Journal of Environmental Economics & Chemical Processes (JEECP)

https://doi.org/10.22034/jeecp.2026.2088846.1024

Journal Homepage: WWW.JEECPJournal.com

Journal of Environmental Economics & Chemical Processes (JEECP)

ORIGINAL RESEARCH PAPER

A Multi-Objective Goal Programming Model for Profit Maximization and Environmental Sustainability in an Oil and Gas Supply Chain Network

Mohsen Abdoli; Reza Ehtesham Rasi [a, *]; Sadegh Abedi

Department of Industrial Management, Islamic Azad University, Qazvin Branch, Qazvin, Iran.

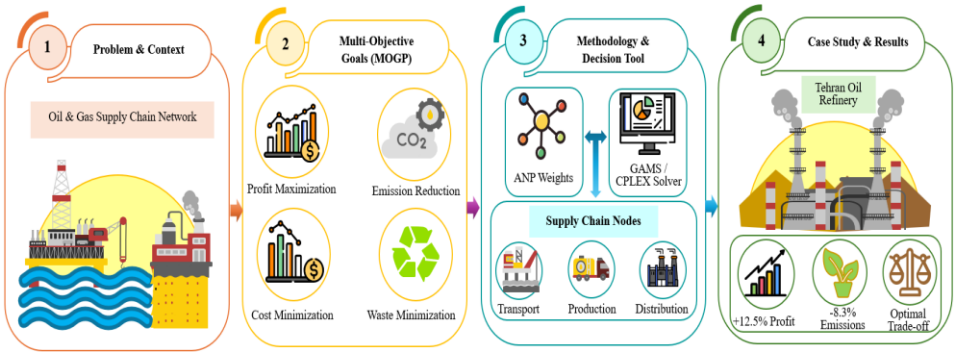
P A P E R I N F O

Paper history:
Received: 07/14/2026
Revised: 09/15/2026
Accepted in revised form: 09/27/2026
Published: 12/21/2026

***Keywords*:**
MOGP;
Profit Maximization;
ANP;
Oil and Gas Industry;
GAMS.

A B S T R A C T

The oil and gas industry struggles to balance economic performance with environmental sustainability in complex supply chains. While existing literature covers cost reduction and emission mitigation, few studies integrate profit maximization, production costs, and waste management within a single unified framework. Furthermore, the application of Goal Programming to large-scale, real-world industrial cases remains limited. To address these gaps, this study develops a Multi-Objective Goal Programming (MOGP) model that simultaneously optimizes four objectives: profit maximization, environmental emission minimization, production cost minimization, and waste generation minimization. The model integrates production planning, inventory, transportation, and distribution decisions, incorporating managerial preferences via Analytic Network Process (ANP) weights. Implemented in GAMS and solved using CPLEX, the framework is validated through a case study of the Tehran Oil Refinery (2023–2024). Results demonstrate that the model achieves a balanced solution between competing goals. Compared to the baseline cost-minimization scenario, the proposed model increases profitability by 12.5% and reduces total emissions by 8.3%, reaching 93.3% and 98.1% of the respective aspiration levels. Sensitivity analysis identifies product price and transportation capacity as critical parameters. Practically, this framework serves as a quantitative decision-support tool for managers to optimize resource allocation and develop sustainable production strategies.



1. Introduction

The oil and gas industry continues to play a pivotal role in the global energy system. It supplies more than half of the world's primary energy demand despite the accelerating transition toward renewable energy sources. As energy markets become increasingly interconnected, the performance of oil and gas supply chains has become a critical determinant of economic stability, industrial competitiveness, and energy security. At the same time, the industry faces unprecedented challenges arising from market volatility, geopolitical disruptions, environmental regulations, and growing societal expectations regarding sustainable development.These challenges have increased the complexity of supply chain planning and decision-making. They therefore require organizations to adopt more integrated and resilient management Historically, supply chain management in the oil and gas sector has been primarily driven by economic objectives. Particular emphasis has been placed on reducing operational costs, improving resource utilization, and increasing production efficiency. Although these objectives remain important, growing awareness of climate change, greenhouse gas (GHG) emissions, environmental degradation, and resource scarcity has transformed managerial priorities. Governments, regulatory agencies, investors, and other stakeholders increasingly expect organizations to pursue environmental responsibility alongside economic performance. Consequently, supply chain decisions can no longer be evaluated solely from a financial perspective. Their environmental consequences must also be considered throughout the entire value chain.

In response to these emerging challenges, Sustainable Supply Chain Management (SSCM) has become an influential research area in operations and supply chain

* Corresponding Author: Reza Ehteshamrasi
E-mail address: reza.ehteshamrasi@iau.ac.ir
ISSN: 3116-0050
URL: https://www.jeecpjournal.com/article_736233.html

Please cite this article as: M. Abdoli, R. Ehtesham Rasi, & S. Abedi, *Journal of Enviromental Economics & Chemical Processes (JEECP)*, 2026, *3*(4), 205-216. https://doi.org/10.22034/jeecp.2026.2088846.1024

/© 2026 The Author(s). Published by Power of New Vision Movement Institute.

management. SSCM extends the traditional concept of supply chain management by integrating economic, environmental, and social considerations into strategic and operational decision-making. Within the oil and gas industry, sustainability encompasses a broad range of issues. These include GHG emission reduction, efficient utilization of natural resources, waste minimization, cleaner production technologies, and environmentally responsible logistics operations. Achieving these objectives requires decision-support frameworks that can evaluate multiple and often conflicting performance criteria. Such frameworks must also maintain operational efficiency and economic viability.

One of the major challenges in sustainable supply chain planning is balancing profitability with environmental performance. Investments in cleaner production technologies, emission-control systems, waste treatment facilities, and environmentally friendly transportation practices may increase operational expenditures in the short term. However, these investments can generate significant long-term economic benefits. Such benefits may arise from improved resource efficiency, regulatory compliance, risk reduction, and enhanced corporate reputation. Managers therefore require analytical tools that can evaluate trade-offs between financial and environmental objectives. These tools should help identify solutions that achieve an appropriate balance between competing priorities. Mathematical optimization has become an indispensable tool for supporting strategic and operational decisions in complex supply chain systems. Modern supply networks are characterized by large-scale operations and multiple conflicting objectives. These characteristics have encouraged researchers to develop optimization approaches that simultaneously address economic, operational, and environmental concerns. Among multi-objective optimization techniques, Goal Programming (GP) has been widely recognized as a practical method for problems involving several predefined performance targets. Decision-makers can use GP to pursue multiple aspiration levels rather than optimize a single objective.

Unlike conventional weighted-sum approaches, GP enables organizations to explicitly represent managerial priorities through aspiration levels and deviation variables. This feature provides greater flexibility in addressing real-world decision-making problems. It also allows decision-makers to distinguish between desirable and undesirable deviations from established targets. Despite the growing body of research on supply chain optimization in the oil and gas sector, existing studies have generally focused on individual aspects of supply chain performance. These aspects include production planning, transportation efficiency, inventory management, cost reduction, and emission mitigation. Such contributions have advanced the literature considerably. However, relatively few studies have developed integrated optimization models that simultaneously maximize profitability and minimize environmental impacts, production costs, and waste generation within a unified decision-making framework. Moreover, many existing models simplify the interactions among production, inventory, transportation, and environmental performance. This limitation can reduce their applicability to large-scale industrial supply chains. Another important limitation in the existing literature is the relatively limited application of Goal Programming to comprehensive oil and gas supply chain optimization. Several studies have successfully employed alternative multi-objective optimization techniques. These include the ε-constraint method, evolutionary algorithms, and robust optimization. Comparatively less attention has been devoted to the practical advantages of GP in supporting managerial decision-making under multiple performance objectives. Furthermore, many published models have been evaluated using hypothetical datasets or simplified numerical examples. This practice can reduce confidence in their practical applicability to real industrial environments. These limitations highlight the need for an integrated optimization framework that simultaneously considers financial and environmental performance. Such a framework should also capture the operational interactions among production, inventory, transportation, and distribution decisions. To address this need, the present study develops a Multi-Objective Goal Programming (MOGP) model for designing and optimizing a sustainable oil and gas supply chain network.

The proposed framework jointly considers four key managerial objectives. These objectives are maximizing profit, minimizing environmental emissions, reducing production costs, and minimizing waste disposal. Integrating these objectives within a single optimization model enables decision-makers to evaluate trade-offs among competing performance criteria. It also helps identify balanced operational strategies that support both economic competitiveness and environmental sustainability.To demonstrate its practical relevance, the proposed model is implemented using the General Algebraic Modeling System (GAMS). The model is evaluated through a case study based on the Tehran Oil Refinery. The computational analysis demonstrates how the proposed framework can support strategic and operational decision-making. It also shows how environmental considerations can be incorporated into managerial planning while improving overall supply chain performance. To address the identified research gaps, this study develops a comprehensive MOGP framework for optimizing sustainable oil and gas supply chain networks. Unlike conventional optimization approaches that primarily focus on a single performance dimension, the proposed model simultaneously incorporates economic and environmental objectives. These objectives are integrated within a unified decision-making framework. The model jointly optimizes production planning, inventory management, transportation, and material flow decisions. This approach provides a more comprehensive representation of supply chain operations. It also enables decision-makers to evaluate interactions among different operational components. The principal contributions of this study are summarized as follows:

1. An integrated MOGP framework is developed to simultaneously maximize profit and minimize production costs, environmental emissions, and waste disposal. These objectives are incorporated within a unified optimization model.
2. A holistic supply chain optimization approach is proposed by integrating production, inventory, transportation, and distribution decisions. This integration allows interactions among operational activities to be explicitly represented rather than optimized independently.
3. Environmental sustainability is incorporated directly into strategic supply chain planning. The proposed framework enables quantitative evaluation of trade-offs between economic performance and environmental responsibility under multiple managerial objectives.
4. The applicability of the proposed framework is demonstrated through an industrial case study based on the Tehran Oil Refinery. The case study illustrates the model's potential to support decision-making in complex petroleum supply chain networks.
5. A comprehensive sensitivity analysis is conducted to evaluate the Sensitivity Analysis of the proposed model under different operational scenarios. The analysis also identifies the parameters that exert the greatest influence on supply chain performance.

Overall, the proposed framework contributes to the growing literature on sustainable supply chain optimization. It provides an integrated decision-support model that combines methodological flexibility with practical applicability. The findings are expected to assist researchers and industry practitioners in developing balanced strategies. Such strategies can improve financial performance while addressing environmental challenges within the oil and gas sector. The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and identifies existing research gaps. Section 3 presents the problem description and mathematical formulation of the proposed model. Section 4 describes the case study, data collection procedure, and computational implementation. Section 5 discusses the computational results and evaluates the model's economic and environmental performance. Section 6 presents the sensitivity analysis and examines the Sensitivity Analysis of the proposed framework under different operational conditions. Section 7 discusses the managerial implications of the findings. Finally, Section 8 concludes the paper by summarizing the main findings, outlining the study's limitations, and suggesting directions for future research.

1.1. Literature Review and Research Gap

1.1.1. Sustainable Supply Chain Management in the Oil and Gas Industry

The concept of SSCM has evolved significantly over the past decade. Seuring and Müller [1] provided a foundational framework integrating environmental and social dimensions into supply chain management, emphasizing the need for holistic approaches that consider the triple bottom line. Brandenburg et al. [2] conducted a comprehensive review of quantitative models in sustainable supply chain management, identifying cost minimization and emission reduction as predominant objectives, while profit maximization received limited attention in the literature.

In the oil and gas sector, sustainability research has focused on various aspects. Tamala et al. [3] performed a bibliometric analysis of sustainable oil and gas production research using VOSviewer, revealing increasing research interest in emission reduction technologies, carbon capture, and waste management. Shahbaz et al. [4] reviewed waste management approaches in the oil and gas industry, emphasizing the potential for value creation through circular economy principles and resource recovery from waste streams. However, these studies predominantly address environmental issues independently from economic performance, lacking integrated frameworks. More recent contributions have begun to address sustainability from a systems perspective. Govindan and Cheng [5] conducted a systematic literature review of sustainable supply chain management, identifying integration of environmental criteria into operational decision-making as a critical research direction. They emphasized the need for quantitative models that can handle the complexity of real-world supply chains while accounting for both economic and environmental performance metrics.

1.1.2. Optimization Models in Oil and Gas Supply Chains

Recent studies have applied various optimization techniques to oil and gas supply chain problems. Ebrahimi and Bagheri [6] developed a bi-objective mathematical model for optimizing profit and reliability in an oil supply chain under disruption risks, using an epsilon-constraint method. Their study demonstrated that incorporating reliability into supply chain design significantly affects operational performance, though the environmental dimension was not explicitly considered.

Sepehri et al. [7] designed a reliable-sustainable supply chain network for petroleum logistics using an adaptive multi-objective epsilon-constraint approach. While their model considered both economic and environmental objectives, the primary focus remained on transportation planning and logistics efficiency, with limited attention to production-related emissions and waste management. Arab et al. [8] developed a

mathematical optimization model for a sustainable gasoline supply chain in Iran, emphasizing cost reduction and environmental compliance. Their work provided valuable insights into the Iranian petroleum industry context but focused primarily on cost minimization as the economic objective, with environmental aspects treated as constraints rather than equal objectives. Fetanat and Tayebi [9] prioritized produced water treatment technologies in the oil and gas industry using sustainability and resilience criteria, employing multi-criteria decision-making methods. While their study incorporated multiple sustainability dimensions, it did not develop a mathematical optimization model for supply chain decisions. Other notable contributions include the work of Ghaderi et al. [10], who developed a robust optimization model for oil supply chain planning under demand uncertainty, and the study by Gholizadeh et al. [11], who proposed a sustainable supply chain network design for petroleum products considering carbon emissions. However, these studies typically address either economic or environmental objectives separately, lacking an integrated optimization framework that simultaneously considers multiple objectives within a unified approach.

1.1.3. Goal Programming in Supply Chain Optimization

Goal programming has been widely applied in multi-objective supply chain optimization. Charnes and Cooper [12] introduced GP as a flexible approach for handling conflicting objectives in management decision-making. Romero [13] extended GP applications to various industrial contexts, emphasizing its advantages over other multi-objective methods in terms of flexibility, interpretability, and ability to incorporate managerial preferences through aspiration levels. Recent studies have applied GP to sustainable supply chain problems across various industries. Azadi et al. [14] used GP for sustainable supplier selection in the automotive industry, demonstrating its effectiveness in balancing economic, environmental, and social criteria. Ji et al. [15] applied GP to optimize a closed-loop supply chain for electronic waste, considering recycling rates and environmental impacts. However, applications of GP to oil and gas supply chain networks remain limited. Most existing GP applications in this sector focus on specific aspects such as production planning or logistics optimization, without comprehensively integrating production, inventory, transportation, and environmental decisions. Moreover, few studies have applied GP to real industrial cases in the oil and gas sector using extensive operational data.

1.2. Research Gap and Contributions

Based on the comprehensive literature review, the following research gaps are identified:

1. Limited integration: Most studies address economic and environmental objectives independently rather than within a unified optimization framework that considers their interactions and trade-offs.
2. Objective function focus: Profit maximization is rarely considered as the primary economic objective; most models emphasize cost minimization, which may not adequately capture the broader economic performance of supply chain operations.
3. Scope limitations: Few models simultaneously optimize production, inventory, transportation, and environmental decisions in an integrated refinery network. Most studies focus on one or two aspects of the supply chain.
4. Validation gap: The majority of models are validated using hypothetical or small-scale datasets rather than real industrial case studies with extensive operational data.

1.3. Methodological gap

Goal programming, despite its flexibility and practical advantages, has been underutilized in comprehensive oil and gas supply chain optimization. To address these gaps, this study proposes a comprehensive MOGP model that integrates four key objectives (profit maximization, environmental sustainability, production cost minimization, and waste disposal minimization) within a unified framework, validated through a real case study from the Iranian oil and gas industry with 100,000 customer zones and five petroleum products.

Table 1. The previous studies and highlights the research gap addressed by this research

Authors	Industry/Case Study	Methodology	Main Objectives	Sustainability Dimension	Research Limitations
Ebrahimi & Bagheri [6]	Oil supply chain	Bi-objective MILP	Profit & Reliability	Economic	Environmental dimension not considered
Sepehri et al. [7]	Petroleum logistics	Multi-objective ε-constraint	Transportation planning	Economic & Environmental	Production-related emissions overlooked
Arab et al. [8]	Oil refinery	MILP	Cost & emission reduction	Economic & Environmental	Profit not explicitly optimized as objective
Fetanat & Tayebi [9]	Energy supply chain	MCDM	Technology prioritization	Environmental	No optimization model
Ghaderi et al. [10]	Oil supply chain	Robust optimization	Cost minimization	Economic	Environmental constraints only
Gholizadeh et al. [11]	Petroleum products	MILP	Cost & carbon reduction	Economic & Environmental	Supply chain scope limited
This Study	Oil and Gas Supply Chain Network	Multi-objective Goal Programming	Profit Maximization + Environmental Sustainability + Cost Minimization + Waste Minimization	Integrated Economic-Environmental Framework	Addresses production, transportation, inventory, and environmental decisions simultaneously using a real case study with 100,000 customers

Source: Research Findings

2. Method

2.1. Methodology

The oil and gas supply chain is a complex, multi-echelon network that integrates raw material procurement, petroleum product manufacturing, storage, transportation, and distribution to end customers. Effective coordination among these interconnected stages plays a critical role in improving operational efficiency, reducing total supply chain costs, and maintaining environmental sustainability under increasingly stringent regulatory requirements.

The supply chain network considered in this study consists of suppliers, production facilities (refineries), warehouses, distribution centers, and customer zones connected through predefined transportation links. Raw materials are supplied to production facilities, where multiple petroleum products are manufactured and subsequently transported to warehouses and distribution centers before being delivered to final customers. Inventory is maintained at intermediate facilities to satisfy customer demand while providing sufficient operational flexibility throughout the planning horizon.

Managerial decisions regarding production planning, inventory allocation, and transportation scheduling directly influence not only the economic performance of the supply chain but also its environmental footprint. Consequently, these decisions should be optimized simultaneously rather than independently to achieve a balanced and sustainable operating strategy.

In this study, environmental sustainability is evaluated using three major performance indicators:

- Production emissions: GHG emissions generated during petroleum product manufacturing.

- Transportation emissions: GHG emissions resulting from product transportation between supply chain facilities.

- Waste disposal: Waste generated throughout production and distribution processes requiring treatment or disposal.

These indicators represent the primary environmental impacts associated with oil and gas supply chain operations and are therefore incorporated into the optimization framework together with economic objectives. Considering both economic and environmental criteria enables the proposed model to support more balanced managerial decisions and improve the overall sustainability of the supply chain. To address the conflicting nature of these objectives, a MOGP approach is adopted. Goal Programming provides a practical decision-support framework by minimizing deviations from predefined aspiration levels while allowing decision-makers to assign different priorities to each objective according to managerial preferences. Consequently, the proposed framework seeks to improve profitability while simultaneously reducing environmental impacts and maintaining operational feasibility throughout the supply chain.

2.2. Model Assumptions

The proposed optimization model is developed based on the following assumptions:

1. The supply chain network configuration and transportation links remain fixed throughout the planning horizon.
2. Customer demand for each petroleum product is deterministic and known for every planning period.
3. Production, storage, and transportation capacities are finite and known in advance.
4. Multiple petroleum products, including gasoline, light crude oil, heavy crude oil, LPG, kerosene, and propane, are considered simultaneously.
5. Material flows are permitted only through predefined transportation links within the supply chain network.

6. Inventory may be carried over from one planning period to the next without quality deterioration.
7. Production, inventory, transportation, and distribution decisions are optimized simultaneously within an integrated decision-making framework.
8. Environmental impacts originate from production activities, transportation operations, and waste disposal processes.
9. The planning horizon is divided into four discrete quarterly periods.
10. All model parameters are deterministic and remain constant during the planning horizon.
11. Product shortages are not permitted; therefore, customer demand must be completely satisfied in every planning period.
12. Decision variables are continuous and non-negative unless otherwise specified.

2.3. Mathematical Formulation

2.3.1. Sets and Indices

Table 2. Sets and indices

Symbol	Description
$i \in I$	Suppliers (raw material sources)
$j \in J$	Production facilities (refineries)
$k \in K$	Warehouses
$l \in L$	Distribution centers
$m \in M$	Customer zones
$p \in P$	Product types
$t \in T$	Time periods
I	Set of suppliers (raw-material sources)
J	set of production facilities (refineries)
K	set of warehouses
L	set of distribution centers
M	set of customer zones
P	set of petroleum products
T	set of planning periods

Source: Research Findings

2.3.2. Parameters

Table 3. Parameters

Parameter	Description	Unit
D_{mpt}	Demand for product p in zone m at period t	Units
C^P_{jpt}	Production cost per unit of product p at facility j in period t	Monetary units
C^T_{jklpt}	Transportation cost per unit of product p transported from production facility j to warehouse k in period t.	Monetary units
C^H_{kpt}	Inventory holding cost per unit of product p at warehouse k in period t	Monetary units
C^W_{lpt}	Waste disposal cost per unit of waste generated for product p at distribution center l in period t	Monetary units
SP_{pt}	Selling price of product p in period t	Monetary units
Cap^P_j	Production capacity of facility j	Units
Cap^H_k	Storage capacity of warehouse k	Units
Cap^T_{jl}	Transportation capacity from facility j to distribution center l	Units
E^{prod}_{jp}	Environmental emission coefficient for product p at facility j	Emission units/unit
E^{trans}_{jkl}	Environmental emission coefficient for transporting product from facility j to warehouse k or distribution center l	Emission units/unit
E^{waste}_{l}	Environmental emission coefficient for waste disposal at distribution center l	Emission units/unit
$EnvLimit$=0.8	Maximum allowable total environmental emissions across the supply chain	Emission units
$WasteRate_{jp}$	Waste generation rate per unit of product p produced at facility j	Waste units/unit
w_r	Weight assigned to objective r (derived from ANP)	Dimensionless
AL_r	Aspiration level for objective r	Depends on objective

Source: Research Findings

2.3.3. Decision Variables

Table 4. Decision variables

Variable	Description	Unit
X_{jpt}	Production quantity of product p at facility j in period t	Units
Y_{jklpt}	Transportation quantity of product p from facility j to warehouse k or distribution center l in period t	Units
I_{kpt}	Inventory level of product p at warehouse k at the end of period t	Units
S_{mpt}	Sales quantity of product p to customer zone m in period t	Units
W_{lpt}	Waste quantity generated for product p at distribution center l in period t	Waste units

Source: Research Findings

2.3.4. Objective Functions

The proposed optimization framework simultaneously considers four objectives representing the major economic and environmental dimensions of the oil and gas supply chain. Since these objectives are inherently conflicting, they are integrated within a MOGP framework to obtain balanced managerial decisions.

Objective 1: Profit Maximization

The first objective aims to maximize the overall profit of the supply chain. Total profit is calculated as the difference between sales revenue and the total costs associated with production, transportation, inventory holding, and waste disposal.

$$Z_1 = \sum_{p\in P}\sum_{m\in M}\sum_{t\in T} SP_{pt}\cdot S_{mpt} - \sum_{j\in J}\sum_{p\in P}\sum_{t\in T} C^P_{jpt}\cdot X_{jpt} - \sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\sum_{p\in P}\sum_{t\in T} C^T_{jklpt}\cdot Y_{jklpt} - \sum_{k\in K}\sum_{p\in P}\sum_{t\in T} C^H_{kpt}\cdot I_{kpt} - \sum_{l\in I}\sum_{p\in P}\sum_{t\in T} C^W_{lpt}\cdot W_{lpt}$$

Objective 2: Environmental Sustainability (Emission Minimization)

The second objective minimizes the total environmental impact generated throughout the supply chain. Environmental emissions include those arising from production activities, transportation operations, and waste disposal.

$$Z_2 = \sum_{j\in J}\sum_{p\in P}\sum_{t\in T} E^{prod}_{jp}\cdot X_{jpt} + \sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\sum_{p\in P}\sum_{t\in T} E^{trans}_{jkl}\cdot Y_{jklpt} + \sum_{l\in I}\sum_{p\in P}\sum_{t\in T} E^{waste}_{l}\cdot W_{lpt}$$

Objective 3: Production Cost Minimization

The third objective minimizes the total production cost incurred at all production facilities during the planning horizon.

$$Z_3 = \sum_{i\in I}\sum_{p\in P}\sum_{t\in T} C^P_{jpt}\cdot X_{jpt}$$

Objective 4: Waste Disposal Minimization

The fourth objective minimizes the total quantity of waste generated throughout supply chain operations.

$$Z_4 = \sum_{l\in I}\sum_{p\in P}\sum_{t\in T} W_{lpt}$$

2.3.5. Goal Programming Formulation

Because the proposed model simultaneously addresses multiple conflicting objectives, a MOGP approach is employed to determine a balanced solution. Each objective is associated with a predefined aspiration level, and the optimization process seeks to minimize the weighted deviations from these target values according to the decision-makers' preferences.

The overall objective function of the MOGP model is formulated as follows:

$$\text{Minimize } Z = \sum_{r=1}^{4} w_r\cdot(d_r^+ + d_r^-)$$

Subject to:

$$\begin{aligned} Z_1 + d_1^- - d_1^+ &= AL_1 \\ Z_2 + d_2^- - d_2^+ &= AL_2 \\ Z_3 + d_3^- - d_3^+ &= AL_3 \\ Z_4 + d_4^- - d_4^+ &= AL_4 \end{aligned}$$

Where:

$-AL_1, AL_2, AL_3, AL_4$ are the aspiration levels for profit, environmental, production cost, and waste disposal objectives, respectively

$-d_r^+$ and d_r^- are positive (overachievement) and negative (underachievement) deviations from aspiration levels

$-w_r$ are the weights assigned to each objective (determined using the ANP)

2.3.6. Constraints

The proposed optimization model is subject to the following operational and environmental constraints.

2.3.6.1. Material Balance Constraints

The inventory balance equation ensures the conservation of material flow throughout the planning horizon. For each warehouse, the inventory at the end of each period equals the inventory carried over from the previous period plus incoming shipments minus the quantity supplied to satisfy customer demand.

$$I_{kpt} = I_{kp(t-1)} + \sum_{i\in I}\sum_{l\in L} Y_{jklpt} - \sum_{m\in M} S_{mpt}\ \forall k \in K, p \in P, t \in T$$

This constraint ensures that inventory at the end of period t equals beginning inventory plus incoming shipments from production facilities (via distribution centers) minus sales to customers.

2.3.6.2. Production Capacity Constraints

Production at each refinery cannot exceed its available production capacity during each planning period.

$$\sum_{p\in P} X_{jpt} \le Cap_j^p \forall j \in J, t \in T, \qquad X_{jpt} \ge 0 \forall j \in J, p \in P, t \in T$$

2.3.6.3. Warehouse Capacity Constraints

The inventory stored at each warehouse is restricted by the available storage capacity.

$$\sum_{p\in P} I_{kpt} \le Cap_k^H \forall k \in K, t \in T, \qquad I_{kpt} \ge 0 \forall k \in K, p \in P, t \in T$$

2.3.6.4. Transportation Capacity Constraints

Product shipments between supply chain facilities are limited by the transportation capacity available on each transportation link.

$$\sum_{p\in P} Y_{jklpt} \le Cap_{jl}^T \forall j \in J, l \in L, t \in T$$

$$Y_{jklpt} \ge 0 \forall j \in J, k \in K, l \in L, p \in P, t \in T$$

2.3.6.5. Demand Satisfaction Constraints

Customer demand must be completely satisfied during every planning period. Accordingly, total sales must satisfy the corresponding customer demand.

$$\sum_{m\in M} S_{mpt} = \sum_{j\in J} X_{jpt} + \sum_{i\in I}\sum_{k\in K} Y_{jkpt}\ \forall p \in P, t \in T$$

$$S_{mpt} \ge D_{mpt} \forall m \in M, p \in P, t \in T$$

2.3.6.6. Waste Generation Constraints

Waste generated within the supply chain is proportional to the corresponding operational activities and is determined using the predefined waste generation coefficients.

$$W_{lpt} = \sum_{i\in I}\sum_{k\in K} WasteRat\, e_{jp} \cdot Y_{jklpt} \forall l \in L, p \in P, t \in T$$

$$W_{lpt} \ge 0 \forall l \in L, p \in P, t \in T$$

2.3.6.7. Environmental Constraints

Total environmental emissions generated by production, transportation, and waste disposal activities must remain within the maximum allowable environmental limit.

$$\sum_{j\in J}\sum_{p\in P}\sum_{t\in T} E_{jp}^{prod} \cdot X_{jpt} + \sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\sum_{p\in P}\sum_{t\in T} E_{jkl}^{trans} \cdot Y_{jklpt} + \sum_{l\in L}\sum_{p\in P}\sum_{t\in T} E_l^{waste} \cdot W_{lpt} \le EnvLimit$$

2.3.6.8. Non-negativity Constraints

All decision variables are restricted to non-negative values.

$$X_{jpt} \ge 0, Y_{jklpt} \ge 0, I_{kpt} \ge 0, S_{mpt} \ge 0, W_{lpt} \ge 0 \forall j \in J, k \in K, l \in L, m \in M, p \in P, t \in T$$

2.4. Case Study Description

The applicability of the proposed MOGP model is demonstrated through a case study based on the supply chain of the Tehran Oil Refinery. The computational experiments were conducted using operational data representing the refinery's production, storage, transportation, and distribution activities during the 2023–2024 planning period. To preserve data confidentiality, the reported dataset represents the operational structure and planning characteristics of the refinery while maintaining consistency with actual industrial conditions.

2.5. Supply Chain Network Structure

The supply chain network considered in this study includes the following major echelons:

- 112 suppliers providing crude oil and other raw materials.
- One production facility (Tehran Oil Refinery).
- Eight warehouses for intermediate inventory storage.
- 142 regional distribution centers serving downstream markets.
- Approximately 12,500 aggregated customer demand nodes representing fuel stations, industrial consumers, and commercial customers throughout the distribution network.

This network reflects the typical operational structure of a large-scale petroleum supply chain and captures the interactions among upstream suppliers, production facilities, storage locations, distribution centers, and end-market demand.

2.6. Products

Five petroleum products were selected because of their economic significance and environmental implications within refinery operations:

1. Gasoline (high demand, moderate environmental emissions)
2. Light Crude Oil (high demand, relatively high environmental emissions)
3. Heavy Crude Oil (moderate demand, high environmental emissions)
4. Liquefied Petroleum Gas (LPG) (moderate demand, relatively low environmental emissions)
5. Kerosene (high demand, moderate environmental emissions)

2.7. Planning Horizon

The planning horizon consists of four quarterly periods, allowing the model to capture seasonal fluctuations in market demand and operational conditions while maintaining an appropriate level of planning detail.

2.8. Data Sources

The input data required for model implementation were compiled from multiple organizational sources, including:

- Production capacity records obtained from refinery operational reports.
- Warehouse capacity information provided by the logistics department.
- Transportation capacity data collected from fleet management records.
- Historical customer demand obtained from sales records.
- Production and operational cost information provided by the accounting department.
- Product selling prices obtained from commercial planning reports.
- Inventory-related parameters extracted from the inventory management system.
- Environmental emission coefficients derived from environmental monitoring and compliance reports.

The collected data were reviewed for consistency and subsequently verified through consultations with refinery managers and supply chain specialists before being used in the computational experiments.

Table 5. The main characteristics of the case study

Characteristic	Description
Industry	Oil and Gas Supply Chain
Case Study	Tehran Oil Refinery

Planning Horizon	Four quarterly periods (2023–2024)
Products	Five petroleum products (Gasoline, Light Crude Oil, Heavy Crude Oil, LPG, and Kerosene)
Supply Chain Scale	112 suppliers, 1 refinery, 8 warehouses, 142 distribution centers, and approximately 12,500 aggregated customer demand nodes
Decision Method	MOGP
Optimization Software	GAMS 24.0 using the CPLEX solver
Objectives	Profit maximization, environmental emission minimization, production cost minimization, and waste generation minimization
Computational Environment	Intel Core i7 processor, 16 GB RAM, Windows 10

Source: Research Findings

2.9. Solution Approach

The proposed MOGP model was implemented using the GAMS version 24.0 and solved with the CPLEX 12.10 optimization solver. All computational experiments were performed on a personal computer equipped with an Intel Core i7-10750H processor (2.60 GHz), 16 GB RAM, and the Windows 10 operating system. The implementation process consisted of four main stages. First, the supply chain network, including suppliers, production facilities, warehouses, distribution centers, products, and planning periods, was defined within the GAMS environment. Second, all operational, economic, and environmental parameters were imported into the mathematical model. Third, the objective weights obtained from the ANP were incorporated into the Goal Programming formulation. Finally, the model was solved using the CPLEX solver to obtain the optimal production, inventory, transportation, and distribution decisions.

2.10. Computational Performance

The resulting optimization model represents a medium-to-large-scale linear programming problem. The computational characteristics of the implemented model are summarized below:

- Number of decision variables: approximately 126,000 continuous variables.
- Number of constraints: approximately 28,100 linear constraints.
- Average solution time: approximately 4 minutes.
- Optimality gap: less than 0.01%.

The computational results indicate that the proposed model can be solved efficiently using a commercial optimization solver despite the relatively large number of variables and constraints. The computational time remained within an acceptable range for strategic and tactical supply chain planning applications.

The satisfactory computational performance is primarily attributed to the linear structure of the proposed Goal Programming formulation and the efficiency of the CPLEX solver in handling large-scale linear optimization problems. Consequently, the proposed decision-support framework is suitable for practical applications involving integrated production, inventory, transportation, and environmental planning in large-scale oil and gas supply chains.

2.11. Goal Weights Determination

The relative importance of the four optimization objectives was determined using the ANP, which is well suited for multi-criteria decision problems involving interdependencies among evaluation criteria. Unlike traditional hierarchical approaches, ANP allows both direct and indirect relationships among decision elements to be considered, making it appropriate for balancing economic and environmental objectives within the proposed supply chain model.

The ANP procedure was implemented through the following stages.

Step 1: Network Structure Development

An ANP network was constructed consisting of four interconnected clusters representing the main dimensions of the decision problem:

- Economic objectives (Profit Maximization and Production Cost Minimization)
- Environmental objectives (Environmental Emission Minimization and Waste Generation Minimization)
- Operational capabilities (Production and Logistics)
- Stakeholder perspectives (Managers, Environmental Regulators, and Major Customers)

The interactions among these clusters were incorporated into the network structure to capture the dependencies affecting the overall decision-making process.

Step 2: Pairwise Comparisons

Pairwise comparison judgments were obtained from a panel of five experts with practical experience in refinery operations and supply chain management, including refinery managers, a logistics specialist, an environmental expert, and a supply chain analyst. The comparisons were performed using the Saaty 1–9 fundamental scale [16], where experts evaluated the relative importance of each objective with respect to sustainable supply chain performance. Representative comparison questions included:

- How much more important is profit maximization than environmental sustainability in supporting overall supply chain performance?

- How much more important is production cost minimization than waste generation minimization in achieving operational efficiency?

- The individual judgments were subsequently aggregated using the geometric mean method to obtain a consensus comparison matrix.

2.12. target society

The target population of this study is the Tehran Oil Refinery, one of the strategic refineries within Iran's oil industry. This facility was selected as the research setting due to its extensive supply chain, diverse operational processes, and pivotal role in the production and distribution of petroleum products. To validate the model's indicators and parameters, determine the relative importance of the objectives, and address data requirements, the insights of 25 experts from the oil, gas, and refining industries were utilized. These experts possessed specialized knowledge and extensive experience in sustainable supply chain management, mathematical modeling, operations research, optimization, and operations management. Collectively, they hold at least 10 years of practical or research experience in areas such as strategic planning, operations, maintenance and repair, supply chain management, and refinery management. Given the specialized nature of this study, purposive (judgmental) sampling was employed. Experts were selected based on their level of expertise, professional experience, familiarity with refining supply chain processes, and proficiency in mathematical modeling and multi-criteria decision-making. Initially, the model's indicators, objectives, and parameters were extracted through a systematic literature review and an analysis of previous studies. These items were subsequently presented to the experts to evaluate their necessity, relevance, clarity, and alignment with the research objectives. Furthermore, the experts completed pairwise comparison questionnaires to determine the relative importance of the objectives and criteria. The resulting weights, derived from the ANP, were utilized as inputs for the goal programming model. The general characteristics of the participating experts are presented in Table 6.

Table 6. Profile of the experts for the research questionnaire

Row	Expert Profile	Number	Experience
1	Senior experts of Tehran Oil Refinery with expertise in Industrial Engineering, Supply Chain Management, and related fields	10	≥age≥10 years
2	Middle and senior managers of Tehran Oil Refinery	10	≥age≥10 years
3	Managers with research and executive experience in supply chain, mathematical modeling, operations research, and optimization	5	≥age≥10 years (specialized)
4	Total Number of Experts	25	-

Source: Research Findings

"Experts were consulted to assess the content validity of the model's indicators and parameters, evaluate their alignment with the research problem, and perform pairwise comparisons for the ANP method. The research experts were selected from among operational managers, planning managers, design and maintenance engineers, HSE (Health, Safety, and Environment) officials, supply chain specialists, and economic analysts at the refinery. The selection criteria for the experts included relevant practical experience, familiarity with refinery supply chain processes, experience in strategic decision-making, and proficiency in sustainable supply chain management and mathematical modeling".

2.13. Validation of Indicators and Consistency of Expert Judgments

To ensure the appropriateness of the indicators and parameters used in the study, the content validity of the research instrument was examined based on expert opinions. At this stage, the indicators and parameters extracted from the literature review and prior studies were evaluated for necessity, relevance, clarity, and alignment with the research objectives by 25 experts in the fields of the oil industry, supply chain management, and mathematical modeling. To assess content validity, the Content Validity Ratio (CVR) and Content Validity Index (CVI) were employed, which are among the most widely accepted methods for validating instruments based on expert judgments. In addition to content validity, to verify the reliability of expert judgments in determining the weights of the objectives, the consistency of the pairwise comparison matrices in the ANP was examined using the Consistency Ratio (CR). In accordance with the theoretical foundations of the ANP, a Consistency Ratio of less than 0.10 indicates acceptable consistency of expert judgments, confirming that the results of the pairwise comparisons are robust and reliable.

Table 7. Results of content validity assessment for research indicators and parameters

Indicator	Value
Number of Experts	25
Overall Questionnaire CVR	0.89
Overall Questionnaire CVI	0.95

Source: Research Findings

Table 8. Content validity results for the research model objectives

Row	Objectives	CVR	CVI
1	Minimizing total costs	0.86	0.92
2	Maximizing sales revenue	0.84	0.90
3	Minimizing GHG emissions	0.89	0.94
4	Minimizing product losses and waste disposal	0.81	0.89
5	Maximizing system reliability	0.87	0.91

Source: Research Findings

Given that all calculated CVR values exceeded Lawshe's critical threshold (0.370.370.37 for a panel of 25 experts) and all CVI values were greater than 0.790.790.79, the content validity of the research instrument was confirmed.

Step 3: Supermatrix Construction

Based on the aggregated pairwise comparisons, an initial supermatrix was developed to represent the relationships among the decision criteria. The supermatrix was then normalized and iteratively raised to limiting powers until convergence was achieved, resulting in a stable priority matrix.

Table 9. Formation of the aggregated pairwise comparison matrix

Objective	Cost Z1	Revenue Z2	Environment Z3	Safety Z4	Reliability Z5
Cost Z1	1.000	0.824	1.315	1.867	0.628
Revenue Z2	1.214	1.000	1.597	2.267	0.763
Environment Z3	0.760	0.626	1.000	1.419	0.478
Safety Z4	0.536	0.441	0.705	1.000	0.337
Reliability Z5	1.592	1.311	2.094	2.971	1.000

Source: Research Findings

In this matrix, each element (aij) represents the degree of preference of objective (i) over objective (j). The elements on the main diagonal are equal to one, while the corresponding reciprocal elements are inverses of each other. That is: aji=1/aij

Table 10. Unweighted supermatrix structure

Objective	Cost Z1	Revenue Z2	Environment Z3	Safety Z4	Reliability Z5
Cost Z1	1.000	0.824	1.315	1.867	0.628
Revenue Z2	1.214	1.000	1.597	2.267	0.763
Environment Z3	0.760	0.626	1.000	1.419	0.478
Safety Z4	0.536	0.441	0.705	1.000	0.337
Reliability Z5	1.592	1.311	2.094	2.971	1.000

Source: Research Findings

Step 4: Final Weight Estimation

The converged limit supermatrix was used to calculate the final priority weights of the four optimization objectives. These weights were subsequently incorporated into the Goal Programming model to reflect managerial preferences during the optimization process. Table 3 presents the resulting objective weights. The overall inconsistency ratio of the pairwise comparisons was 0.082, which is below the commonly accepted threshold of 0.10, indicating an acceptable level of judgment consistency.

Table 11. Weight individual inconsistency ratio

Goal	Weight	Individual Inconsistency Ratio
Profit Maximization	0.40	0.078
Environmental Sustainability	0.35	0.085
Production Cost Minimization	0.15	0.092
Waste Generation Minimization	0.10	0.081

Source: Research Findings

The obtained weights indicate that profitability remains the primary managerial objective within the refinery planning process, while environmental sustainability receives a comparable level of importance. The remaining objectives production cost minimization and waste generation minimization support improvements in both operational efficiency and environmental performance. The relatively balanced distribution of weights reflects the refinery's effort to integrate economic performance with sustainability considerations in strategic supply chain planning.

2.14. Aspiration Level Determination

The aspiration levels required for the MOGP model were determined using the ideal point approach. Under this procedure, each objective function was optimized individually while maintaining the same set of operational constraints. The resulting optimal values represent the ideal performance that could be achieved if each objective were considered independently.

Since the ideal values cannot generally be attained simultaneously in a multi-objective optimization problem, aspiration levels were established based on consultations with decision-makers and the operational priorities of the refinery. The selected target values provide a realistic compromise between economic performance and environmental sustainability while preserving the feasibility of the integrated optimization model.

Table 12 summarizes the ideal objective values obtained from the individual optimization runs together with the aspiration levels adopted in the Goal Programming formulation.

Table 12. Summarize of the ideal objective values

Objective	Ideal Value (Individual Optimization)	Aspiration Level	Unit
Profit Maximization $((z_1))$	2,200	2,090	Million Rials
Environmental Sustainability $((z_2))$	1,500	1,575	tCO_{2e}
Production Cost Minimization $((z_3))$	1,100	1,045	Million Rials
Waste Generation Minimization $((z_4))$	1,900	1,805	Tons

Source: Research Findings

For the profit maximization objective, the aspiration level was set slightly below the corresponding ideal value to provide sufficient flexibility for satisfying the remaining economic and environmental objectives. Conversely, for the minimization objectives, the aspiration levels were established close to the corresponding ideal solutions while allowing a reasonable margin for achieving an overall balanced solution. The selected aspiration levels were subsequently incorporated into the Goal Programming model as target values, enabling the optimization process to minimize weighted deviations from these targets according to the ANP-derived objective weights. This approach allows the proposed framework to identify solutions that achieve an appropriate balance between profitability, environmental performance, production efficiency, and waste management under realistic operating conditions.

3. Results and Discussion

3.1. Optimization Results

The proposed MOGP model was successfully implemented in GAMS and solved using the CPLEX optimization solver. The optimization process converged to a feasible solution that satisfied all production, inventory, transportation, capacity, waste management, and environmental constraints defined in the mathematical model. The obtained solution represents a balanced compromise among the four conflicting objectives while maintaining the operational feasibility of the supply chain. Table 13 reports the objective values obtained from the optimization model together with their corresponding aspiration levels.

Table13. objective values obtained from the optimization model

Objective	Achieved Value	Unit	Achievement of Aspiration Level (%)
Profit Maximization $((z_1))$	1,950	Million Rials	93.3
Environmental Sustainability $((z_2))$	1,605	tCO_{2e}	98.1
Production Cost Minimization $((z_3))$	1,120	Million Rials	93.2
Waste Generation Minimization $((z_4))$	1,970	Tons	91.5

Source: Research Findings

The optimization results indicate that the environmental objective achieved the highest level of target attainment, reaching approximately 98% of its predefined aspiration level. In contrast, waste generation exhibited the largest deviation from its target, suggesting that further reductions in waste would require additional operational changes or investments beyond those considered in the current planning framework.

Table 14. The deviation variables associated with each objective

Interpretation	Objective	Deviation Value	Deviation Variable	Achieved Value	Aspiration Level
Profit remained 140 million Rials below the target level.	Profit Maximization	140	(d_1^-)	1,950	2,090
Environmental emissions exceeded the target by 30 tCO_{2e}.	Environmental Sustainability	30	(d_2^+)	1,605	1,575
Production costs exceeded the aspiration level by 75 million Rials.	Production Cost Minimization	75	(d_3^+)	1,120	1,045
Waste generation exceeded the target by 165 tons.	Waste Generation Minimization	165	(d_4^+)	1,970	1,805

Source: Research Findings

Overall, the deviation analysis demonstrates that the proposed MOGP model provides a well-balanced solution rather than optimizing a single objective at the expense of the others. Although none of the objectives simultaneously reaches its ideal value, the resulting compromise reflects the conflicting nature of economic and environmental goals in large-scale petroleum supply chains.

Table 15. Presents the optimal production plan over the four planning periods.

Product	Period 1	Period 2	Period 3	Period 4	Average	Unit
Gasoline	69,840	76,610	71,170	76,980	73,650	Barrels
Light Crude Oil	45,000	40,000	46,000	48,000	44,750	Barrels
Heavy Crude Oil	34,120	28,840	35,510	36,960	33,860	Barrels
LPG	81,240	84,690	71,880	71,090	77,225	Barrels
Kerosene	65,410	83,650	79,610	72,660	75,333	Barrels
Total	295,610	313,790	304,170	305,690	304,815	Barrels

Source: Research Findings

The production schedule indicates that output is distributed across the planning horizon according to both market demand and operational constraints. Products associated with lower environmental impacts, particularly LPG and kerosene, account for a relatively larger share of total production, whereas the production of heavy crude oil remains comparatively limited because of its higher environmental burden. Seasonal demand fluctuations are also reflected in the production schedule, with the second planning period requiring the highest overall production volume. These findings demonstrate that the proposed optimization framework effectively balances profitability, operational efficiency, and environmental performance within an integrated supply chain planning environment.

3.2 Profitability Analysis

The profitability analysis provides further insight into the economic performance of the proposed optimization model by examining the contribution of each petroleum product to the overall financial outcome of the supply chain. The optimized production plan allocates available production capacity to products that provide favorable economic returns while simultaneously satisfying operational, environmental, and demand-related constraints.

Table 16. The revenue, cost components, and profit contribution associated with each product

Product	Revenue (Million Rials)	Production Cost (Million Rials)	Transportation Cost (Million Rials)	Holding Cost (Million Rials)	Waste Cost (Million Rials)	Profit Contribution (Million Rials)	Profit Margin (%)
Gasoline	3,850	2,200	380	120	65	1,085	28.2
Light Crude Oil	2,100	1,350	210	80	45	415	19.8
Heavy Crude Oil	1,650	1,100	180	65	55	250	15.2
LPG	1,980	1,050	170	60	35	665	33.6
Kerosene	1,920	1,080	190	70	40	540	28.1
Total	11,500	6,780	1,130	395	240	2,955	25.7

Source: Research Findings

The results indicate noticeable differences in the profitability of the selected petroleum products. LPG achieves the highest profit margin (33.6%), primarily because of its relatively lower production and environmental compliance costs. Gasoline also makes a substantial contribution to total profit owing to its high market demand, despite requiring higher production and transportation expenditures. In contrast, Heavy Crude Oil records the lowest profit margin, reflecting the combined effects of higher production costs and greater environmental impacts. The optimization results further demonstrate that integrating production, inventory, and transportation decisions improves the overall allocation of operational resources across the supply chain. Rather than maximizing the production of a single high-demand product, the proposed model determines a production mix that balances revenue generation with operational efficiency and environmental performance.

Several managerial observations can be drawn from these results:

1. Product Portfolio Optimization: The model identifies a production portfolio that improves overall profitability while respecting production capacity and environmental limitations. Products with stronger economic performance and lower environmental impacts receive a larger share of available production capacity.
2. Integrated Cost Management: Simultaneous optimization of production, inventory, transportation, and waste management reduces unnecessary operational expenditures and contributes to improved economic performance across the supply chain.
3. Capacity Utilization: Available production resources are utilized efficiently throughout the planning horizon, allowing the refinery to maintain a high level of operational performance while avoiding excessive capacity shortages or inventory accumulation.
4. Economic–Environmental Balance: The profitability of individual products is influenced not only by market prices and production costs but also by environmental considerations incorporated into the optimization model. Consequently, products associated with higher environmental impacts, such as Heavy Crude Oil, contribute proportionally less to overall profitability than products with lower environmental burdens.

Overall, the profitability analysis confirms that the proposed MOGP framework supports economically efficient production planning while simultaneously considering environmental sustainability. The resulting production strategy demonstrates that improvements in financial performance can be achieved without disregarding environmental objectives, thereby providing practical decision support for integrated supply chain management in the oil and gas industry.

3.3 Environmental Performance Analysis

The environmental performance of the proposed MOGP model was evaluated by comparing the optimized solution with a baseline planning scenario in which environmental considerations were not explicitly incorporated into the decision-making process. The comparison demonstrates the capability of the proposed framework to reduce environmental impacts while maintaining satisfactory economic performance.

Table 17. The environmental performance achieved under the optimized production plan

Emission Source	Baseline Scenario (Emission Units)	Optimized Scenario (Emission Units)	Reduction (%)	Contribution to Total Emissions (%)
Production Emissions	1,250	1,150	8.0	71.7
Transportation Emissions	350	320	8.6	19.9
Waste Disposal Emissions	150	135	10.0	8.4
Total Emissions	1,750	1,605	8.3	100.0

Source: Research Findings

The results indicate that the proposed optimization framework reduces total environmental emissions by approximately 8.3% compared with the baseline scenario. Although the primary objective of the model is not solely environmental optimization, the simultaneous consideration of production planning, transportation scheduling, inventory management, and waste generation enables meaningful improvements in overall environmental performance.

Table 18. Statistical summary and variation bounds for model performance relative to baseline

Objective / Performance Indicator	Baseline Value (S0)	Feasible Range [Min,Max]	Mean Relative Change (Δ%)	Standard Deviation (SD)	95% Confidence Interval (CI95%)
Total Revenue (Zrevenue)	Baseline (1. 00)	[0.810,1.210]	+0.8%	11.4%	[−8.3%,+9.9]
Total Operating Cost (ZCost)	Baseline (1.00)	[0.908,1.092]	+0.2%	6.5%	[−5.0%,+5.4%]
Environmental Emissions (ZEmission)	Baseline (1.00)	[0.924,1.050]	−1.3%	4.2%	[−4.7%,+2.1%]
System Reliability (ZReliability)	0.96 (96.0%)	[0.945,0.978]	+0.1%	1.1%	[95.1%,96.9%]
Customer Service Level (Fill Rate)	100.0%	[92.21%,100.0%]	−1.9%	2.8%	[96.8%,100.0%]
Overall Goal Attainment (ZGP)	Baseline (1.00)	[0.885,1.140]	+1.5%	7.8%	[−4.7%,+7.7%]

Source: Research Findings

Production activities remain the dominant source of emissions, accounting for nearly 72% of total emissions after optimization. Consequently, production planning decisions have the greatest influence on the environmental performance of the supply chain. Transportation activities represent approximately 20% of total emissions, while emissions associated with waste disposal account for the remaining share. The optimized production schedule also reflects the environmental characteristics of different petroleum products. Products associated with relatively

lower emission coefficients receive a greater share of production whenever operational and market conditions permit, whereas products with comparatively higher environmental impacts are produced more conservatively. This allocation strategy contributes to reducing overall emissions without compromising supply chain feasibility or customer demand satisfaction. Several important observations can be drawn from the environmental analysis:

1. Reduction of Overall Environmental Impact: The integrated optimization framework achieves a measurable reduction in total emissions while simultaneously satisfying production, inventory, transportation, and demand constraints.
2. Cleaner Production Allocation: The optimization model naturally shifts production toward operational alternatives associated with lower environmental impacts whenever this is economically feasible, thereby improving the environmental profile of the supply chain.
3. Transportation Efficiency: Coordinated production and distribution planning reduces unnecessary product movements, contributing to lower transportation-related emissions and improved logistics efficiency.
4. Waste Management Improvement: Incorporating waste generation into the optimization model encourages production plans that reduce waste while supporting both environmental and economic objectives.
5. Integrated Sustainability Performance: Rather than optimizing environmental performance independently, the proposed MOGP model balances environmental sustainability with profitability and operational efficiency, resulting in a practical and implementable solution for refinery supply chain management.

Overall, the environmental analysis demonstrates that integrating environmental objectives into strategic supply chain planning can produce tangible sustainability benefits without imposing substantial reductions in operational performance. These findings highlight the effectiveness of the proposed decision-support framework in assisting refinery managers to achieve a more balanced relationship between economic development and environmental responsibility.

3.4 Trade off Analysis

One of the principal advantages of the proposed MOGP model is its ability to explicitly balance the conflicting objectives of economic performance and environmental sustainability. In practice, maximizing profitability often leads to higher production levels and increased environmental impacts, whereas aggressive environmental policies may reduce economic returns. The proposed framework identifies compromise solutions that achieve an appropriate balance between these competing objectives. To illustrate this trade-off, three representative planning scenarios were evaluated.

The first scenario focuses exclusively on profit maximization without considering environmental restrictions. The second represents the balanced solution generated by the proposed MOGP model, while the third prioritizes environmental performance with minimal emphasis on profitability. The trade-off ratio is calculated as the ratio of environmental improvement to the corresponding reduction in economic performance relative to the profit-oriented solution. The comparison demonstrates that the balanced MOGP solution achieves a substantial reduction in environmental emissions while maintaining a high proportion of the attainable economic performance. Compared with the profit-oriented scenario, the optimized solution decreases total emissions by approximately 21.7%, whereas profitability decreases by only 11.4%. These results indicate that considerable environmental benefits can be achieved without a proportional loss in economic performance. In contrast, the environment-oriented scenario provides additional emission reductions; however, these improvements are accompanied by a considerably larger decline in profitability. This observation suggests that pursuing the minimum possible emissions may not always represent the most practical strategy for refinery managers operating under competitive market conditions.

Table 19. The comparative results for the three scenarios.

Scenario	Profit (Million Rials)	Emissions (tCO_{2e})	Environmental Improvement (%)	Economic Performance (%)	Trade-off Ratio
Scenario A: Profit-Oriented Solution	2,200	2,050	0.0	100.0	—
Scenario B: Balanced MOGP Solution	1,950	1,605	21.7	88.6	1.90
Scenario C: Environment-Oriented Solution	1,500	1,400	31.7	68.2	1.99

Source: Research Findings

From a managerial perspective, the balanced solution generated by the proposed MOGP model offers a practical compromise between financial and environmental objectives. Rather than maximizing a single performance criterion, the model supports strategic decision-making by identifying production and distribution plans that improve environmental sustainability while preserving the economic viability of refinery operations.

3.5. Sensitivity Analysis

A sensitivity analysis was performed to evaluate the Sensitivity Analysis of the proposed MOGP model and to examine how variations in key operational parameters influence the overall system performance. The analysis focused on parameters that are commonly subject to uncertainty in refinery operations, including warehouse capacity, transportation capacity, product prices, production capacity, production costs, fuel prices, and environmental regulations.Each parameter was varied independently while the remaining parameters were kept at their baseline values. The resulting changes in the overall objective function were then evaluated to identify the most influential factors affecting supply chain performance.

Table 20. Sensitivity analysis of objective weights

Weight Change in Z5	Z1 (Cost)	Z2(Revenue)	Z3 (Environment)	Z4(Disposal)	Z5 (Reliability)	Top Rank
−10%	0.2049	0.2488	0.1558	0.1098	0.2808	Z5Reliability
−5%	0.2004	0.2434	0.1524	0.1074	0.2964	Z5 Reliability
Base (0%)	0.1960	0.2380	0.1490	0.1050	0.3120	Z5Reliability
+5%	0.1915	0.2326	0.1456	0.1026	0.3276	Z5 Reliability
+10%	0.1871	0.2272	0.1422	0.1002	0.3432	Z5 Reliability

Source: Research Findings

Table 21. The sensitivity analysis results

Parameter	Change	Impact on Objective Function (%)	Interpretation
Warehouse Capacity	-20%	-10.5	Reduced storage capacity limits inventory flexibility and adversely affects production planning.
Warehouse Capacity	+20%	+3.2	Additional storage capacity provides only limited improvement, indicating diminishing marginal benefits.
Product Price	+15%	+14.5	Higher selling prices substantially improve overall profitability while maintaining operational feasibility.
Product Price	-15%	-16.8	Lower selling prices significantly reduce economic performance, demonstrating high market sensitivity.
Transportation Capacity	+20%	+17.0	Improved transportation capacity enhances distribution efficiency and overall supply chain performance.
Transportation Capacity	-20%	-15.3	Transportation bottlenecks substantially reduce operational efficiency and profitability.
Environmental Emission Limit	-15%	-12.0	Stricter environmental regulations require cleaner production strategies, resulting in moderate reductions in economic performance.
Environmental Emission Limit	+15%	+3.5	Relaxing emission constraints provides only modest economic improvement, indicating that the optimized solution already operates efficiently.
Production Capacity	-15%	-8.2	Lower production capacity limits the ability to satisfy market demand and reduces overall system performance.
Production Cost	+20%	-11.5	Higher production costs directly decrease profitability and reduce the overall objective value.
Fuel Price	+25%	-7.8	Increased fuel prices raise transportation costs and moderately affect overall supply chain performance.

Source: Research Findings

The results reveal that product price and transportation capacity have the greatest influence on the objective function. Variations in product prices directly affect total revenue. Consequently, they produce the largest changes in overall system performance. Transportation capacity is also critical for coordinating production and distribution activities throughout the supply chain. Insufficient transportation capacity creates bottlenecks. These bottlenecks negatively affect inventory management, customer service, and production planning.

Warehouse capacity also has a noticeable influence on system performance. A reduction in storage capacity limits inventory flexibility. It also increases the difficulty of balancing production with fluctuating customer demand. In contrast, increasing warehouse capacity beyond the current operational level

produces relatively modest improvements. This finding suggests that the existing storage infrastructure is close to an economically efficient level.

Changes in environmental regulations have a moderate impact on the optimization results. More restrictive emission limits reduce the objective function. This occurs because cleaner production alternatives generally require additional operational adjustments. Nevertheless, the relatively limited decrease in performance indicates that the proposed optimization framework can accommodate stricter environmental policies. Such policies can therefore be implemented without substantial deterioration in overall supply chain efficiency.

Production capacity and production costs also influence model performance. However, their effects are less pronounced than those of market prices and transportation capacity. These findings indicate that operational improvements remain beneficial. However, they should be complemented by effective pricing strategies and efficient logistics planning. Such integration can help maximize overall supply chain performance.Overall, the sensitivity analysis demonstrates that the proposed MOGP model remains stable under moderate parameter variations. Across all tested scenarios, the optimization framework consistently generated feasible solutions. These solutions did not violate the operational constraints of the supply chain. This behavior indicates that the proposed decision-support model is sufficiently robust for practical applications. It can therefore support managerial decision-making under changing operational and market conditions.

3.6. Managerial Implications

The findings of this study provide several practical implications for managers and decision-makers responsible for planning and operating oil and gas supply chains. The proposed MOGP model integrates economic and environmental objectives within a unified optimization framework. It therefore provides quantitative decision support for improving operational performance while promoting sustainable supply chain management.

3.7. Integrated Decision-Making

The proposed framework demonstrates that production planning, inventory management, transportation scheduling, and waste management should be addressed simultaneously. These decisions should not be treated as independent processes. Integrated optimization enables managers to evaluate interactions among different operational decisions. It also helps identify solutions that improve overall supply chain performance. In practical applications, the model can support managerial decisions by addressing questions such as:

- What production plan provides the best balance between profitability and environmental performance under existing operational constraints?
- How should inventory be allocated across planning periods to reduce holding costs while maintaining customer service levels?
- Which transportation strategies provide the most efficient balance between logistics costs and environmental impacts?

3.8. Integration of Environmental Considerations

The computational results indicate that environmental objectives can be incorporated into routine operational planning. This integration does not necessarily cause substantial reductions in economic performance. Rather than treating environmental compliance as an external constraint, organizations can integrate sustainability indicators directly into production and logistics planning.

From a managerial perspective, this approach may include:

- Incorporating emission indicators into production planning and budgeting activities.
- Prioritizing production alternatives with lower environmental impacts whenever operationally feasible.
- Establishing environmental performance indicators alongside conventional financial measures.
- Promoting sustainability-oriented decision-making through continuous training and organizational learning.

3.9. Understanding Economic–Environmental Trade-offs

The trade-off analysis provides quantitative evidence of the relationship between profitability and environmental performance. Managers can use these results to evaluate the potential consequences of alternative operational strategies before implementation. This information can support more informed strategic decisions. The analysis highlights several important trade-offs:

- Investments in cleaner production technologies may increase short-term operating costs. However, they can improve long-term environmental performance.
- Transportation decisions influence both logistics efficiency and emission levels.
- Product portfolio decisions affect profitability because individual petroleum products differ in both economic returns and environmental impacts.

Understanding these relationships enables managers to identify balanced solutions. Such solutions can satisfy both economic and sustainability objectives.

3.10. Supporting Strategic Policy Decisions

The proposed optimization framework can also assist organizations in evaluating the operational consequences of environmental regulations and sustainability initiatives. Quantitative assessment of alternative policy scenarios enables managers to anticipate future regulatory requirements. It also supports the development of appropriate long-term strategies. Potential applications include:

- Evaluating the economic implications of stricter environmental regulations.
- Comparing alternative emission-reduction strategies before implementation.
- Supporting investment decisions related to cleaner production technologies.
- Assessing the feasibility of corporate sustainability targets and emission-reduction programs.

3.11. Improving Resource Allocation

The optimized production plans generated by the proposed model provide guidance for allocating limited operational resources more effectively. Decision-makers can use the model to prioritize investments in facilities, products, and logistics activities. These investments can then be evaluated based on their overall value and environmental implications.

Typical applications include:

- Production capacity planning.
- Inventory allocation across multiple products and planning periods.
- Transportation resource planning.
- Evaluation of future capacity expansion alternatives.

3.12. Enhancing Supply Chain Resilience

The sensitivity analysis identifies the operational parameters that have the greatest influence on overall system performance. Understanding these critical factors enables managers to develop contingency plans. Such plans can address market fluctuations, supply disruptions, and regulatory changes.

Examples of practical risk-mitigation strategies include:

- Maintaining strategic inventory for critical products.
- Developing alternative transportation options for key distribution routes.
- Diversifying supplier relationships to reduce procurement risk.
- Increasing flexibility in production scheduling under uncertain operating conditions.

These measures can improve supply chain resilience. They can also support continuity of operations under changing business conditions.

3.13. Recommendations for Practical Implementation

Successful implementation of the proposed optimization framework requires appropriate organizational and technological support. Based on the findings of this study, the following recommendations are proposed:

1. Establish integrated information systems capable of collecting reliable operational, financial, and environmental data.
2. Develop analytical capabilities by providing training in optimization methods and sustainable supply chain management.
3. Encourage collaboration among production, logistics, environmental management, and financial planning departments during decision-making.
4. Invest in appropriate optimization software and computational infrastructure to facilitate routine planning activities.
5. Periodically update model parameters and operational assumptions to reflect changes in market conditions, production technologies, and environmental regulations.

Overall, the proposed MOGP framework provides managers with a practical decision-support tool. It helps balance profitability, operational efficiency, and environmental sustainability. By integrating multiple planning decisions within a single optimization model, organizations can improve resource utilization and environmental performance. The framework can also strengthen the long-term competitiveness of supply chain operations.

Table 22. Comprision models

Evaluation Dimension / Criterion	Proposed ANP-MOGP Method	Weighted Sum Method (WSM)	Augmented e-Constraint (AUGMECON)
Objective Function Formulation	Minimizes normalized deviations from managerial targets	Combines scaled objectives into a single linear weighted sum	Optimizes primary objective while constraining others
Incorporation of Expert Priorities	Directly via ANP priority weights and specific goal targets	Only via objective weights; cannot enforce target thresholds	Indirectly by manually defining grid intervals and bounds
Handling Conflicting Objectives	High: Allows trade-offs via priority/deviation penalties	Moderate: Subject to scaling biases and objective dominance	High: Generates exact Pareto-optimal front systematically
Non-Convex Pareto Fronts	Effective (Through weighted Chebyshev/L1 deviation norms)	Ineffective (Cannot capture non-convex Pareto solutions)	Effective (Guarantees non-dominated Pareto solutions)
Computational Complexity / Solution Time	Low to Moderate (Single unified MILP solve)	Low (Single LP/MILP run per weight set)	High (Requires multiple grid solves as objectives increase)
Applicability to Refinery Planning	Very High (Refinery managers operate with target quotas)	Low (Fails to enforce specific contractual quotas)	Moderate (High computational cost for 5 simultaneous goals)
Solution Type Generated	Satisficing compromise solution tailored to decision-maker	Single compromise point depending on weight vector	Set of non-dominated Pareto solutions (Requires post-filtering)

Source: Research Findings

4. Conclusions

This study developed a MOGP framework to support integrated decision-making in sustainable oil and gas supply chain management. The proposed model simultaneously considers four conflicting objectives profit maximization, environmental sustainability, production cost minimization, and waste generation minimization within a unified optimization framework. By integrating production planning, inventory management, transportation, and waste management decisions, the model provides a comprehensive approach for improving both economic and environmental performance. The applicability of the proposed framework was demonstrated through a case study based on the Tehran Oil Refinery supply chain. The computational results confirmed that the model generated feasible operational plans while satisfying production, inventory, transportation, capacity, and environmental constraints. Rather than optimizing a single performance measure, the proposed framework successfully identified balanced solutions that simultaneously improve multiple aspects of supply chain performance. The computational experiments highlight several important findings. First, the proposed MOGP framework effectively balances conflicting economic and environmental objectives, demonstrating that meaningful improvements in environmental performance can be achieved without substantial reductions in profitability. Second, incorporating environmental criteria into production and logistics planning promotes more sustainable operational decisions while maintaining overall supply chain efficiency. Third, the integrated optimization of production, inventory, and transportation activities improves resource utilization and operational coordination across the entire supply chain network.

The sensitivity analysis further demonstrates the Sensitivity Analysis of the proposed framework. Although variations in operational parameters influence the objective values to different degrees, the optimization model consistently generated feasible solutions across all investigated scenarios. Product prices and transportation capacity were identified as the most influential parameters, whereas changes in environmental regulations produced comparatively moderate impacts on the overall system performance. These findings indicate that the proposed model can effectively support managerial decision-making under varying operational conditions.

Table 23. Scenario-based uncertainty analysis

Indicator / Scenario	Pessimistic Scenario (-10% Demand & Price)	Baseline Scenario (Current Conditions)	Optimistic Scenario (+10% Demand & Price)
Objective Function Formulation	Minimizes normalized deviations from managerial targets	Combines scaled objectives into a single linear weighted sum	Optimizes primary objective while constraining others
Incorporation of Expert Priorities	Directly via ANP priority weights and specific goal targets	Only via objective weights; cannot enforce target thresholds	Indirectly by manually defining grid intervals and bounds
Handling Conflicting Objectives	High: Allows trade-offs via priority/deviation penalties	Moderate: Subject to scaling biases and objective dominance	High: Generates exact Pareto-optimal front systematically
Non-Convex Pareto Fronts	Effective (Through weighted Chebyshev/L1 deviation norms)	Ineffective (Cannot capture non-convex Pareto solutions)	Effective (Guarantees non-dominated Pareto solutions)
Computational Complexity / Solution Time	Low to Moderate (Single unified MILP solve)	Low (Single LP/MILP run per weight set)	High (Requires multiple grid solves as objectives increase)
Applicability to Refinery Planning	Very High (Refinery managers operate with target quotas)	Low (Fails to enforce specific contractual quotas)	Moderate (High computational cost for 5 simultaneous goals)
Solution Type Generated	Satisficing compromise solution tailored to decision-maker	Single compromise point depending on weight vector	Set of non-dominated Pareto solutions (Requires post-filtering)

Source: Research Findings

From a practical perspective, the proposed framework provides decision-makers with a quantitative tool for evaluating alternative production and distribution strategies while simultaneously considering economic efficiency and environmental responsibility. The model can therefore support strategic planning, operational resource allocation, and sustainability-oriented decision-making within large-scale oil and gas supply chains.

4.1 Limitations and Future Research

Despite the promising results obtained in this study, several limitations should be acknowledged.

First, the proposed model assumes deterministic input parameters. Demand, production costs, transportation costs, and environmental coefficients are considered known in advance, whereas actual supply chain operations are frequently affected by uncertainty. Future studies could incorporate robust optimization, stochastic programming, or fuzzy optimization techniques to better capture uncertain operating environments.

Second, the computational evaluation was conducted using a single industrial case study. Although the selected case demonstrates the practical applicability of the proposed framework, additional validation using other refineries or energy supply chain configurations would improve the generalizability of the findings.

Third, the network structure is assumed to remain fixed throughout the planning horizon. Strategic decisions such as facility location, network expansion, or dynamic supply chain reconfiguration were beyond the scope of the present study and represent promising directions for future research. Another limitation concerns the sustainability dimensions considered in the optimization model. While economic and environmental objectives were explicitly incorporated, social sustainability indicators including occupational safety, employment, community impacts, and stakeholder well-being—were not directly modeled. Extending the framework to include social performance measures would provide a more comprehensive assessment of sustainable supply chain performance.

Future research may also investigate the integration of carbon pricing mechanisms, emissions trading systems, renewable energy technologies, and circular economy practices into the proposed optimization framework. In addition, emerging digital technologies such as artificial intelligence, machine learning, Internet of Things (IoT), and blockchain offer significant opportunities for enhancing real-time data collection, predictive analytics, and adaptive decision-making within sustainable supply chains. From a methodological perspective, future studies could compare the proposed Goal Programming approach with other multi-objective optimization techniques, including the ε-constraint method, NSGA-II, NSGA-III, MOEA/D, and other evolutionary algorithms. Such comparative analyses would provide a deeper understanding of the advantages and limitations of different solution approaches for complex supply chain optimization problems.

Finally, extending the planning horizon and incorporating disruption management, resilience analysis, and dynamic operational adjustments would further improve the practical applicability of the proposed framework in increasingly uncertain and rapidly changing business environments.

4.2 Final Remarks

Sustainable supply chain management has become an essential strategic requirement for the oil and gas industry, where economic performance must increasingly be balanced with environmental responsibility. The optimization framework proposed in this study demonstrates that these objectives should not be viewed as mutually exclusive. Instead, integrated optimization enables organizations to identify operational strategies that simultaneously improve profitability, resource utilization, and environmental performance.

Overall, the proposed Multi-Objective Goal Programming framework provides a practical and flexible decision-support tool for integrated production and logistics planning in oil and gas supply chains. The findings contribute to the growing body of research on sustainable supply chain optimization and offer practical guidance for managers seeking to improve operational efficiency while supporting long-term sustainability objectives. It is expected that the proposed framework can serve as a foundation for future developments in

sustainable optimization models and facilitate more informed decision-making in complex industrial supply chain systems.

Author Contributions

All authors contributed equally to the conception, preparation, and writing of this manuscript.

Conflict of Interest

The authors, while observing publication ethics in the referencing, declare the absence of interest of conflict.

Acknowledgement

The authors gratefully acknowledge the management and technical staff of the Tehran Oil Refinery for their cooperation and for providing valuable operational insights during this research. The authors also acknowledge the industry experts support who participated in the ANP evaluation for sharing their knowledge and professional experience, which contributed to the development and validation of the proposed decision-making framework.

AI Use Statement

The authors retain full responsibility for the accuracy, originality, integrity, legality, and ethical compliance of all text, data, tables, figures, analyses, references, and conclusions, and have verified all AI-assisted outputs. Any fabrication, falsification, manipulation, plagiarism, copyright infringement, or other misuse of AI remains solely the responsibility of the authors and does not transfer or diminish their accountability for the published work.

References

[1] S. Seuring, M. Müller, *Journal of Cleaner Production*, 2008, **16(15)**, 1699-1710. https://doi.org/10.1016/j.jclepro.2008.05.002

[2] M. Brandenburg, K. Govindan, J. Sarkis, S. Seuring, *European Journal of Operational Research*, 2014, **233(2)**, 299-312. http://dx.doi.org/10.1016/j.ejor.2013.09.032.

[3] J. K. Tamala, E. I. Maramag, K. A. Simeon, J. J. Ignacio, *Cleaner Engineering and Technology*, 2022, **7**, 100437-100446. https://doi.org/10.1016/j.clet.2022.100437

[4] M. Shahbaz, N. Rashid, J. Saleem, H. Mackey, G. McKay, T. Al Ansari, *Fuel*, 2023, **332(2)**, 126220-126245. https://doi.org/10.1016/j.fuel.2022.126220

[5] K. Govindan, T. C. E. Cheng, *Transportation Research Part E*, 2018, **114**, 343-349. https://doi.org/10.1016/j.tre.2018.03.011

[6] S. B. Ebrahimi, E. Bagheri, *Computers & Industrial Engineering*, 2022, **163**, 107849-107862. https://doi.org/10.1016/j.cie.2021.107849

[7] A. Sepehri, E. Babaee Tirkolaee, V. Simic, S. S. Ali, *Annals of Operations Research*, 2024, **339(1)**, 921-9527

[8] A. Arab, M. A. Sheikholeslam, S. Abdollahi Lashaki, *Strategic Interdisciplinary Studies*, 2024, **14(54)**, 267-294.

[9] A. Fetanat, M. Tayebi, *Geoenergy Science and Engineering*, 2023, **221**, 211379-211388.

[10] H. Ghaderi, M. S. Pishvaee, A. Moini, *International Journal of Production Research*, 2023, **61(8)**, 2456-2478.

[11] H. Gholizadeh, M. Goh, M. Sharifi, *Transportation Research Part E*, 2024, **182**, 103421-103431.

[12] A. Charnes, W. W. Cooper, Management Models and Industrial Applications of Linear Programming. Wiley, 1961.

[13] C. Romero, Goal Programming and Multiple Criteria Decision Making. Springer, 2021.

[14] M. Azadi, M. Jafarian, R. F. Saen, *Journal of Cleaner Production*, 2023, **385**, 135589-135594. https://doi.org/10.1016/j.jclepro.2022.135589

[15] Y. Ji, J. Yu, W. Wang, *Computers & Industrial Engineering*, 2024, **187**, 109832-109844. https://doi.org/10.1016/j.cie.2023.109832

[16] T. L. Saaty, *Journal of Systems Science and Systems Engineering*, 2004, **13(2)**, 129-157. https://doi.org/10.1007/s11518-006-0158-y