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A Mixed-Integer Nonlinear Programming Model for Solving Integrated Oil and Gas Supply Chain Problem by Considering Enhanced Oil Recovery Methods

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Abstract *–This paper presents a model to solve a multi-objective optimization problem for optimal oil field development and supply chain management (SCM) of oil and gas, considering Enhanced Oil Recovery (EOR) methods in both upstream and midstream sectors. Unlike previous studies that primarily investigated EOR in the upstream sector, this study focuses on integrating EOR methods within a comprehensive supply chain model. The problem is formulated as a mixed integer nonlinear program (MINLP) to accurately capture the complexities and interdependencies of oil field development and SCM. To facilitate solution, the multi-objective problem is converted into a single-objective problem using the LP-metric method. The transformed problem is then solved using the BARON solver within the GAMS software environment. To evaluate the efficiency and robustness of the proposed solution method, a set of 15 test problems with varying dimensions was solved. The results demonstrate that the solution method is highly efficient for small-size problems, achieving a relative gap of 0.01 in less than 100 seconds. However, the computational time increases significantly as the problem size grows, highlighting the challenges of scaling the model for larger and more complex scenarios. This study provides a novel approach to incorporating EOR methods into an integrated supply chain model, offering valuable insights for optimizing oil and gas field development and SCM strategies.*

Keywords*– Mixed-Integer Nonlinear Programming, Oil and Gas Supply Chain, Enhanced Oil Recovery, Multi-Objective.*

I. INTRODUCTION

The oil industry is widely recognized as one of the pivotal sectors driving the economies of oil-rich nations globally (Saidov, 2023). Optimizing the operations within this industry is crucial for bolstering countries' profits and economic metrics. Oil industry activities span across three primary sectors: upstream, midstream, and downstream. Upstream activities encompass exploration, drilling, and the extraction of crude oil and natural gas from reservoirs. Companies operating in this sector are tasked with discovering new oil and gas sources and maximizing the output of existing ones (Emeka-Okoli et al., 2024).

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Midstream companies play a vital role in transporting, storing, and refining crude oil and natural gas. This involves constructing and maintaining pipelines, pumping stations, and tank trucks to facilitate the movement of resources over extensive distances. Moreover, midstream companies provide storage facilities to temporarily hold these resources before onward transportation to downstream facilities (Yang et al., 2024).

Downstream operations involve the conversion of crude oil and natural gas into a diverse array of finished products. These downstream companies operate closer to end-users and engage in post-production activities such as refining, marketing, and distributing finished products like fuels, plastics, and synthetic rubbers (Patidar et al., 2024).

In essence, upstream companies focus on extracting raw materials, midstream companies specialize in their transportation and storage, while downstream companies transform these resources into finished goods. Collaboration across these three sectors is integral to ensuring a seamless flow of fuels and materials. This study delves explicitly into the application of supply chain management (SCM) principles within the upstream and midstream sectors of the oil industry.

Furthermore, the life cycle of a hydrocarbon field encompasses exploration, appraisal, development planning, production, and decommissioning phases (Khamechi et al., 2017). The production phase, in particular, entails the extraction of economically viable hydrocarbons, marking a phase of capital compensation and potential reinvestment. Predicting production profiles and understanding reservoir mechanisms are fundamental to shaping operational and production programs. The decommissioning phase comes into play when a field ceases to generate sufficient capital to cover operating costs, prompting the cessation of production. During this phase, recycling methods and chemical processes may be employed to utilize remaining hydrocarbon resources before decommissioning occurs. Upstream activities yield crude oil and associated gas destined for local refineries or export terminals, while refining and distribution processes are handled in the intermediate and downstream sectors of the oil industry (Khamechi et al., 2017).

Production planning and supply chain management are critical tasks in productivity management for all industrial fields (Keshmiry Zadeh et al., 2021; Mohammadi Jozani et al., 2022; Hemmati et al., 2023). Over the past three decades, numerous studies have introduced mathematical optimization programming models across various facets of the oil and gas industry, including field development, crude oil and associated gas supply and processing, refinery planning, and product distribution to customers (Kumar et al., 2021). While previous research predominantly delved into downstream issues such as oil product refinement and supply, limited attention has been devoted to understanding the intricate relationship between upstream and midstream challenges in the oil industry, particularly in the context of simultaneous oil and gas co-production.

This study endeavors to fill this gap by developing a comprehensive understanding of oil and gas supply chain management within the upstream and midstream sectors, focusing on optimal decision-making processes. Illustrated in Figure 1 is the hydrocarbon network of the oil and gas industry, serving as a visual representation of the interconnectedness of various operational components.

Specifically, our research addresses the management of the crude oil chain alongside gas production, aiming to optimize the location of oil wells, the extraction volumes of oil and gas, transfer rates, separation and collection processes, and the transportation of crude oil and gas to designated demand areas. The integrated management of these activities has the potential to significantly enhance the profitability of crude oil companies through efficient oil field development and operation.

To achieve this objective, we present a mathematical programming model designed to determine strategic and tactical decision variables, including the optimal placement of oil wells, enhanced oil recovery (EOR) operations, gas injection rates, crude oil, and associated gas extraction volumes, and the subsequent production and distribution of these resources to demand points within predefined time periods. Central to our study is the optimization of extraction and operational strategies for oil reservoirs (oil fields), considering seismic operations and reservoir exploration as integral components.

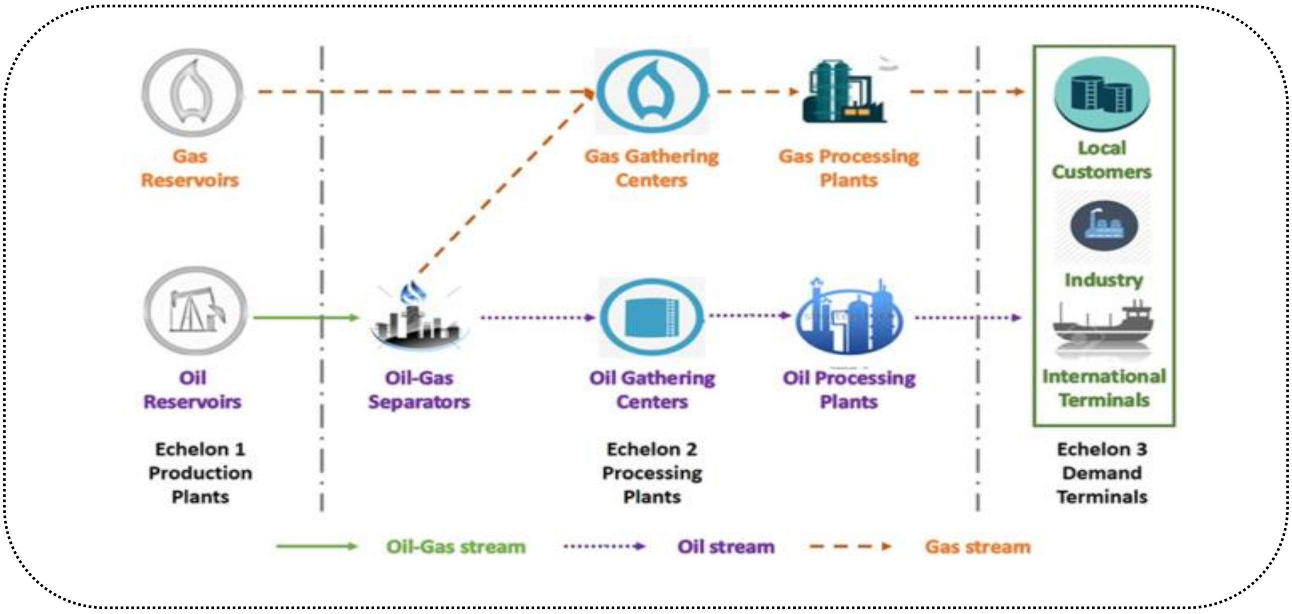

Fig. 1. Hydrocarbon network of oil and gas industry; Source: Attia et al. (2019)

To effectively utilize oil fields, appropriate places for drilling and extracting oil wells must be selected from the existing discovered oil reservoirs. Subsequently, drilling and extraction operations commence. In the next procedure, new facilities or existing equipment are used for transferring crude oil and associated gas from the wells to the production units, where oil and gas are separated. Finally, desalting and de-hydration are conducted in the production units until the prepared crude oil is supplied to domestic refineries or export terminals.

The models presented in previous research on the oil industry had gaps in communication between the upstream and midstream sectors. This study aims to fill those gaps by examining the strategic and tactical relationship between these two sectors. While previous research focused on crude oil and gas production in the exploration and production phases, this study takes into account the need for EOR to re-operate an oil well after several years of operation due to declining reservoir pressure. The behavior of oil reservoirs is an important factor in crude oil extraction and production. This study models this behavior with a nonlinear relationship between the amounts of crude oil extracted in each period compared to the total extraction rate. To address the gaps in previous research, a mathematical optimization model is presented that brings the modeling closer to the real world. The motivation for conducting this study is to provide more accurate models of the activities of the world's largest crude oil companies and suppliers for better management and control.

The presented model makes several significant contributions to the field of oil and gas supply chain management. First, this paper integrates EOR methods into the supply chain model to optimize production and minimize costs. This approach allows for a more accurate representation of the complex interactions between EOR methods and the supply chain. Second, this paper proposes an LP-metric modeling that considers the trade-offs between EOR methods and supply chain operations, resulting in a more efficient and effective supply chain. This model can be used to make strategic decisions regarding the use of EOR methods and supply chain management. Finally, this paper contributes to the literature on sustainable oil and gas production by incorporating the environmental impacts of EOR methods into the supply chain model. Overall, the current research provides a comprehensive framework for the integrated modeling of oil and gas supply chains that considers the unique challenges posed by EOR methods.

II. LITERATURE REVIEW

The Hydrocarbon Supply Chain (HSC) has been studied in various forms, either as an integrated system or by analyzing each section separately. The petroleum industry is divided into three main segments: upstream, midstream, and downstream. The upstream segment includes activities related to petroleum exploration, production, and transportation until the crude oil reaches the refineries. The midstream segment focuses on converting crude oil into refined products and petrochemicals at the refineries. Lastly, the downstream segment involves the storage, primary and secondary distributions, and marketing of refined products. Petroleum companies rely on physical infrastructures throughout the network to carry out these functions in each segment (Fernandes et al., 2014). Previous studies have classified HSC into oil or gas products or into upstream, downstream, or midstream segments without focusing on the integrated model. The downstream sector of the oil industry has unique characteristics that make it challenging to apply conventional supply chain management techniques and tools. Firstly, inventory is considered a commodity and can be resold multiple times before being consumed. It is also non-discrete, not packaged, and cannot be individually identified, making traditional management methods irrelevant. These intrinsic features increase the complexity of downstream operations. However, there are some factors decrease this complexity, such as stable and static product mix, predictable demand, and fewer products to track. Despite this, managing the downstream sector involves addressing numerous challenges, including inefficient demand planning, supply chain planning, and the optimization of total cost function. Downstream oil companies must also tackle issues like limited visibility in truck and rail transportation, low asset utilization in maritime transportation, ad-hoc carrier selection, and inventory management at storage facilities. Consequently, oil companies need to make complex strategic and tactical decisions on site location, capacity sizing, transportation strategy, and inventory planning (Rocha et al., 2017). All this makes downstream operations complex, and implementing them cost-effectively requires a sophisticated decision-making process. Then, we consider upstream and midstream segments in this paper.

A. Single segment model

Many research studies have focused on studying the oil and gas supply chain in one segment (upstream, midstream, or downstream) because each segment has its unique set of challenges and complexities that require specialized knowledge and expertise. Additionally, each segment of the oil and gas supply chain is distinct and has its unique set of activities and processes.

Studying each segment separately allows researchers to delve deeper into the specific challenges and complexities of each segment and to develop specialized solutions to address them. Moreover, it enables researchers to gain a more comprehensive understanding of the entire oil and gas supply chain by examining each segment's distinct processes and activities. This knowledge can help companies optimize their operations, improve efficiency, reduce costs, and enhance their overall performance (Khamechi et al., 2017).

In the study by Rocha et al. (2017), a decomposition algorithm was proposed based on a cascading knapsack structure to solve a large-scale model of the oil supply chain. Khamechi et al. (2017) developed a model for optimizing production from a mature hydrocarbon field in southern Iran, and selected the best production scenario for the field under study based on the amount of cumulative oil production and the project's profit. The simulation and optimization results showed that gas injection is prioritized over artificial gas processing in the current field situation due to reduced costs and time, as well as increasing the net present value.

To achieve a global optimal solution, Moradinasab et al. (2018) developed a multi-period and multi-product supply chain model for the downstream oil supply chain. They designed an integrated supply chain model that simultaneously considered both the installation and capacity of pipelines and facilities and optimized the location-allocation problem for facilities and routes. The optimal solution was less sensitive to changes in cost parameters, while changes in demand and injectable crude oil altered the objective value considerably. This model provides the best strategy in complex market conditions.

Papi et al. (2018) presented a robust model based on designing the crude oil supply chain network under uncertain conditions. The aim of this research is to provide a mathematical optimization model to assist in decision facilities' location, allocation, and transportation to maximize the total profit of the chain. For this purpose, the activities of the upstream supply chain of the oil industry for specific time horizon are considered. Deciding on the development activities of oil fields and crude oil logistics is among the most important variables of the model, and it should be determined in the best way due to the uncertainty related to some important parameters, such as crude oil demand and prices. To deal with uncertainty, the scenario-based robust possibility programming approach is utilized. Finally, the applicability and usefulness of the model in different dimensions of the problem were studied and its numerical results were presented. Zeng et al. (2021a) proposed a new production optimization model to maximize the net present value. Mathematical model considered development and production for an oil field. A new optimal control model is proposed here, which aims to maximize the net present value of development and production. The efficient combination of simulation and steepest gradient descend solution improves the quality of the model solution and reduces the calculation time. In addition, different sample reservoirs were analyzed through theoretical research, and it was found out that the optimal production plan corresponds to the real situation of the oil field by providing theoretical and technical support for a smart oil field system. In another study, Zeng et al. (2021b) presented a new optimal control model for maximizing the net present value of reservoir development and production. By solving the mathematical model of development and production, the input and output control parameters of the reservoir were optimized in real-time to achieve the optimal production plan. Further, the model was developed based on the theory of numerical simulation and reservoir optimization. By solving the model, several plans such as optimal program aiming to optimize oil and water production and economic benefits can be achieved based on different needs to help decide on the production of oil fields.

In the downstream segment, Amiri et al. (2019) presented a novel two-echelon model which predicts the problem of planning to supply ships with time windows and locating facilities in the oil and gas industry. This mixed integer nonlinear programming model consists of a fleet composition problem and a location routing problem. The model is used for determining the size of large ships in the first echelon and supplying ships in the second echelon. Warehouse locating, optimal trips, and related programs at both stages, along with minimizing the total cost and fulfilling the needs of operational areas and maritime facilities, are considered other objectives of the present study. Etemadi and Kasraei (2019) presented a lean supply chain model in one of the largest companies in the offshore oil and gas sector. For this purpose, by reviewing the literature and a survey of experts, 11 key factors effective in making a supply chain lean were identified in the offshore of oil and gas industry. Then, using the interpretive structural modeling technique, a research model was developed upon which "leadership and management", "information sharing", "financing" and" supplier contact" were recognized as the underlying factors of the lean supply chain. In the next step, the model was validated in quantitative and statistical analyses as well as qualitative. Finally, based on five levels of the model, some suggestions were made to lean the supply process in the offshore sector of oil and gas industry. Ghaithan et al. (2017) developed an integrated multi-objective OGSC model for medium-term tactical decision-making for the OGSC downstream segment.

Lima et al. (2021) present a mixed-integer linear programming (MILP) model for strategic and tactical planning of a downstream oil supply chain (DOSC) under uncertainty, using chance-constrained programming with fuzzy parameters. A real case study in the Brazilian oil industry validates the model as an effective decision-support tool for network design and product distribution planning.

Wang et al. (2022) optimize the multimodal petroleum supply chain under uncertainty, combining heuristic algorithms and exact optimization to improve economic, energy, and environmental efficiency. Applied to Vietnam's petroleum supply chain, it uniquely includes pipeline logistics and uses a fuzzy min-max goal programming model to handle uncertainties in demand, resources, costs, and prices, showing both short-term and long-term benefits.

Derakhti and Gonzalez (2024) explore the impact of social objectives on reservoir openness and total costs in Carbon Capture and Storage (CCS) supply chains. Through a two-stage mixed-integer linear programming model, they optimize network design, considering economic and social factors. Findings suggest that maximizing social objectives increases costs and influences reservoir openness based on cultural dimensions, while higher CO_2 tax prices enhance carbon capture and pipeline network complexity, offering insights for policy-making and industry adoption of CCS technology.

B. Integrated models

Regarding supply chain management, the goal should be to establish a collaborative environment that integrates and coordinates the activities of different entities (different decision levels) involved in the supply chain. This is particularly important in countries where the downstream market is liberalized, but it can be a complex challenge that requires decision-making tools to aid the process (Barbosa-Póvoa, 2014). Papageorgiou (2009) and Barbosa-Póvoa (2014) both recognize the need to increase scientific research on this topic to optimize the entire system as a whole, ensuring each entity receives appropriate compensation.

Several studies have been conducted on this theme (e.g., Fernandes et al., 2014, 2015; Tong et al., 2014a, 2014b, 2014c; MirHassani and Noori, 2011; Ghatee and Hashemi, 2009; Kim et al., 2008; MirHassani, 2008; and Dempster et al., 2000). The integrated modeling is explicitly explored by Fernandes et al. (2015), who extend their previous work (Fernandes et al., 2014) to study collaborative design in an uncertain context, aiming to achieve better results in terms of costs, tariffs, revenues, and profits. On the other hand, Tong et al. (2014a, 2014b, 2014c) investigate integration and coordination between biofuel and petroleum supply chains to improve the competitiveness of biofuel products in terms of costs, while also benefiting petroleum refineries in terms of profits and environmental impact. MirHassani and Noori (2011) and MirHassani (2008) explore collaboration to efficiently meet refined product demand through system integration and coordination. Ghatee and Hashemi (2009) consider expert knowledge and decision maker preferences to investigate storage tank status across the supply chain, with the goal of designing a network that meets demand.

Azadeh et al. (2017) presented a nonlinear programming model for designing the crude oil chain by considering upstream and some midstream decisions related to oil industry. In addition, Farahani and Rahmani (2017) developed a model for planning oil supply chain production and distribution by considering the effect of gas injection on production. Sheykhan et al. (2019) presented an effective framework for finding possible perspectives on an important challenge in making the right decisions and policy in the oil industry. Further, they proposed a framework for developing possible future scenarios through Fuzzy Cogitative Map (FCM). As a new method scenario planning, the FCM model attempts to provide a set of rational, reliable and credible plausible scenarios together with the analysis of the dynamic behavior of the parameters. In the presented model, the STEEP analysis method was used to identify the parameters, and the method of analyzing the cross-sectional effects was employed to determine the key factors, the analysis method was utilized for selecting the vectors of scenario production, and finally, the FCM simulations was implemented for preparing a possible scenario. In addition, the developed model was used to develop Iran's post-sanction oil production scenarios. The simulation results indicated that the proposed method could be used to produce semi-quantitatively consistent and probable scenarios, as a good alternative, to cover the disadvantages of solely quantitative and qualitative methods. Attia et al. (2019) presented a multi-objective optimization model for intermediate term planning of the supply chain in upstream hydrocarbon resources. The proposed model considered the environmental aspects and sustainability in planning chain operations. The model considers sustainability as an objective by minimizing the depletion rate of the reservoir. Beiranvand et al. (2018) developed a mathematical programming model for Iran's crude oil supply chain. The model consists of crude oil, refinery, petro chemistry, and downstream uses. By increasing the revenue from the sale of oil and its derivatives, as well as decreasing the related costs, the model attempts to maximize the amount of profit from the crude oil market and its derivatives. In order to consider real-world conditions with regard to the uncertainties, a robust optimization model was developed to increase the profitability of the whole chain by considering different scenarios. The model considers the possibility of violating the demand limit. In another study, Nicoletti and You (2020) modeled the crude oil supply chain from the oil well to the refinery as a mixed integer bi level linear program, including the conflicting objectives and interactions among different stakeholders. The composition, pricing, transportation distances, and environmental impacts of crude oil were considered in the model. In the bi level problem, crude oil producers aim to maximize their profits from selling crude oil, while crude oil refiner has dual objectives of both maximizing the profit from selling products to the market and minimizing the environmental effect of refinery products during their life cycle, which is determined by the type of crude oil purchased by the refinery. Then, the resulting model was applied in the two case studies. Zarrinpoor and Omidvari (2021) presented a mathematical model for designing the crude oil supply chain through considering related to facility location, demand allocation, transportation, and distribution planning. The proposed model considered the environmental requirements for greenhouse gas emissions, where the amount of greenhouse gas emissions from oil transportation cannot exceed a certain amount. The uncertainty of budget parameters, capacity of transportation units, capacity of exploitation units, quantity of exports, and amount of crude oil extraction and production, as well as the demand for refinery products and their production rate were included in the proposed model. In addition, a robust optimization approach was employed to deal with uncertainty in the model parameters. Numerical results verified the efficiency of the proposed model and indicated that the efficiency of the model decreases by increasing the uncertainty level of profitability. However, the profitability of oil supply chain can be guaranteed by handling the uncertainties of the parameters and appropriate production and distribution management.

Some papers also included gas-natwork in their models. For example, Mikolajková et al. (2017) designed an optimization model for gas distribution pipeline network by considering supply of gas. Behrooz and Bozarjmehri (2017) studied the daily planning of natural gas transmission systems under demand uncertainty. Bittante et al. (2018) developed a mathematical model to help decide on the tactical aspects of gas supply chain design by focusing on maritime transport between a set of supply ports and sparsely distributed receiving ports with given demands. Zarei and Naseri (2019) designed a natural gas supply chain (NGSC composed of oil and gas fields, refineries, distribution centers (DCs), or major consumption centers, import and export terminals, and underground storage reservoirs (USRs) by developing a mixed integer linear programming (MILP) model which optimizes the location of new facilities and pipeline routes together with the capacity and number of pipelines. Additionally, they formulated the expansion of the existing facilities and pipeline routes, extraction and production rates, gas storage, transmission flow rates, and import and export volumes on a limited time horizon.

Azarakhsh et al. (2021) present a multi-objective, scenario-based mixed-integer linear programming model for the entire oil supply chain, addressing uncertainties and incorporating social, environmental, and risk management aspects, validated using real data.

Redutskiy and Balycheva (2024) address a research gap by proposing a mixed-integer nonlinear programming model for planning capacities and coordinating activities in the integrated petroleum supply chain, focusing on minimizing energy consumption and enhancing operational efficiency.

C. Strategic and tactical planning

According to Chopra and Meindl (2007), the strategic problem in supply chain management involves designing the infrastructure of the supply chain to align it with the strategic objectives of companies in the network. Optimization models aid decision-making processes across the network, improving overall profitability by balancing sourcing, production, inventory, and transportation costs while maintaining required service levels, as highlighted by Barbosa-Póvoa (2014). Facility location, capacity sizing, technology selection, transportation modes, outsourcing, and investment decisions are key strategic decisions (Sahebi et al., 2014) that have a long-term impact on the supply chain due to high setup costs.

In tactical planning, the goal is to optimize the established configuration by making decisions related to production, distribution, resource planning, inventory management, and control policies within a timeframe of a few months to a year. Combining strategic and tactical decisions in network design leads to better outcomes, as noted by Barbosa-Póvoa (2014) and Papageorgiou (2009).

Rafie and Sahebi (2021) introduce an optimization model for integrating gas-oil and biodiesel supply chains, optimizing their connection points with economic and environmental objectives. Applied to a real case study in Iran, the model addresses location, allocation, production planning, inventory management, and capacity expansion, showing promise for future fuel source management and supply chain integration research.

Alnaqbi et al. (2023) propose a stochastic model for tactical planning of the Crude Oil Supply Chain (COSC) to address cost and demand uncertainties. The model integrates multi-echelon supply chains, multiple products, and a multi-period planning horizon, considering inventory and backorder penalties. Using Sample Average Approximation (SAA) with Multiple Replications Procedure (MRP), the model illustrates the impact of cost uncertainty on planning decisions and synergy gains, highlighting the value of modeling uncertainty in supply chain planning. Finally, in this paper, we consider strategic and tactical planning in an integrated model.

D. Research gap and contribution

The existing gaps included the upstream and midstream communication of the oil industry in the presented models. The present study examines the relationship between the upstream and midstream sectors at strategic and tactical levels. In some cases, the previous research indicated the crude oil and gas production chain in the exploration and production phases. After several years of operation of an oil well, there is a need for stream or water injection operations to re-operate the well due to the drop in reservoir pressure. The behavior of oil reservoirs is considered one of the influential parameters in extracting and producing crude oil. Previous research considered a linear relationship between the amounts of crude oil extracted in each period compared to the total extraction rate, while the present study attempts to model the oil reservoir behavior with the nonlinear behavior of crude oil extracted in each period. In other words, we present a mathematical optimization model that covers the gaps mentioned in the previous research and brings the modeling closer to the real world. One of the motivations for conducting the present study is that the activities related to the world's largest crude oil companies and suppliers should be accurately modeled for better management and control. Hence, providing more comprehensive mathematical models that are much closer to the real world can help make more efficient decisions in this area. The main assumptions of the model are completely in line with Attia et al. (2019). Some Similar problems can be found in Attia et al. (2019), Nicoletti and You (2020), and Calderón and Pekney (2020). However, a research gap analysis table is provided below, including some of the most important previous research.

Table I. Research gap analysis

References	Objective/Focus	Uncertainties Tackled	Sustainability/Efficiency Considerations	Notable Gaps
Mikolajková et al. (2017)	Optimization model for gas distribution pipeline network	N/A	Focuses on daily supply of gas	Does not integrate with oil supply chain; limited to pipeline optimization
Behrooz and Bozarjmehri (2017)	Daily planning of natural gas transmission	Demand uncertainty	N/A	Short-term planning focus; lacks broader supply chain considerations
Beiranvand et al. (2018)	Maximize profit in crude oil supply chain	Robust optimization, scenarios	Focus on increasing revenue, decreasing costs; considers violation of demand limits	Limited to Iran’s context; lack of broader generalizability
Bittante et al. (2018)	Tactical aspects of gas supply chain	N/A	Maritime transport between supply and receiving ports	Does not cover upstream oil supply chain integration
Attia et al. (2019)	Intermediate-term planning of upstream hydrocarbon supply chain	N/A	Environmental aspects, sustainability by minimizing reservoir depletion rate	Does not address downstream supply chain; lacks robust optimization for uncertainties
Zarei and Naseri (2019)	Natural gas supply chain design	N/A	Optimize location, capacity, and number of pipelines; considers import/export volumes	No detailed focus on environmental aspects
Nicoletti and You (2020)	Crude oil supply chain from oil well to refinery	Scenarios	Composition, pricing, transportation distances, environmental impacts; conflicting stakeholder objectives	Complex multi-stakeholder interaction; applicability to other regions not demonstrated

Continue Table I. Research gap analysis

References	Objective/Focus	Uncertainties Tackled	Sustainability/Efficiency Considerations	Notable Gaps
Zarrinpoor and Omidvari (2021)	Design of crude oil supply chain	Robust optimization	Environmental requirements for greenhouse gas emissions; impact of uncertainty on profitability	Focuses mainly on design; less on operational/tactical aspects
Azarakhsh et al. (2021)	Entire oil supply chain; multi-objective optimization	Address multiple uncertainties	Social, environmental, and risk management aspects	Complex model; may be challenging to apply without real data
Rafie and Sahebi (2021)	Integrating gas-oil and biodiesel supply chains	N/A	Economic and environmental objectives; applied to a real case study in Iran	Limited to a specific use case; needs broader application
Alnaqbi et al. (2023)	Tactical planning of the COSC	Cost/demand uncertainties	Inventory and backorder penalties; integrates multi-echelon supply chains	Focuses primarily on tactical aspects; lacks integration of long-term strategic planning
Redutskiy and Balycheva (2024)	Planning capacities in petroleum supply chain	N/A	Minimize energy consumption, enhance operational efficiency	Does not address tactical planning thoroughly; focus on energy only

In summary, the main contributions of this paper are:

- Integration of Upstream and Midstream Sectors: This paper examines the relationship between the upstream and midstream sectors at both strategic and tactical levels.
- Realistic Modeling of Oil Reservoir Behavior: This paper models the nonlinear behavior of crude oil extraction, as opposed to the linear models used in previous research.
- Enhanced Mathematical Optimization: This paper presents an integrated mathematical optimization model that addresses existing gaps in the literature, bringing the modeling closer to real-world scenarios.
- Improved Decision-Making: This paper provides a more realistic and detailed model to support more efficient decision-making in the oil and gas industry.

III. MATHEMATICAL MODELING

A. Sets/Indexes

i, j	All nodes
ro, rg	Set of reservoirs (gas, oil); i.e., production areas
$W^P(i)$	Set of potential wells of reservoir i ; $i \epsilon ro$
$W^E(i)$	Set of existing wells of reservoir i ؛ $i \epsilon ro$
n	Set of GOSPs
go, gg	Set of gathering centers (oil, gas)
po, pg	Set of processing plants (oil, gas)
do , dg	Set of demand terminals (oil, gas)
O	Set of crude oil, including heavy oil ah

g	Set of natural gas by-products, includes subsets (Gn natural gas, Gp gas by- produced at processing plants, H2S and CO2)
t	Set of time periods

B. Yield parameters

GOR_{ijt}^{0}	Gas-oil ratio of crude oil type *o* produced during period t from reservoir i linked to GOSP j, where $(i,j) \in (ro,n)$
$P_{ijt}{}^{o}$	Yield of crude oil of type *o* liberated during time period *t* at node *i* transported to node *j*, Percentage; where $(i,j) \in (ro,n)$, (go,po)
$P_{ijt}{}^{g}$	Yield of gas product g obtained during time period *t* at node *i* transported to node *j*, Percentage, where$(i,j) \in (gg,pg)$

C. Capacity parameters

c_j^o	Capacity of node *j* for crude oil *o* where; $j \in n$, go, po, do
wc_{iw}^o	Extraction capacity of oil type *o* from well w of reservoir i
c_j^g	Capacity of node *j* for gas product g where; $j \in gg, pg, dg$
c_{ij}^o	Capacity of the route linking node *i* to node j for the transfer of crude oil *o*, where $(i,j) \in (W^P(k),n),(W^E(k),n),k\epsilon ro,(n,go),(go,po),(po,do)$
c_{ij}^g	Capacity of the route linking node *i* to node j for gas product *g*, where $(i,j) \in (rg,gg),(n,gg),(gg,pg),(pg,dg)$

D. Volume parameters

R_i^0	Amount of reserves in node *i* reservoir for oil type *o*, where $i \in ro$
R_i^g	Amount of reserves in the node *i* reservoir for gas by-product, where $i \in rg$
C_{max}	Maximum amount of CO2 to be emitted to the environment in time period *t*
OPECQ	The OPEC market or share per planning period *t*

E. Cost parameters

ec_{ijt}^o	Production cost per unit of stream $Prod_{i,w,t,j}$, at node *i* during time period *t* from well *w* to node *j*, where $(i,j) \in (W^P(k),n),(W^E(k),n),k\epsilon ro$
ec_{ijt}^g	Production cost per unit of stream y_{ijt}^g , at node *i* during time period *t*, where $(i,j) \in (rg,gg)$
pc_{ijt}^o	Processing cost per unit of stream x_{ijt}^o , at node *j* during time period *t*, where $(i,j) \in (W^P(k),n),(W^E(k),n),k\epsilon ro,(go,po)$
pc_{ijt}^g	Processing cost per unit of stream y_{ijt}^g, at node *j* during time period *t*, where $(i,j) \in (gg,pg)$

tc^{o}_{ijt}	Transportation cost per unit stream x^{o}_{ijt} from node *i* to node *j* during time period *t*, where $(i,j) \in (W^{P}(k),n),(n,go),(go,po),(po,do),(W^{E}(k),n),k\epsilon ro$
tc^{g}_{ijt}	Transportation cost per unit stream y^{g}_{ijt} from node *i* to node *j* during time period *t*, where $(i,j) \in (rg,gg),(n,gg),(gg,pg),(pg,dg)$
c^{g}_{jt}	Cost per unit of emitting CO2 to environment at plant *i* during time period *t*, where $j \in pg$
w^{o+}_{jt}	Penalty cost per unit for producing oil of type *o* above the specified demand at node *j* during time period *t* (i.e., holding cost), where $j \in go, do$
w^{o-}_{jt}	Penalty cost per unit for producing oil of type *o* below the demand at node *j* during time period *t* (i.e., Penalty of filling part of the demand from the outside market), where $j \in go, do$
w^{g+}_{jt}	Penalty cost per unit for producing gas product *g* above the specified demand at node *j* during time period *t* (i.e., Holding cost), where $j \in$ gg, dg
w^{g-}_{jt}	Penalty cost per unit for producing gas product *g* below the demand at node *j* during time period *t* (i.e., Penalty of filling part of the demand from the outside market), where $j \in gg, dg$
FCD_{iw}	Fixed cost of drilling and equipping well *w* in reservoir *i*, $i\epsilon ro, w\epsilon w^{p}(i)$

F. Enhanced Oil Recovery parameters

CI_i	Injection cost per unit of reservoir *i* , $i \in ro$
FCI_i	Enhanced Oil Recovery fixed cost for reservoir *i*
IRF_i	Enhanced Oil Recovery coefficient *i* ،$i \in ro$
$PCap_i$	Estimated capacity of reservoir *i* without Enhanced Oil Recovery, $i \in ro$
$MinInj_i$	Minimum amount of gas injection into reservoir *i* in each period, $i \in ro$
$MaxInj_i$	Maximum amount of gas injection into reservoir *i* in each period, $i \in ro$
$TotInj$	Maximum amount of gas available for injection
δ	A very small number
ψ	A very large number

G. Demand and price parameters

d^{o}_{jt}	Demand at terminal *j* for oil type *o* in time period *t*, where $j \in do$
d^{g}_{jt}	Demand at terminal *j* for gas byproduct g in time period *t*, where $j \in dg$
pr^{0}_{jt}	Selling price per unit of oil *o* during time period *t* at demand node *j*, where $j \in do$
pr^{g}_{jt}	Selling price of per unit of gas byproduct g during time period *t* at demand node *j*, where $j \in dg$
dr	Discount rate per period *t*

H. Decision variables

x_{ijt}^{o}	Amount of crude oil type *o* produced in time period *t* transferred from node *i* to node *j*, where $(i,j) \in (n,go),(go,po),(ro,n),(po,do)$
y_{ijt}^{g}	Amount of natural gas of type *g* produced in time period *t* transferred from node *i* to node j, where $(i,j) \in (rg,gg)$, (n,gg), (gg,pg), (pg,dg)
x_{jt}^{o+}	Crude oil production of type *o* in time period *t* above the demand at node *j*, where $j \in go, do,$
x_{jt}^{o-}	Crude oil production of type *o* in time period *t* below the demand at node *j* (which is satisfied from the outside market), where $j \in go, do,$
y_{jt}^{g+}	Natural gas production of byproduct g in time period *t* above the demand at node *j*; where $j \in gg, dg,$
y_{jt}^{g-}	Natural gas production of byproduct g in time period *t* below the demand at node *j* (i.e., satisfied from the outside market), where $j \in gg, dg,$
Inj_{it}	Amount of gas injected into reservoir *i* in time period *t*, where $i\epsilon ro, t\epsilon T$
$CumO_{it}$	Cumulative amount of oil extracted from reservoir *i* before time period *t*, $i\epsilon ro, t\epsilon T$
$Prod_{i,w,t,j}^{o}$	Amount of oil sent from well *w* in production period *t* to GOSP number *j*, $, i\epsilon ro, w\epsilon w^{p}(i) \cup w^{E}(i), j \in n$
$I_{i,t}$	Equal to one if injected into gas reservoir *i* in time period t; otherwise, equal to zero, $i\epsilon ro, t\epsilon T$
Z_i	Equal to one if Enhanced Oil Recovery happens in reservoir *i*; otherwise, equal to zero, $i\epsilon ro$
$FEOR_{it}$	Equal to one if the first gas injection happens for the purpose of Enhanced Oil Recovery from reservoir *i* in time period *t*; otherwise, equal to zero, $i\epsilon ro$
$Drill_{iwt}$	Equal to one if well *w* is drilled from reservoir *i* in time period *t*; otherwise, equal to zero, $i\epsilon ro, w\epsilon w^{p}(i)$
D	Depletion rate of crude oil and natural gas reserves

I. Mathematical model

$$Maximize\ Profit = Revenue - Total\ Cost \tag{1}$$

$$minimize\ D \tag{2}$$

$$\begin{aligned} Total\ Cost &= \sum_t (1+dr)^{-(t-1)} \Big[\sum_{o;(i,j)\in(W^P(k),n),(W^E(k),n),k\epsilon ro} ec_{ijt}^{o} Prod_{i,w,t,j}^{o} + \sum_{g;(i,j)\in(rg,gg)} ec_{ijt}^{g} y_{ijt}^{g} + \\ &\sum_{o;(i,j)\in(W^P(k),n),(W^E(k),n),k\epsilon ro} pc_{ijt}^{o} Prod_{i,w,t,j}^{o} \\ &+ \sum_{g;(i,j)\in(rg,n),pg} pc_{ijt}^{g} y_{ijt}^{g} + \sum_{o;i\in((W^P(k)),(W^E(k)),k\epsilon ro);j} tc_{ijt}^{o} x_{ijt}^{o} + \sum_{g;i;j} tc_{ijt}^{g} y_{ijt}^{g} + \\ &\sum_{o;j\in(go,d0)} ({w_j}^{o+} {x_{jt}}^{o+} + {w_j}^{o-} {x_{jt}}^{o-}) + \sum_{g;j\in(gg,dg)} ({w_j}^{g+} {y_{jt}}^{g+} + {w_j}^{g-} {y_{jt}}^{g-}) + \sum_{g\in C02;j\in pg} c_{jt}^{g} y_{jt}^{g} + \\ &\sum_{i\in ro} (CI_i * Inj_{it} + FEOR_{it} * FCI_i) + \sum_{i\in ro} \sum_{w\epsilon w^p(i)} Drill_{iwt} * FCD_{iw} + \\ &\sum_{o;(i,j)\in(W^P(k),n),(W^E(k),n),k\epsilon ro} tc_{ijt}^{o} Prod_{i,w,t,j}^{o} \Big] \end{aligned} \tag{3}$$

$$Revenue = \sum_{t}(1+dr)^{-(t-1)}[\sum_{O;(i,j)\in(po,do)} pr_{jt}^{o}(x_{ijt}^{o}-x_{jt}^{o+}) + \sum_{g;(i,j)\in(pg,dg)} pr_{jt}^{g}(y_{ijt}^{g}-y_{jt}^{g+})] \quad (4)$$

$$\sum_{i\in ro} P_{ijt}^{o}\, Prod_{i,w,t,j}^{o} = \sum_{i\in go} x_{jit}^{o}\ \forall o, \forall j \in n, \forall t, w\epsilon w^{p}(i) \cup w^{E}(i) \quad (5)$$

$$\sum_{i\in ro} GOR_{ijt}^{o} Prod_{i,w,t,j}^{o} = \sum_{i\in gg} y_{jit}^{g}\ \forall o, \forall j \in n, \forall t,\ w\epsilon w^{p}(i) \cup w^{E}(i) \quad (6)$$

$$x_{ijt}^{o}=\sum_{w\epsilon w^{p}(i)\cup w^{E}(i)} Prod_{i,w,t,j}^{o} \quad \forall o, \forall j \in n, \forall t, i \in ro \quad (7)$$

$$Prod_{i,w,t,j}^{o} \leq \sum_{\tau=1}^{t-1} Drill_{iw\tau} * wc_{iw}^{o}\ \ \forall o, \forall j \in n, \forall t, i \in ro, w\epsilon w^{p}(i) \quad (8)$$

$$\sum_{t=1}^{T} Drill_{iwt} \leq 1\ \forall i \in ro, w\epsilon w^{p}(i) \quad (9)$$

$$Prod_{i,w,t,j}^{o} \leq wc_{iw}^{o}\ \ \forall o, \forall j \in n, \forall t, i \in ro, w\epsilon w^{E}(i) \quad (10)$$

$$\sum_{i\in n} x_{ijt}^{o} + x_{jt-1}^{o+} = \sum_{i\in po} x_{jit}^{o} + x_{jt}^{o+}\ \forall o, \forall j \in go, \forall t \quad (11)$$

$$\sum_{i\in go} P_{ijt}^{o}\, x_{ijt}^{o} = \sum_{i\in do} x_{jit}^{o}\ \forall o, \forall j \in po, \forall t \quad (12)$$

$$\sum_{i\in go} P_{ijt}^{o}\, x_{ijt}^{o} = \sum_{g\in H2S; i\in dg} y_{jit}^{g}\ \forall o, \forall j \in po, \forall t \quad (13)$$

$$\sum_{i\in rg} y_{ijt}^{g} + \sum_{i\in n} y_{ijt}^{g} + y_{jt-1}^{g} = \sum_{i\in pg} y_{jit}^{g} + y_{jt}^{g}\ \forall g, \forall j \in gg, \forall t \quad (14)$$

$$\sum_{i\in gg} P_{ijt}^{g}\, y_{ijt}^{g} = \sum_{i\in dg} y_{ijt}^{g}\ \forall g, \forall j \in pg, \forall t \quad (15)$$

$$\sum_{i\in ro} p_{ijt}^{o}\, x_{ijt}^{o} \leq C_{j}^{o}\ \forall o, \forall j \in n, \forall t \quad (16)$$

$$\sum_{i\in go} p_{ijt}^{o}\, x_{ijt}^{o} \leq C_{j}^{o}\ \forall o, \forall j \in po, \forall t \quad (17)$$

$$\sum_{i\in n} x_{ijt}^{o} + x_{jt-1}^{o+} \leq C_{j}^{o}\ \forall 0, \forall j \in go, \forall t \quad (18)$$

$$\sum_{i\in po} x_{ijt}^{o} + x_{jt-1}^{o+} \leq C_{j}^{o}\ \forall 0, \forall j \in do, \forall t \quad (19)$$

$$\sum_{i\in gg} p_{ijt}^{g}\, y_{ijt}^{g} \leq C_{j}^{g}\ \forall g, \forall j \in pg, \forall t \quad (20)$$

$$\sum_{i\in rg} y_{ijt}^{g} + \sum_{i\in n} y_{ijt}^{g} + y_{jt-1}^{g+} \leq C_{j}^{g}\ \forall g, \forall j \in gg, \forall t \quad (21)$$

$$\sum_{i\in pg} y_{ijt}^{g} + y_{jt-1}^{g+} \leq C_{j}^{g}\ \forall g, \forall j \in dg\ , \forall t \quad (22)$$

$$x_{ijt}^{o} \leq C_{ij}^{o}\ \forall o, \forall i, \forall j\ , \forall t \quad (23)$$

$$y_{ijt}^{g} \leq C_{ij}^{g}\ \forall g, \forall i, \forall j\ , \forall t \quad (24)$$

$$\sum_{i\in po} x_{ijt}^{o} - x_{jt}^{o+} + x_{jt}^{o-} = d_{jt}^{o} - x_{jt-\iota}^{o+} \ \forall o, \forall j \in do\ \forall t \quad (25)$$

$$\sum_{i\in pg} y_{ijt}^{g} - y_{jt}^{g+} + y_{jt}^{g-} = d_{jt}^{g} - y_{jt-1}^{g+} \ \forall g, \forall j \in dg\ \forall t \quad (26)$$

$$\sum_{o;(i,j)\in(po,into)} x_{ijt}^{o} + \sum_{o;j\in into} x_{jt-1}^{o+} \leq \text{OPECQ} \ \ \forall t \quad (27)$$

$$\sum_{g\in C02;j\in pg} y_{jt}^{g} \leq C_{\max} \ \ \forall t \quad (28)$$

$$\frac{\sum_{o;(i,j)\in(ro,n)} x_{ijt}^{o}}{\sum_{o;i\in ro} R_{i}^{0}} \leq D \ \ \forall t \quad (29)$$

$$\frac{\sum_{o;(i,j)\in(rg,gg)} y_{ijt}^{g}}{\sum_{g;i\in rg} R_{i}^{g}} \leq D\ \forall t \quad (30)$$

$$\sum_{j\in n} \sum_{\tau=1}^{t} x_{ij\tau}^{o} = CumO_{it} \ \ \forall t, i \in ro \quad (31)$$

$$CumO_{it} - PCap_{i} \ \leq \psi * I_{i,t} \quad \forall t, i \in ro \quad (32)$$

$$CumO_{it} - PCap_{i} \ \geq \psi * (I_{i,t} - 1) \quad \forall t, i \in ro \quad (33)$$

$$Inj_{it} \leq I_{i,t} * MaxInj_{i} \qquad \forall t, i \in ro \quad (34)$$

$$Inj_{it} \geq I_{i,t} * MinInj_{i} \qquad \forall t, i \in ro \quad (35)$$

$$\sum_{i\epsilon ro} \sum_{t} Inj_{it} \leq TotInj \quad (36)$$

$$I_{i,t} * \left(Inj_{it} * IRF_{i} * (R_{i}^{0} - CumO_{it}) - \sum_{j\epsilon n} x_{ijt}^{o}\right) = 0 \qquad \forall t, i \in ro \quad (37)$$

$$Z_{i} \geq I_{i,t} - \delta \qquad \forall t, i \in ro \quad (38)$$

$$\sum_{t} FEOR_{it} = Z_{i} \qquad \forall\ i \in ro \quad (39)$$

$$\sum_{t} t * FEOR_{it} \leq t * I_{i,t} + \left(1 - I_{i,t}\right) * t \ \ \forall t, i \in ro \quad (40)$$

$$\sum_{j\epsilon n. o\in O. t\in T} x_{ijt}^{o} \leq Z_{i} * \left((1 + \sum_{t} Inj_{it} * IRF_{i}) * PCap_{i}\right) + (1 - Z_{i}) * PCap_{i} \ \ \forall i \in ro \quad (41)$$

$$x_{ijt}^{o}, x_{jt}^{o+}, x_{jt}^{o-}, y_{ijt}^{g}, y_{jt}^{g+}, y_{jt}^{g-}, D, Inj_{it}, Prod_{i,w,t,j}^{o} \geq 0 \qquad \forall t, i, j, w \quad (42)$$

Equations (1) and (2) represent the objective functions of profit and depletion rate, respectively. Equations (3) and (4) show the definition of income and cost variables, respectively, while equations (5) and (6) indicate the flow balance between the reservoir wells and the oil and gas separation centers, respectively (i.e. sum of inflow must be in balance with some of outflow). Equation (7) shows that incoming stream oil and gas separation centers are equal to the total stream from the wells sent to that product center.

Based on Equation (8), no production can occur from any potential well before drilling. Regarding equation (9), each potential well can be drilled at most once. Equation (10) represents the production constraints of each well (i.e. the maximum capacity of that).

Equation (11) shows a balance between oil and gas separation centers and oil processing plants (i.e. sum of inflow must be in balance with some of the outflow). Equations (12-13) indicate the balance between the incoming and outgoing balance of oil and gas separation centers, respectively. Equations (14-15) represent an incoming and outgoing balance of gas gathering centers, respectively (i.e. sum of inflow to gas gathering centers must be in balance with some of the outflow from them).

Equations (16), (17) and (20) reflect the maximum processing capacity of oil and gas, respectively, while Equations (18), (19), (21) and (22) indicate that gathering centers and demand terminals for oil and gas, respectively. Route capacity constraints for all products and all proposed network routes are shown in Equations (23) and (24), respectively (i.e. the maximum flow that can be transferred through a path).

Equations (25) and (26) indicate the balance of the oil and gas produced from the processing plants, respectively, which is used to satisfy demand at terminals (i.e. each plant cannot provide demand without considering its inflow). The OPEC quota constraint in Equation (27) shows that the total amount of crude oil for all types at international terminals should not exceed the OPEC's quota or the market share. Moreover, CO2 emissions must be within the constraints set by the environmental regulations and Equation (28) represents the CO2 emission. Equations (29) and (30) are considered sustainability constraints.

Equations (31), (32) and (33) represent the time in which EOR occurs, upon which $I_{i,t}$ can only take a value of 1 if the cumulative rate of Enhanced Oil Recovery is higher than the previous period without Enhanced Oil Recovery.

Equations (34) and (35) show the maximum and minimum amount for gas injections, respectively. Equation (36) indicates the total amount of available gas for injection (i.e. sum of all injected gas must not exceed the available amount for injection). The rate of extraction in the case of Enhanced Oil Recovery periods is shown in Equation (37) (i.e. in the case of Enhanced Oil Recovery, the reservoirs can yield with more capacity in proportion to the amount of injection). In addition, Equations (38), (39) and (40) represent the first period of Enhanced Oil Recovery to determine the period of enacting its fixed cost. Equation (41) considers an increase in reservoir capacity when a gas injection occurs for Enhanced Oil Recovery. Finally, Equation (42) displays the non-negativity constraint.

IV. SOLUTION APPROACH

The LP-metric method is used to solve the bi-objective problem. This method has several advantages over other methods, including (Zeng et al., 2022):

- Simplicity: The LP-metric method is a simple and straightforward approach that does not require complex algorithms or mathematical concepts. This makes it easy to understand and implement.
- Efficiency: LP-metric method can solve multi-objective optimization problems efficiently in terms of computational time and resources required. This is particularly useful for large-scale problems.
- Flexibility: LP-metric method is a flexible approach that can handle different types of constraints and objectives. It can also be used to solve both linear and nonlinear optimization problems.
- Pareto optimality: The LP-metric method guarantees that the solution obtained is Pareto optimal. This means that it is impossible to improve one objective's value without compromising the value of another.
- Interpretability: The LP-metric method provides insight into the trade-offs between different objectives. This allows decision-makers to make informed decisions based on the results obtained.

Using the LP-metric method, the main bi-objective problem is converted into a single-objective problem through the following function:

$$Min\ Z = W_1\left(\frac{Profit - Profit^*}{Profit^*}\right)^2 + W_2\left(\frac{D - D^*}{D^*}\right)^2$$

A. Sample problem assumptions

We validated the model by solving a relatively small illustrative example and checking the logical relationships among different variables. We provided this example in the manuscript and explained it in detail. To validate the presented mathematical model, the sample problem assumptions are given in Table II, along with the dimensions and specifications of the oil reservoirs. Due to the large volume of the problem parameters, the values are provided in the attached Excel file. This is a made-up sample. In real-world cases, all the required parameters (including yield parameters; capacity parameters; volume parameters; cost parameters; enhanced oil recovery parameters; and demand and price parameters) can be achieved by referring to estimations and predictions provided by oil and gas companies. However, these parameters are usually uncertain, which may require considering uncertain modeling in future research.

Table II. Sample problem assumptions

Sample problem assumptions			Reservoir specifications		
Node	**Number**	**Display mode**	**Reservoir**	**ro1**	**ro2**
GOSPs: gas and oil separation centers	4	n 1 to n4	$W^E(i)$:existing wells	1 to 10	1 to 10
ro: oil Reservoirs	2	ro 1 to ro2	$W^P(i)$: potential wells	11 to 20	11 to 20
rg: gas Reservoirs	2	rg 1 to rg2	$MaxInj_i$:max gas injection	1.077208	2.256361
go: oil gathering centers	4	go 1 to go4	$MinInj_i$:min gas injection	0	0
gg: gas gathering centers	4	gg 1 to gg4	Maximum amount of gas available for injection	29.20	26.45
po: oil processing centers	5	po 1 to po5	$PCap_i$: Capacity without Enhanced Oil Recovery	5.84	5.29
pg: gas processing centers	4	pg1 to pg4			
do: oil demand centers	4	do 1 to do4			
dg: gas demand centers	4	dg 1 to dg4			
t: Set of time Periods	3	1 to 3			

B. Computational results

First, the model is optimized based on maximized profit in a single objective. The value of profit is 719856.7. Additionally, the optimal amount of depletion rate in a single objective for reducing the depletion rate is zero. Accordingly, the LP metric objective function by using the weights 0.8 and 0.2 for the objective functions of profit and extraction rate, respectively, is as follows:

$$Min\ Z = 0.8 * \left(\frac{Profit - 719856.7}{719856.7}\right)^2 + 0.2 * (D)^2$$

Tables (III), (IV), (V), (VI), (VII), and (VIII) indicate the optimal values of decision variables. As shown, both of the problem reservoirs were injected during the second and third gas injection periods for Enhanced Oil Recovery. Moreover, all potential wells in both reservoirs were drilled in the first period for the purpose of more Enhanced Oil Recovery.

Solving the sample problem with the above objective function led to a profit and depletion rate of 532043.9 and 0.714, respectively. Table (III) shows the values of other decision variables. This table shows that there is no injection to none of the reservoirs at the first period and the first EOR is implemented at the second time period. In addition, all the potential wells (wells 11 to 20) are drilled at the first time period.

Table III. Numerical results

Reservoir	(Inj_{it})		$(I_{i.t})$		$(FEOR_{it})$	(Z_i)	$(Drill_{iwt})$									
	Period		**Period**		**Period**	**Period**	**Period**									
							1									
							Well									
	2	3	2	3	2	2	11	12	13	14	15	16	17	18	19	20
ro1	0.256394	0.705084	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ro2	0.336403	0.925107	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table IV displays the amount of oil flow from node i to node j in each period. For example, ro2 interacts with n2 with values 0.324645, 1.85168, and 1.85168 for periods 1, 2, and 3, respectively, while ro2 interacts with n3 with values 0.92584, 1.85168, and 1.85168 for the same periods. The table shows the set of source nodes (n1, n2, n3, n4, ro1, ro2 among others) interacting with other nodes (go1, go2, go3, go4, po1, po2, po3, po4, po5, do1, do2, do3, do4) across three different periods, with the metrics evolving over time.

Table IV. Amount of crude oil type o produced in time period t transferred from node i to node j (x^{o}_{ijt})

Node i	**Node j**	**Period**			**Node i**	**Node j**	**Period**		
		1	**2**	**3**			**1**	**2**	**3**
n1	go1	0	3.62858	0	ro2	n2	0.324645	1.85168	1.85168
n1	go2	1.636207	0	0	ro2	n3	0.92584	1.85168	1.85168
n1	go4	0	0	3.108083	ro2	n4	0.92584	1.85168	1.85168
n2	go2	1.097913	0	0	go1	po4	0	3.648351	0
n2	go3	0	0	3.173188	go2	po3	5.400641	0	0
n2	go4	0	2.75492	0	go3	po1	0	0	7.344082
n3	go2	1.079843	0	0	go3	po5	0	6.784523	0
n3	go3	0	3.492434	0.605445	go4	po3	0	2.75492	0
n3	go4	0	0	2.578756	go4	po4	0	0	5.686839
n4	go1	0	0.019771	0	po1	do2	0	0	6.964857
n4	go2	1.586679	0	0	po3	do1	5.08705	0	0
n4	go3	0	3.292088	3.565448	po3	do3	0	2.414959	0
ro1	n1	1.022078	2.044156	2.044156	po4	do2	0	0	1.141744
ro1	n2	1.022078	2.044156	2.044156	po4	do3	0	2.056224	4.193491
ro1	n3	0.358391	2.044156	2.044156	po4	do4	0	1.149447	0
ro1	n4	1.022078	2.044156	2.044156	po5	do4	0	6.21322	0
ro2	n1	0.92584	1.85168	1.85168	0	0	0	0	0

Table V indicates the amount of oil extracted from each well of reservoirs sent to the oil and gas separation centers. As shown, the total oil outgoing stream from reservoir ro1 is 19.78, while its capacity without Enhanced Oil Recovery is 5.84 units, the difference of which was provided by gas injection. In addition, the total oil outgoing stream from reservoir ro2 is 17.91, while its capacity without Enhanced Oil Recovery is 5.29 units, the difference of which was provided by gas injection. This fact highlights the importance of embedding the EOR methods in the model.

Table V. Amount of oil sent from well w in production period t to GOSP j ($Prod^{o}_{i,w,t,j}$)

Reservoir(i)	Well(w)	Period(t)	j=n1	j=n2	j=n3	j=n4	Reservoir(i)	Well(w)	Period(t)	j=n1	j=n2	j=n3	j=n4	Reservoir(i)	Well(w)	Period(t)	j=n1	j=n2	j=n3	j=n4	Reservoir(i)	Well(w)	Period(t)	j=n1	j=n2	j=n3	j=n4
ro1	1	1	0.1	0.1	0.1	0.1	ro2	1	1	ro1	1	1	0.1	0.1	0.1	0.1	ro2	1	1	ro1	1	1	0.1	0.1	0.1	0.1	ro2
ro1	1	2	0.1	0.1	0.1	0.1	ro2	1	2	ro1	1	2	0.1	0.1	0.1	0.1	ro2	1	2	ro1	1	2	0.1	0.1	0.1	0.1	ro2
ro1	1	3	0.1	0.1	0.1	0.1	ro2	1	3	ro1	1	3	0.1	0.1	0.1	0.1	ro2	1	3	ro1	1	3	0.1	0.1	0.1	0.1	ro2
ro1	2	1	0.1	0.1	0	0.1	ro2	2	1	ro1	2	1	0.1	0.1	0	0.1	ro2	2	1	ro1	2	1	0.1	0.1	0	0.1	ro2
ro1	2	2	0.1	0.1	0.1	0.1	ro2	2	2	ro1	2	2	0.1	0.1	0.1	0.1	ro2	2	2	ro1	2	2	0.1	0.1	0.1	0.1	ro2
ro1	2	3	0.1	0.1	0.1	0.1	ro2	2	3	ro1	2	3	0.1	0.1	0.1	0.1	ro2	2	3	ro1	2	3	0.1	0.1	0.1	0.1	ro2
ro1	3	1	0.1	0.1	0	0.1	ro2	3	1	ro1	3	1	0.1	0.1	0	0.1	ro2	3	1	ro1	3	1	0.1	0.1	0	0.1	ro2
ro1	3	2	0.1	0.1	0.1	0.1	ro2	3	2	ro1	3	2	0.1	0.1	0.1	0.1	ro2	3	2	ro1	3	2	0.1	0.1	0.1	0.1	ro2
ro1	3	3	0.1	0.1	0.1	0.1	ro2	3	3	ro1	3	3	0.1	0.1	0.1	0.1	ro2	3	3	ro1	3	3	0.1	0.1	0.1	0.1	ro2
ro1	4	1	0.1	0.1	0	0.1	ro2	4	1	ro1	4	1	0.1	0.1	0	0.1	ro2	4	1	ro1	4	1	0.1	0.1	0	0.1	ro2
ro1	4	2	0.1	0.1	0.1	0.1	ro2	4	2	ro1	4	2	0.1	0.1	0.1	0.1	ro2	4	2	ro1	4	2	0.1	0.1	0.1	0.1	ro2
ro1	4	3	0.1	0.1	0.1	0.1	ro2	4	3	ro1	4	3	0.1	0.1	0.1	0.1	ro2	4	3	ro1	4	3	0.1	0.1	0.1	0.1	ro2
ro1	5	1	0.1	0.1	0.1	0.1	ro2	5	1	ro1	5	1	0.1	0.1	0.1	0.1	ro2	5	1	ro1	5	1	0.1	0.1	0.1	0.1	ro2
ro1	5	2	0.1	0.1	0.1	0.1	ro2	5	2	ro1	5	2	0.1	0.1	0.1	0.1	ro2	5	2	ro1	5	2	0.1	0.1	0.1	0.1	ro2
ro1	5	3	0.1	0.1	0.1	0.1	ro2	5	3	ro1	5	3	0.1	0.1	0.1	0.1	ro2	5	3	ro1	5	3	0.1	0.1	0.1	0.1	ro2
ro1	6	1	0.1	0.1	0	0.1	ro2	6	1	ro1	6	1	0.1	0.1	0	0.1	ro2	6	1	ro1	6	1	0.1	0.1	0	0.1	ro2
ro1	6	2	0.1	0.1	0.1	0.1	ro2	6	2	ro1	6	2	0.1	0.1	0.1	0.1	ro2	6	2	ro1	6	2	0.1	0.1	0.1	0.1	ro2
ro1	1	1	0.1	0.1	0.1	0.1	ro2	1	1	ro1	1	1	0.1	0.1	0.1	0.1	ro2	1	1	ro1	1	1	0.1	0.1	0.1	0.1	ro2
ro1	1	2	0.1	0.1	0.1	0.1	ro2	1	2	ro1	1	2	0.1	0.1	0.1	0.1	ro2	1	2	ro1	1	2	0.1	0.1	0.1	0.1	ro2
ro1	1	3	0.1	0.1	0.1	0.1	ro2	1	3	ro1	1	3	0.1	0.1	0.1	0.1	ro2	1	3	ro1	1	3	0.1	0.1	0.1	0.1	ro2
ro1	2	1	0.1	0.1	0	0.1	ro2	2	1	ro1	2	1	0.1	0.1	0	0.1	ro2	2	1	ro1	2	1	0.1	0.1	0	0.1	ro2
ro1	2	2	0.1	0.1	0.1	0.1	ro2	2	2	ro1	2	2	0.1	0.1	0.1	0.1	ro2	2	2	ro1	2	2	0.1	0.1	0.1	0.1	ro2
ro1	2	3	0.1	0.1	0.1	0.1	ro2	2	3	ro1	2	3	0.1	0.1	0.1	0.1	ro2	2	3	ro1	2	3	0.1	0.1	0.1	0.1	ro2
ro1	3	1	0.1	0.1	0	0.1	ro2	3	1	ro1	3	1	0.1	0.1	0	0.1	ro2	3	1	ro1	3	1	0.1	0.1	0	0.1	ro2
ro1	3	2	0.1	0.1	0.1	0.1	ro2	3	2	ro1	3	2	0.1	0.1	0.1	0.1	ro2	3	2	ro1	3	2	0.1	0.1	0.1	0.1	ro2

Table VI details the amount of natural gas of type g produced in time period t, transferred from node i to node j. The table is organized into multiple sections, each illustrating the source node (i), destination node (j), the gas type (g), and the amount transferred during three periods (t=1, 2, 3). For instance, natural gas type Gn from node n1 to node gg1 shows amounts 0.65, 0, and 0 for periods 1, 2, and 3, respectively. This structure repeats for various combinations of gas types, source nodes, and destination nodes.

The table further lists data for other gas types, such as Hs, Gp, and Co, each having their respective nodes and transfer amounts for different periods. For example, gas type Hs from node n3 to node gg3 shows amounts of 0.11, 1.09, and 0.25 for periods 1, 2, and 3, respectively. Similarly, gas type Co from node n1 to node gg1 shows amounts 0.65, 0, and 0.45 for the same periods. Each entry across these sections provides a snapshot of the transfer dynamics of various types of natural gas between nodes over the specified periods, highlighting the varying amounts transferred and the interactions between different nodes.

Table VI. Amount of natural gas of type g produced in time period t transferred from node i to node j (y_{ijt}^{g})

Gas type(g)	source Node(i)	Destination node(j)	Period(t)			Gas type(g)	source Node(i) 1	Destination node(j)	Period(t)			Gas type(g)	source Node(i)	Destination node(j)	Period(t)			Gas type(g)	source Node(i) 1	Destination node(j)	Period(t)		
			1	2	3				1	2	1				1	2	3				1	2	3
Gn	n1	gg1	0.65	0	0	Hs	n3	gg3	0.11	1.09	0.25	Gp	n2	gg4	0.47	0.27	0.7	Hs	pg4	dg2	2.12	2.12	0
Gn	n1	gg3	0	0	0.15	Hs	n4	gg1	0	1.21	0	Gp	n3	gg1	0	0	1.26	Hs	pg4	dg3	0	1.97	0
Gn	n1	gg4	0	1.43	1.05	Hs	n4	gg2	0	0	1.45	Gp	n3	gg3	0	1.09	0	Hs	pg4	dg4	1.65	2.16	0
Gn	n2	gg1	0.47	0	0.97	Hs	n4	gg3	0.68	0.23	0	Gp	n3	gg4	0.35	0	0	Co	n1	gg1	0.65	0	0.45
Gn	n2	gg3	0	1.26	0	Hs	rg1	gg1	2.23	2.23	2.21	Gp	n4	gg1	0	0	1.45	Co	n1	gg2	0	0	0.75
Gn	n3	gg1	0.35	0	0	Hs	rg1	gg2	2.68	2.31	2.68	Gp	n4	gg3	0.36	1.44	0	Co	n1	gg3	0	1.43	0
Gn	n3	gg3	0	0	1.26	Hs	rg1	gg3	2.84	1.68	2.84	Gp	n4	gg4	0.32	0	0	Co	n2	gg1	0.47	0	0
Gn	n3	gg4	0	1.09	0	Hs	rg1	gg4	3	2.77	0	Gp	rg1	gg1	2.18	0	0	Co	n2	gg2	0	0.83	0.97
Gn	n4	gg1	0.68	0	0	Hs	rg2	gg1	2.48	2.48	0	Gp	rg1	gg2	2.72	0.64	0	Co	n2	gg4	0	0.43	0
Gn	n4	gg3	0	0.67	1.45	Hs	rg2	gg2	2.26	0	1.42	Gp	rg1	gg3	2.34	1.24	0	Co	n3	gg2	0	0	1.26
Gn	n4	gg4	0	0.77	0	Hs	rg2	gg3	2.79	0	0	Gp	rg1	gg4	2.74	2.74	0	Co	n3	gg3	0.35	1.09	0
Gn	rg1	gg1	2.62	0	1.87	Hs	rg2	gg4	2.34	0	2.34	Gp	rg2	gg1	2.96	2.92	0	Co	n4	gg2	0	0	1.45
Gn	rg1	gg2	2.06	0.16	0	Hs	gg1	pg1	0	2.5	0.11	Gp	rg2	gg2	2.75	2.75	0	Co	n4	gg3	0.68	1.44	0
Gn	rg1	gg3	2.89	2.89	0	Hs	gg1	pg2	2.1	0	2.1	Gp	rg2	gg3	2.04	2.04	0	Co	rg1	gg1	3	2.29	0
Gn	rg1	gg4	2.08	2.08	1.54	Hs	gg1	pg3	0.01	2.08	0	Gp	rg2	gg4	2.09	2.09	0.5	Co	rg1	gg2	2.99	2.99	0
Gn	rg2	gg1	2.23	0.68	2.23	Hs	gg1	pg4	2.59	2.59	0	Gp	gg1	pg1	0.09	0	0	Co	rg1	gg3	2.25	1.94	0
Gn	rg2	gg2	2.32	2.32	0	Hs	gg2	pg1	2.12	0	2.12	Gp	gg1	pg2	2.92	2.92	0	Co	rg1	gg4	2	1.45	0
Gn	rg2	gg3	2.2	0.07	0	Hs	gg2	pg2	1.37	0	2.76	Gp	gg1	pg3	2.13	0	0	Co	rg2	gg1	2.69	0	0
Gn	rg2	gg4	2.21	2.21	0	Hs	gg2	pg4	1.69	2.31	1.69	Gp	gg1	pg4	0	0	2.99	Co	rg2	gg2	2.74	2.74	0
Gn	gg1	pg1	0	0.68	2.15	Hs	gg3	pg1	2.78	0	0	Gp	gg2	pg1	0	2.28	0	Co	rg2	gg3	2.62	2.62	0
Gn	gg1	pg2	2.94	0	0	Hs	gg3	pg2	2.26	2.26	2.26	Gp	gg2	pg2	2.11	2.11	0	Co	rg2	gg4	2.9	2.9	0
Gn	gg1	pg3	2.85	0	0	Hs	gg3	pg3	0	0	2.57	Gp	gg2	pg3	2.35	0	0	Co	gg1	pg1	1.99	0	0
Gn	gg1	pg4	1.21	0	2.93	Hs	gg3	pg4	2.5	2.19	0	Gp	gg2	pg4	1	0	0	Co	gg1	pg2	2.29	2.29	0
Gn	gg2	pg2	2.48	2.48	0	Hs	gg4	pg1	0.26	2.77	2.77	Gp	gg3	pg1	0	2.98	0	Co	gg1	pg3	2.53	0	0.45
Gn	gg2	pg4	1.9	0	0	Hs	gg4	pg2	2.37	0	0	Gp	gg3	pg2	2.74	0	0	Co	gg2	pg1	1.33	2.16	2.16
Gn	gg3	pg1	2.03	2.03	0	Hs	gg4	pg3	2.71	0	0	Gp	gg3	pg3	0	2.22	0	Co	gg2	pg2	2.3	2.3	0
Gn	gg3	pg3	0.25	2.86	2.86	Hs	po1	dg1	0	0	2.09	Gp	gg3	pg4	2	2.05	0	Co	gg2	pg3	2.1	2.1	0
Gn	gg3	pg4	2.8	0	0	Hs	po1	dg3	0	0	2.91	Gp	gg4	pg1	2.46	2.46	0	Co	gg2	pg4	0	0	2.28

Continue Table VI. Amount of natural gas of type g produced in time period t transferred from node i to node j (y_{ijt}^{g})

Gas type(g)	source Node(i)	Destination node(j)	Period(t)			Gas type(g)	source Node(i) 1	Destination node(j)	Period(t)			Gas type(g)	source Node(i)	Destination node(j)	Period(t)			Gas type(g)	source Node(i) 1	Destination node(j)	Period(t)		
			1	2	3				1	2	3				1	2	3				1	2	3
Gn	gg4	pg1	2.16	2.55	0	Hs	po1	dg4	0	0	1.96	Gp	gg4	pg2	1.52	0	0	Co	gg3	pg1	2.85	2.85	0
Gn	gg4	pg2	0	2.45	0	Hs	po3	dg1	2.53	0	0	Gp	gg4	pg3	0	0	2.4	Co	gg3	pg3	2.84	2.84	0
Gn	gg4	pg3	2.14	0	0	Hs	po3	dg2	0.01	0	0	Gp	gg4	pg4	2.65	2.65	0	Co	gg3	pg4	0.21	2.83	0
Gn	gg4	pg4	0	2.59	2.59	Hs	po3	dg3	2.54	2.41	0	Gp	pg1	dg1	0.13	1.51	0	Co	gg4	pg1	2.43	0	0
Gn	pg1	dg1	1.47	0	0	Hs	po4	dg1	0	0	2.68	Gp	pg1	dg2	0	2.96	0	Co	gg4	pg2	0.33	2.41	0
Gn	pg1	dg2	2.13	1.86	0	Hs	po4	dg2	0	0	0.11	Gp	pg1	dg4	2.2	2.2	0	Co	gg4	pg3	0	2.37	0
Gn	pg1	dg3	0	2.94	1.97	Hs	po4	dg3	0	0.66	0	Gp	pg2	dg1	2.31	0	0	Co	gg4	pg4	2.15	0	0
Gn	pg2	dg1	2.5	0	0	Hs	po4	dg4	0	2.54	2.54	Gp	pg2	dg2	0.85	2.75	0	Co	pg1	dg1	0	2.65	0
Gn	pg2	dg2	0.04	2.47	0	Hs	po5	dg1	0	0.91	0	Gp	pg2	dg3	2.98	0	0	Co	pg1	dg2	2.59	1.85	0
Gn	pg2	dg3	2.27	1.9	0	Hs	po5	dg2	0	2.76	0	Gp	pg2	dg4	2.43	1.63	0	Co	pg1	dg3	2.09	0.08	0
Gn	pg3	dg1	2.22	0	0	Hs	po5	dg3	0	2.54	0	Gp	pg3	dg1	2.04	1.26	2.24	Co	pg1	dg4	2.26	0	1.93
Gn	pg3	dg2	0	2.44	0	Hs	pg1	dg1	2.19	0	2.51	Gp	pg3	dg2	0	0.76	0	Co	pg2	dg1	0	1.41	0
Gn	pg3	dg3	2.54	0.2	2.47	Hs	pg1	dg2	2.36	2.36	0	Gp	pg3	dg3	1.86	0	0	Co	pg2	dg2	0.97	2.78	0
Gn	pg3	dg4	0	0	0.14	Hs	pg1	dg3	0	0	2.16	Gp	pg4	dg1	2.55	0	2.76	Co	pg2	dg3	0	2.19	0
Gn	pg4	dg1	2.38	0	0	Hs	pg1	dg4	0	2.06	0	Gp	pg4	dg2	0	1.46	0	Co	pg2	dg4	2.99	0	0
Gn	pg4	dg2	0	0.87	0	Hs	pg2	dg1	2.17	0	2.17	Gp	pg4	dg3	2.22	0	0	Co	pg3	dg1	0	2.24	0
Gn	pg4	dg3	2.35	1.34	2.73	Hs	pg2	dg2	2.76	1.54	2.76	Gp	pg4	dg4	0	2.42	0	Co	pg3	dg2	2.55	1.95	0
Gn	pg4	dg4	0	0	2.42	Hs	pg2	dg3	0	0	1.77	Hs	n1	gg3	0.65	1.43	1.2	Co	pg3	dg3	1.72	2.49	0
Gp	n1	gg3	0	1.43	0	Hs	pg2	dg4	1.94	0.54	0	Hs	n2	gg1	0	1.26	0	Co	pg3	dg4	2.21	0	0.4
Gp	n1	gg4	0.6	0	1.2	Hs	pg3	dg1	1.78	0	2.43	Hs	n2	gg3	0.47	0	0.54	Co	pg4	dg2	0.47	0	0
Gp	n2	gg1	0	0	0.28	Hs	pg3	dg2	0.52	1.73	0	Hs	n2	gg4	0	0	0.43	Co	pg4	dg3	0.07	2.48	0
Gp	n2	gg2	0	0.9	0	Hs	pg4	dg1	2.48	0	1.55	Co	pg4	dg3	1.51	0	2.15	0	0	0	٠	٠	0

Tables VII and VIII represent the shortage of oil and gas at different demand points, respectively. As shown in these tables, despite Enhanced Oil Recovery, the demand for oil is not satisfied in any of the periods, resulting in a consistent shortage in this regard. Similar conditions are used for gas demand points. Furthermore, the extra production of oil and gas for all periods under these conditions equals zero.

Table VII. Crude oil shortage of type o in time period t below the demand at node j (x_{jt}^{o-})

Demand point	Period		
	1	2	3
do1	6.658313	10.87426	27.59692
do2	22.50531	25.8216	20.51908
do3	19.94677	19.0981	7.402859
do4	29.84801	6.391676	23.18036

Table VIII. Natural gas shortage of byproduct g in time period t bellow the demand at node j (y_{jt}^{g-})

Gas type	Demand point	Period			Gas type	Demand point	Period		
		1	2	3			1	2	3
Gn	dg1	3.156265	16.61016	15.02641	Hs	dg1	1.23495	10.27609	10.41089
Gn	dg2	20.513	14.01286	10.91722	Hs	dg2	2.469724	16.12369	12.87526
Gn	dg3	13.96902	1.936239	11.02446	Hs	dg3	22.30495	10.0107	17.35922
Gn	dg4	16.29727	8.962897	8.307459	Hs	dg4	13.9845	17.49496	13.38098
Gp	dg1	5.980831	7.776982	6.198722	Co	dg1	23.29533	2.543137	14.06083
Gp	dg2	19.40333	11.15849	16.39044	Co	dg2	12.4584	3.177585	18.06209
Gp	dg3	1.462315	22.07855	23.33871	Co	dg3	9.41575	1.270179	12.25031
Gp	dg4	11.16153	6.433564	9.78362	Co	dg4	12.03277	9.223881	7.741645

Figures II, III, and IV serve as detailed visual representations of the oil and gas flow dynamics across different time periods within the supply chain network. Each figure depicts the sequential movement of resources, with distinct arcs indicating the flow between corresponding nodes. Notably, green arcs denote gas flow, while black arcs represent oil flow, offering a clear differentiation between the two commodities. As can be seen, in all the time periods, oil reservoir ro1 sends oil to all oil-gas separation centers. Similarly, oil reservoir ro2 sends oil to all gas-oil separation centers. Then, the oil separated in GOSPs goes to the oil gathering center go2, and other oil gathering centers do not have any input or output during this period. The processed oil is sent to oil processing center po3 and then to oil demand point do1. In addition, gas flow is displayed here.

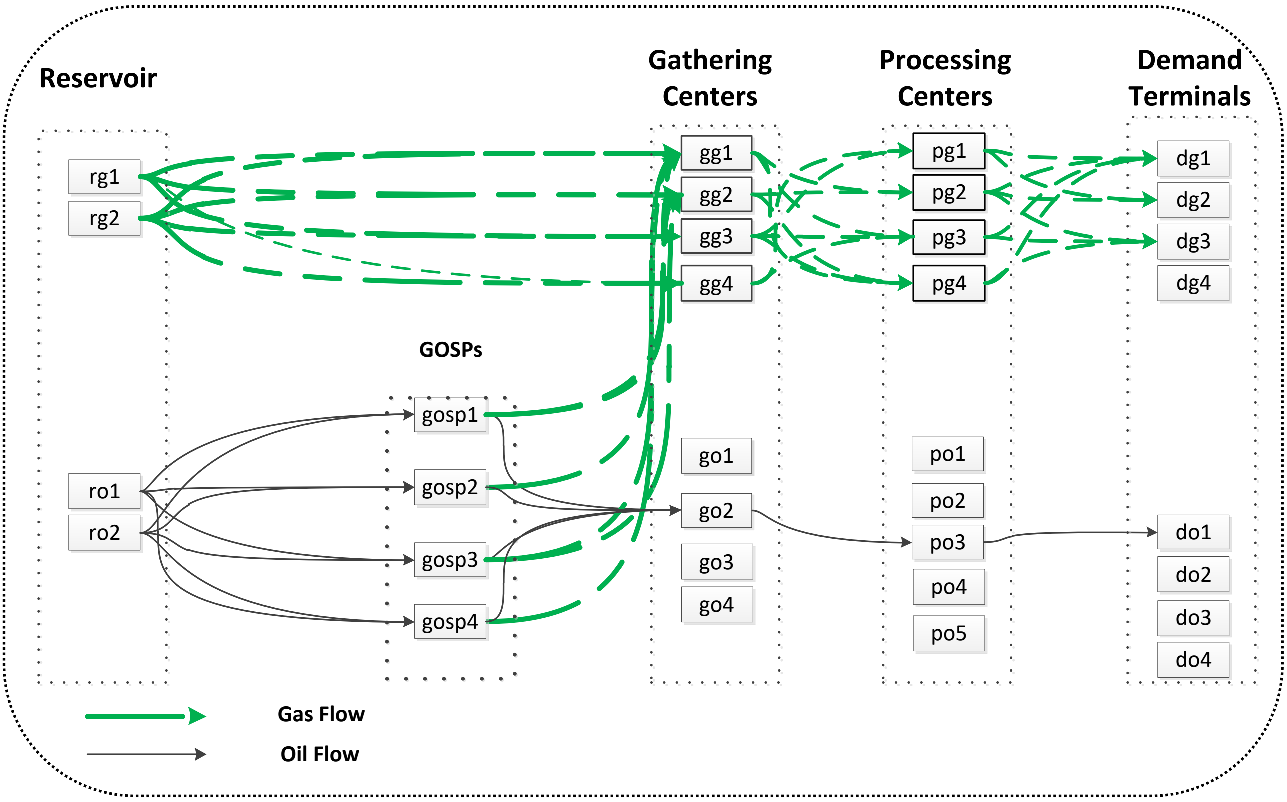

Fig. 2. Oil and gas network in the sample problem (t=1)

Figure 3 showcases the evolving flow patterns in the subsequent time period, with oil from GOSPs now distributed to different oil gathering centers, facilitating processing and eventual delivery to demand points. Notably, the utilization of oil processing centers reflects the strategic allocation of resources to optimize operational efficiency and meet demand requirements. At the time period 2, the oil separated GOSPs go to oil gathering centers go1, go3, go4, and the oil gathering center go2 do not have any input or output during this period. Then the processed oil is sent to oil processing center po4 and po5 and then to oil demand points do3 and do4. Note that the processing center po3 has no inflow in period 2 and uses the oil remained from the inflow that occurred at the time period 1 as outflow to the demand point do3 at time period 2.

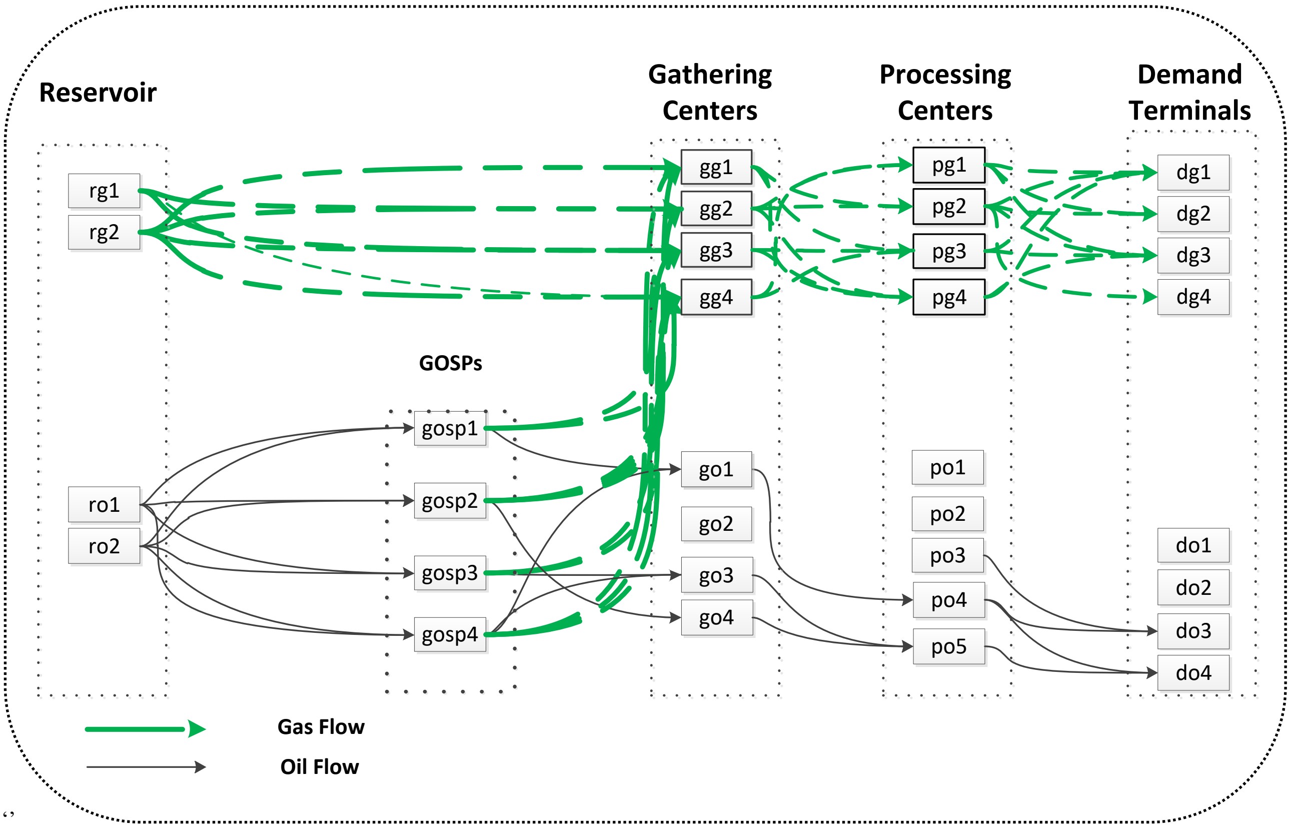

Fig. 3. Oil and gas network in the sample problem (t=2)

In the final depiction in Figure 4, at the time period 3, the oil from GOSPs goes to oil gathering centers go3 and go4 and the oil gathering centers go1 and go2 do not have any input or output. At the next stage, the processed oil is sent to oil processing center po4 and po1 and from there to oil demand point do2 and do3. By visualizing the sequential progression of oil and gas flow across multiple time periods, these figures provide valuable insights into the dynamic nature of supply chain operations and underscore the importance of strategic decision-making in resource management.

Figure 5 provides a comprehensive insight into the trade-off dynamics between profit maximization and depletion rate (D) within the model's objectives. By iteratively adjusting the weight allocated to the profit objective against the depletion rate in the LP-metric function, we discern the intricate interplay between these crucial factors. Notably, the gradual increase in the weight of the profit objective coincides with a proportional rise in the depletion rate, indicative of the complex trade-offs inherent in resource management. This nuanced relationship underscores the critical need for multi-objective modeling techniques to effectively navigate and optimize conflicting objectives, ensuring sustainable resource utilization and strategic decision-making.

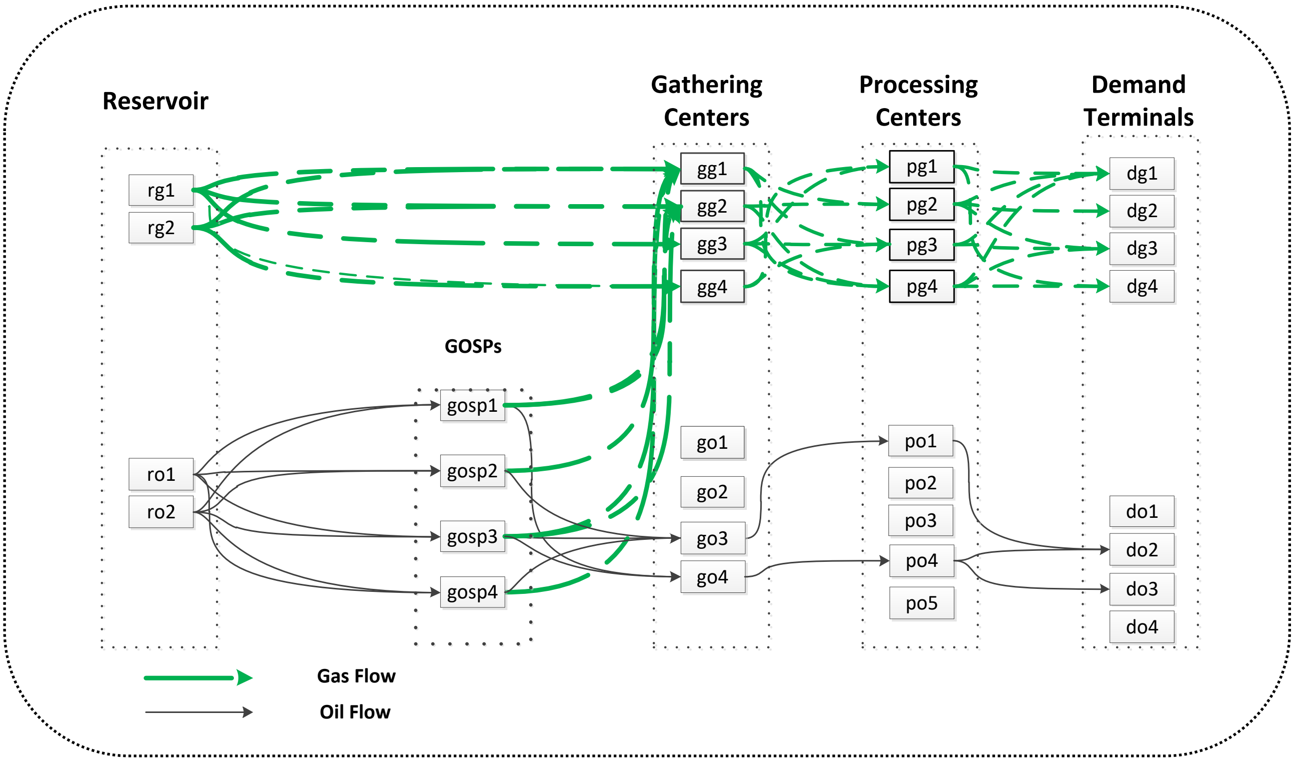

Fig. 4. Oil and gas network in the sample problem (t=3)

Figure 5 serves as a visual representation of the strategic decision-making process, illustrating how choices aimed at maximizing profit can impact the rate at which resources are depleted. As stakeholders aim to strike a balance between economic viability and environmental sustainability, this depiction highlights the inherent challenges and complexities involved. Moreover, it underscores the importance of adopting holistic approaches that account for multiple objectives simultaneously, enabling informed decision-making that considers the long-term implications of resource utilization. Through such comprehensive modeling frameworks, organizations can better navigate the intricate landscape of resource management, ultimately fostering more sustainable and resilient operational strategies.

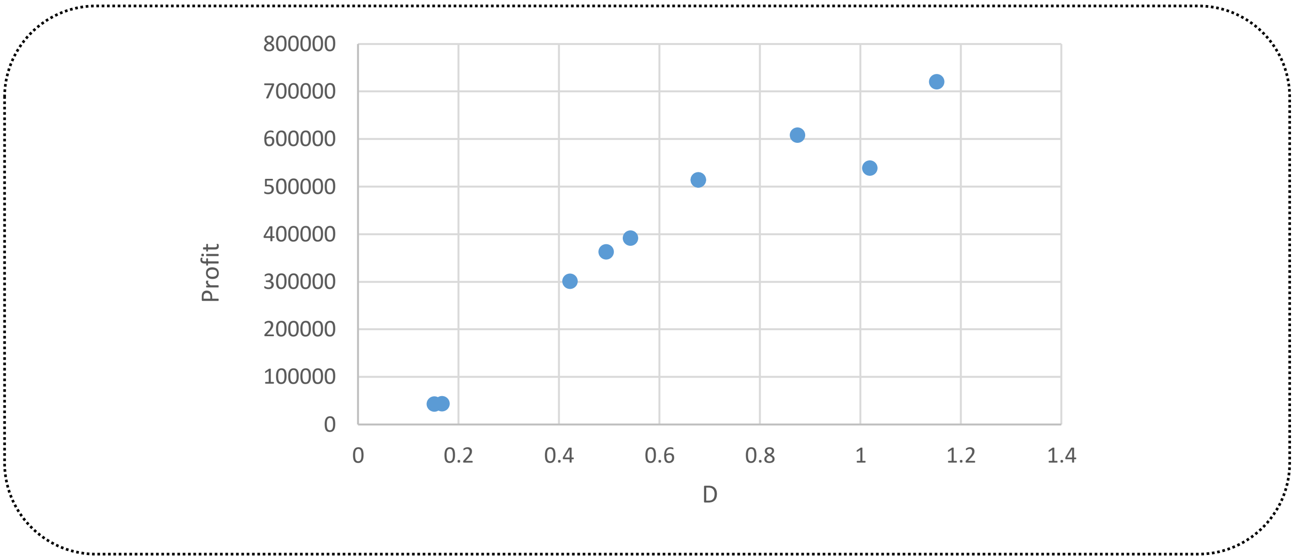

Fig. 5. Objectives Pareto chart

C. Computational efficiency

To evaluate the computational efficiency of the presented model, 15 problems in various dimensions were solved by Baron Solver in the GAMS software. The BARON solver provides an option called "optcr" as relative optimality criterion. This attribute specifies a relative termination tolerance for use in solving all mixed-integer models. Solutions with relative gap of less than the specified optcr are considered (near) optimal solution. We set this parameter at 0.01 in our model. The stop criterion is to reach a relative gap of less than 0.01 or to reach the maximum set time (400 or 600 seconds with respect to the problem required for forming the LP-metric objective function). Table VII indicates the problem-solving results. As shown in this table, small problems (numbers 1-4) were solved in less than 100 seconds. However, an increase in the problem size due to considering longer time horizon has led to a sudden increase in solution time (Fig. 4) such that problems 5-11 can only be solved in about 700 seconds, and problems 12 and 13 can be solved in less than 1100 seconds. Finally, problems 14 and 15 cannot be solved in a reasonable time.

Table VIII. Solving problems of different dimensions

Problem No.	Number of oil reservoir	Number of gas reservoir	Number of GOSP	Number of demand point	Number of gas plant	Number of oil plant	Number of gas collection centers	Number of oil collection centers	Time horizon	Calculation of profit * and D * in single-objective functions for use in LP-Metric function				LP-metric approach					Total solution time
										Profit*	Relative gap	Solution time	D*	LP-metric function	Profit	Relative gap	Solution time	D	
1	2	2	4	3	2	2	2	2	2	170987	0	23	1	0/019	165857	0.048	3	0.304	26
2	2	2	2	3	2	2	2	2	3	241186	0.041	46	1	0/057	220619	0.048	7	0.508	53
3	2	2	4	3	2	2	2	2	3	252399	0.038	66	1	0/057	231220	0.476	9	0.497	75
4	2	2	3	3	2	2	2	2	3	236737	0.05	87	1	0/044	218740	0.048	4	0.444	91
5	2	2	3	3	2	2	2	2	4	316490	0.05	167	1	0/072	286038	0.048	11	0.567	178
6	2	2	2	3	2	2	2	2	4	266255	0.05	95	0/665	0/104	274745	0.048	115	0.647	210
7	2	2	3	3	2	2	2	2	5	357453	0.024	284	1	0/094	311570	0.048	14	0.636	298
8	2	2	2	3	2	2	2	2	10	453684	0.007	312	1	0/232	313265	0.048	34	0.884	346
9	2	2	2	3	2	2	2	2	15	601420	0.014	529	1	0/305	357073	0.476	88	0.931	617
10	2	2	2	3	2	2	2	2	12	542960	0.01	572	1	0/264	348760	0.048	69	0.9	641
11	2	2	2	3	2	2	2	2	18	517796	0.007	502	1	0/26	31394	0.048	168	0.902	670
12	2	2	2	3	2	2	2	2	5	300902	0.075	401	0/897	0/138	312219	0.115	410	0.842	811
13	2	2	3	3	2	2	2	2	6	342107	0.05	464	0/997	0/135	271743	0.186	631	0.714	1095
14	2	2	3	3	2	2	2	2	15	-	-	-	-	-	-	-	-	-	-
15	2	2	2	3	2	2	2	2	16	-	-	-	-	-	-	-	-	-	-

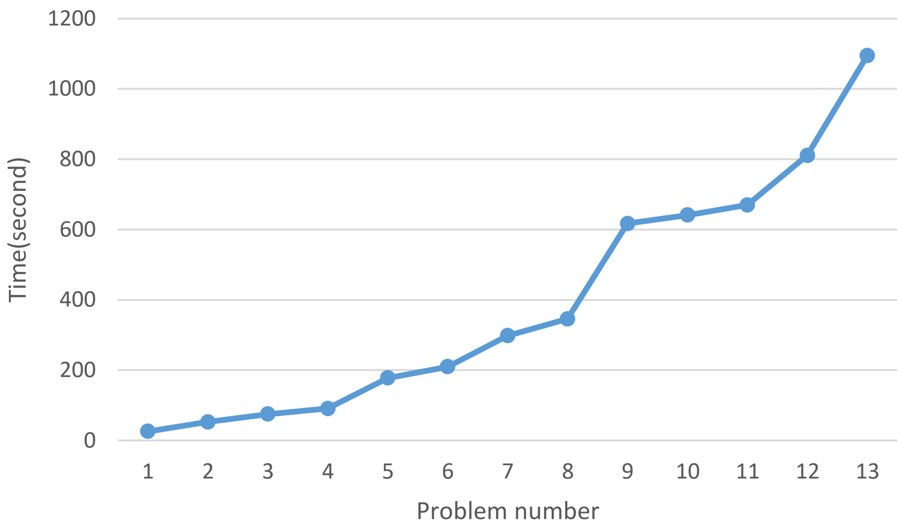

Fig. 4. Time required for solving problems

V. CONCLUSION

The optimization of oil industry activities across upstream, midstream, and downstream sectors is pivotal for effective supply chain management (SCM) at both strategic and operational levels. While existing literature has predominantly focused on downstream activities because of neglecting the upstream sector and its interplay with the midstream segment, this study addresses this gap comprehensively.

Our research contributes significantly by integrating Enhanced Oil Recovery (EOR) operations into the optimization of oil field development and SCM of crude oil and associated gas across upstream and midstream sectors. By formulating the problem as a mixed integer nonlinear program and leveraging the BARON Solver in GAMS software, we provide a robust solution framework.

The strength of the proposed methodology lies in its comprehensive approach to integrating Enhanced Oil Recovery (EOR) operations into the optimization of oil field development and supply chain management (SCM) across upstream and midstream sectors. By considering both strategic and tactical decisions, our methodology offers a holistic solution framework for the complex challenges faced by the oil industry.

The paper's key strengths revolve around its comprehensive and integrative approach to optimizing activities across the oil industry's upstream, midstream, and downstream sectors. A major strength is addressing a significant gap in existing literature, which predominantly focuses on downstream activities and often neglects the upstream sector and its interaction with the midstream segment. This study effectively incorporates Enhanced Oil Recovery (EOR) operations into the optimization process for oil field development and the supply chain management (SCM) of crude oil and associated gas, offering a more holistic view of the industry's supply chain dynamics.

Another notable strength is the methodological rigor and robustness demonstrated by formulating the problem as a mixed integer nonlinear program and utilizing the BARON Solver within the GAMS software. This combination ensures high accuracy and robustness in solving complex optimization problems, enabling the simultaneous consideration of multiple objectives and constraints. This allows decision-makers to balance economic, environmental, and technical considerations effectively. The methodology's efficiency is evidenced by its ability to solve small-scale problems in under 100 seconds with a relative gap of less than 0.01. However, the paper also acknowledges scalability challenges with larger problems, suggesting future exploration of heuristic and metaheuristic methods to enhance scalability further. Overall, the study's integrative approach, rigorous methodology, and practical implications for the oil industry's SCM optimization are its key strengths.

Furthermore, the use of a mixed integer nonlinear programming model, coupled with the powerful BARON Solver in GAMS software, ensures robustness and accuracy in solving the optimization problem. This approach allows for the simultaneous consideration of multiple objectives and constraints, enabling decision-makers to make informed choices that balance economic, environmental, and technical considerations.

Through extensive testing on 15 problems of varying dimensions, our methodology demonstrates promising efficiency, with small-scale problems solvable in under 100 seconds and a relative gap of less than 0.01. However, scalability challenges arise with larger problem sizes, prompting future investigations into heuristic and metaheuristic methods for scalability enhancement.

Other future research directions may include:

- Applying the model to new EOR methods: While there are currently several EOR methods in use, such as water flooding, gas injection, and thermal methods, there is always room for innovation. Future research could focus on applying the model to new EOR techniques that may be more effective, efficient, and environmentally friendly.
- Investigating the impact of EOR on the environment: EOR methods can have a significant impact on the environment, particularly when it comes to greenhouse gas emissions. Future research could explore the environmental impact of EOR methods and look for ways to minimize their negative effects.
- Optimizing the supply chain: This research focuses on integrated modeling of the oil and gas supply chain, but future research could take this a step further by optimizing the supply chain using advanced analytics and artificial intelligence techniques. This could involve developing models to predict demand, optimize inventory, and minimize supply chain disruptions.
- Incorporating renewable energy sources: With the increasing focus on renewable energy, future research could explore ways to integrate renewable energy sources into the oil and gas supply chain. For example, researchers could investigate the feasibility of using solar or wind power to generate the electricity needed for EOR methods.
- Addressing economic and regulatory challenges: The oil and gas industry is subject to a wide range of economic and regulatory challenges, and future research could explore ways to address these challenges. For example, researchers could investigate the impact of changing oil prices on the supply chain or explore ways to navigate the complex regulatory environment surrounding the industry.

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