 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 defects of the first and second categories are that the decision-maker does not have a general view about the trade-off before getting the Pareto optimal set. To avoid the mentioned defects, 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, are generated. To eliminate the weakly efficient solutions, Mavrotas and Florios 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 [36]. Therefore, the augmented ε -constraint algorithm avoids the generation of weakly Pareto optimal solutions and accelerates the whole process by avoiding redundant iterations.

5- Findings

5-1- Case Study

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. Model statistics are shown in the Table 1. 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 Figure 2:

Table 1- Model statistics

Blocks of Equations	74	Single Equations	63,856
Blocks of Variables	20	Single Variables	20,525
Non Zero Elements	198,605		

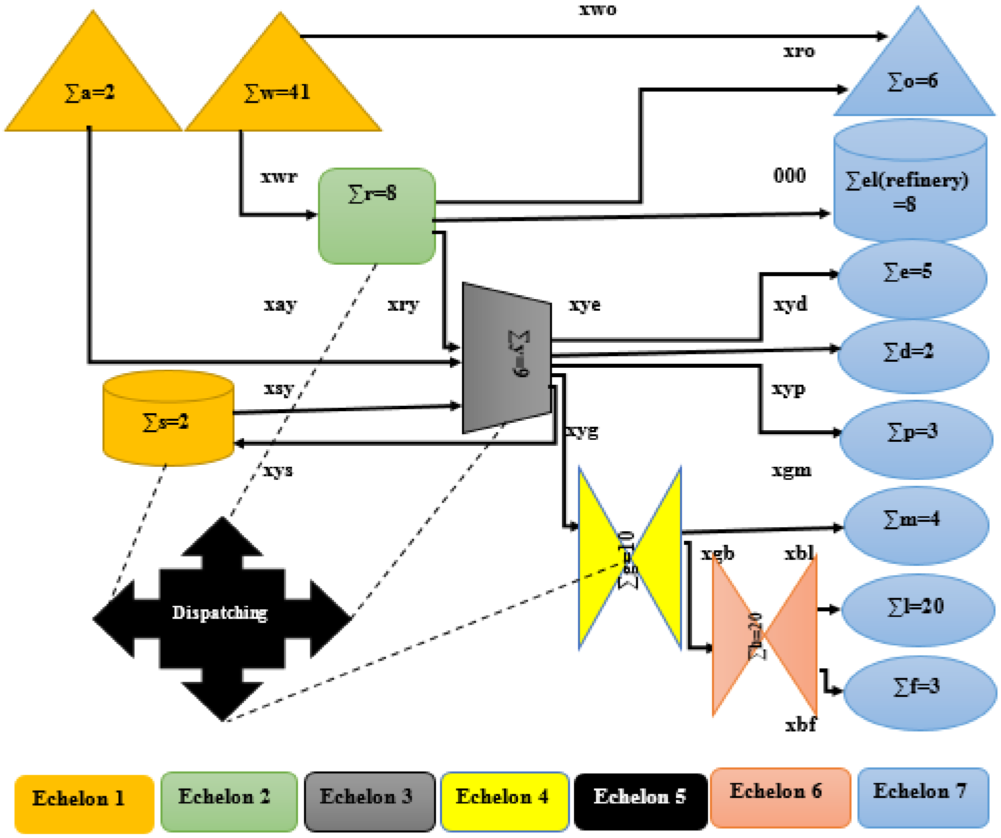

Figure 2- A small-sized of the natural gas supply chain

In this section, the obtained payoff table and Pareto optimal solutions and the mentioned real case study are analyzed. Table 2 epitomizes the payoff results obtained by the lexicographic optimization of the three objectives, as follows: Firstly, the problem is optimized as a single objective problem, including, maximizing the total revenue Obj1 (9.097109E+9). Then, the economic costs Obj2 (3.691506E+8) is optimized by adding the obtained total revenue value as a constraint. In the following, the environmental costs of emission of greenhouse gases Obj3 (1900729.129) is optimized by adding the obtained total revenue and economic costs as a constraint. After that, the same manner is repeated considering the economic and environmental costs shown in the second and third rows, respectively.

Table 2- Payoff results of the three objectives for 12 months

	Obj_1	Obj_2	Obj_3
Max Obj_1	9.097109E+9	3.691506E+8	1900729.129
Min Obj_2	8.208615E+9	3.222105E+8	1792972.364
Min Obj_3	7.908254E+9	3.427781E+8	1769560.560

In the following, the Pareto optimal solutions consisting of 6 categories for 3 objective functions are generated. The decision makers have to select the preferred scheme based on their selected criteria. The best scheme for the first objective gives a high total revenue of 9.085000E+9 /12 months, but with high total cost of economic (3.691500E+8) and environmental (1894787.100) / 12 months. Therefore, a high total revenue and a low total economic and environmental costs cannot be achieved. The worst scheme for the first objective gives low values for total revenue of 7.900000E+9 /12 months, and a low total cost of economic (3.415500E+8) and environmental

(1769659.650) /12 months. Consequently, there is big trade-offs among the three objective functions. It is obvious that as total revenue increases, total economic and environmental costs increase. Accordingly, decision makers have to select the preferred scheme. Results of the Pareto optimal solutions are shown in the Table 3:

Table 3- Results of the Pareto optimal solutions for 12 months

	Obj_1	Obj_2	Obj_3
1	7.900000E+9	3.415500E+8	1769659.650
2	8.216000E+9	3.208500E+8	1805410.350
3	8.769000E+9	3.450000E+8	1841161.050
4	8.769000E+9	3.588000E+8	1841161.050
5	9.006000E+9	3.450000E+8	1894787.100
6	9.085000E+9	3.691500E+8	1894787.100

5-2- 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 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 1 to 0.97, decrease the total revenue, while increase the economic costs in the objective functions. Despite the decrease in gas production, the economic costs are increased because of the increase in import in order 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 economic and environmental costs, while decrease the total revenue in the objective functions.

Changes in the γ parameter of the demand for gas from oil wells, lead to different amounts in the objective functions. i.e. by increasing the γ parameter by 2.5, 3 and 3.5 times, decrease the total revenue, while increases the economic and environmental costs in the objective functions. Accordingly, 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 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. Sensitivity analysis of various α, β and γ values and the amount of the objectives are shown in the Table 4, 5 and 6, 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 sustainability aspects of the supply chain. Multi-objective model includes the total revenue, economic and environmental costs of the gas throughout the supply chain.

Finally, the contributions of this research, compared to the former researches, are as follows: 1. Development of the model and consideration of seven natural gas supply chain echelons integrated into it, 2. Consideration of the sustainability aspects in the proposed model, and trade-offs among them and their Pareto optimal solution, 3. Application of Improved Augmented ε-constrained method 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 resilience and sustainability aspects of the natural gas supply chain. The key features of this model, along with previous studies, are presented in Table 7:

Table 4- Results of sensitivity analysis on parameters of the production capacity of gas wells

	Obj_1	Obj_2	Obj_3
α=1	9.097109E+9	3.222105E+8	1769560.560
α=0.98	9.050928E+9	3.231407E+8	1770541.992
α=0.97	9.021153E+9	3.234224E+8	1769968.020

Table 5- Results of sensitivity analysis on parameters of Storage tanks

	Obj_1	Obj_2	Obj_3
β =0.45	9.096880E+9	3.221503E+8	1769025.796
β =0.50	9.095292E+9	3.222676E+8	1769270.514

Table 6- Results of sensitivity analysis on parameters of demand volume of oil wells

	Obj_1	Obj_2	Obj_3
γ =2.50	9.096879E+9	3.206870E+8	1818217.062
γ =3	9.087074E+9	3.213438E+8	1824230.136
γ =3.50	9.059579E+9	3.276220E+8	1829461.611

Table 7- Classification and features of this study versus former studies

Reference articles	Level of SC			Objective		Sustainability		Development	Solution method
	Transmission	Distribution	All	Single	Multi	Economic	Environmental		
Mahlke et al. [37]	✓			✓		✓			Simulated annealing algorithm
Kabirian and Hemmati [38]	✓			✓		✓			A heuristic random search
Wu et al. [39]		✓		✓		✓			Primal-relaxed dual decomposition
Tabkhi et al. [40]	✓			✓		✓			Branch and bound
Hamedi et al. [30]			✓	✓		✓			A hierarchic algorithm
Mahdavi et al. [41]		✓		✓		✓			Minimum spanning tree

Dos Santos et al. [42]		✓			✓	✓			Monte Carlo simulation
Santibanez Gonzalez et al. [43]	✓				✓	✓	✓		Genetic Algorithm
Jamshidi et al. [44]				✓		✓	✓		Hybrid genetic Taguchi algorithm
Azadeh et al. [28]			✓		✓	✓	✓		An interactive method resolution
Azadeh et al. [29]	✓				✓	✓	✓		ε-constraint algorithm
Ghaithan et al. [34]			✓		✓	✓			ε-constraint algorithm
Sapkota et al. [31]			✓		✓	✓	✓		A comparative assessment
Zamanian et al. [32]			✓		✓	✓	✓	✓	A fuzzy goal programming
This study			✓		✓	✓	✓	✓	ε-constraint algorithm

6- Discussion and Conclusions

In this paper, based on the general structure of the Iranian gas industry and the relationship among its components, seven echelons were introduced for the natural gas supply chain and a multi-objective model was developed to optimize the sustainability aspects at all its echelons. Objective functions of the proposed model included the total revenue, economic and environmental costs for the natural gas, and all four products derived from natural gas in multiple time periods (12 months). Therefore, 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 on 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 a 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 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 increased 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 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. 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 are recommended for further research.

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