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Crude Oil Distribution Optimization: A Multi-Objective Mathematical Model Aligned with Sustainable Development Goals

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ABSTRACT

Crude oil, serving as the world's primary energy source, plays a pivotal role in shaping a nation's economic standing and global reputation. The intricate orchestration of its supply chain stands as a paramount global concern. In this research, we present a multi-objective, multi-period mathematical programming model tailored for the design of an upstream oil supply chain network. Our model is intricately aligned with the principles of sustainable development, simultaneously optimizing economic, environmental, and social objectives. Our approach to sustainability encompasses economic and environmental dimensions. We minimize total costs while addressing the pressing issue of greenhouse gas emissions. Furthermore, we uphold the social aspect of sustainability by maximizing job creation opportunities. Our comprehensive model encompasses various components, including crude oil production and gas extraction centers, oil storage facilities, processing centers, and oil demand terminals. To tackle the multi-objective nature of the model, we employ a solution approach rooted in fuzzy concepts. Numerical results substantiate the model's robustness and underscore the paramount importance of integrating sustainable development goals into the design of crude oil supply chains. Moreover, this model offers a strategic framework for upstream oil industry companies seeking to develop sustainable crude oil supply chain management strategies.

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1. Introduction

Crude oil stands as a significant energy source, playing a pivotal role in economic development. According to some energy experts, global energy demand is projected to surge by up to 100% between

2020 and 2030 (Ma and Khayatnezhad, 2021, Shafipour-Omrani et al. 2021). The management of the crude oil supply chain is an immensely intricate undertaking, encompassing the development of oil fields, the oversight of crude oil transmission and processing operations, and the distribution of the resulting products (Mirzagoltabar et al., 2021).

This intricate process commences by transferring crude oil from production units' tanks to separation facilities that extract gases from the oil. Subsequently, the crude oil needs to be transported to storage facilities, and from there, it's directed to sweetening facilities for the removal of hydrogen sulfide and other gases. Ultimately, the refined sweet crude oil and its gas by-products are distributed among terminals, from where the products are dispatched to customers (Attia et al., 2019). Given the heavy reliance of numerous industries, including chemical, health, and pharmaceutical, on oil and petroleum products, establishing efficient oil supply chains is paramount in managing this substantial demand (Wang et al., 2019).

In our increasingly complex world, demand management plays a pivotal role in the strategic planning of energy sectors within oil-rich nations. This is primarily due to the fact that oil stands as one of the foremost determinants and pillars of economic security for these countries. Consequently, estimating the oil demand function and analyzing its evolution over time emerge as critical components in achieving this overarching objective. Simultaneously, the rapid expansion of global economic growth and the emergence of new economic powerhouses have intensified the pressing need for energy resources. Within this context, the present article endeavors to scrutinize the nexus between the energy demands of these nations, particularly their reliance on crude oil as a primary energy source, and their economic growth. The central hypothesis of this study posits a direct correlation between the demand for crude oil and economic growth (Tao et al., 2022; de Jongh, 2020).

Sustainable development can be defined as a holistic approach encompassing the economic, social, and environmental facets of business operations. In the context of supply chains, this discourse centers around the incorporation of environmental and social considerations into supply chain planning and management, ensuring their alignment with sustainability imperatives. Given the extensive and ubiquitous use of oil-based products in economic and social activities, sustainability assumes paramount importance within the oil industry. The establishment of a sustainable oil supply chain has the potential to significantly mitigate the adverse impacts associated with supply chain operations (Florescu, 2019).

Over the years, researchers have proposed a variety of mathematical models for the planning of oil supply chain networks. For instance, Farahani et al. (2017) introduced a mixed-integer mathematical programming model for upstream oil supply chains to maximize profits within the supply chain. In a study conducted by Beiranvand et al. (2018), they devised a single-objective mathematical model for crude oil supply chain planning under uncertain demand, again with the goal of profit maximization. Moradinasab et al. (2018) presented a multi-objective mathematical model for the sustainable planning of oil supply chains, spanning the upstream, midstream, and downstream sectors in alignment with sustainability requirements. Attia et al. (12) developed a multi-objective model for crude oil supply chain planning, with the objective of minimizing production, transportation, and processing costs, while also reducing reservoir exploitation rates. Wang et al. (2019) presented an integer programming model for downstream oil supply chain planning, specifically addressing pipeline routing and product distribution. Yuan et al. (2019) devised a downstream oil supply chain model aimed at minimizing the costs associated with building refineries, storage facilities, and pipelines, while accounting for potential modifications to pipeline networks. Lima et al. (2019) proposed a model for downstream oil supply chain planning under conditions of uncertainty, striving to maximize supply chain profits through logistics optimization. A study by Yuan et al. (2020) delved into the impact of oil import disruptions on downstream oil supply chain operations. Zhou et al. (2020) introduced a multi-objective integer programming model to minimize overall supply chain costs, encompassing facility construction, pipelines, pumps, maintenance costs, and the reduction of carbon dioxide emissions.

A glance at the literature on oil supply chains reveals that most articles have focused on either midstream or downstream oil supply chains, with only limited consideration of integrating sustainability objectives into supply chain planning. The latest contributions in this field come from the work of Goli et al. (2019; 2021) and Pahlavan et al. (2021), who have developed meta-heuristic approaches to address distribution problems with a specific emphasis on reducing environmental pollution. Additionally, Xu et al. (2022) have introduced a multi-objective model for refined oil distribution, simultaneously optimizing costs and customer satisfaction. These researchers have also devised a multi-objective particle swarm optimization algorithm for solving this model.

2. Problem Description and Mathematical Model

Following the Industrial Revolution, the world has borne witness to the remarkable growth of organizations, both in terms of their size and complexity. The once-modest workshops of skilled artisans have given way to the colossal corporations of the modern era. Undoubtedly, these developments have borne significant fruit. However, alongside the multitude of advantages that this increase in expertise has brought, it has also ushered in new challenges that many organizations continue to grapple with. These challenges include the propensity of individual parts of an organization to seek independent growth to attain their objectives, often guided by their unique value systems, all without comprehensive coordination within the overarching organization.

As expertise and organizational complexity rise, the allocation of available resources among various departments becomes increasingly challenging in the pursuit of overall efficiency. The quest to find better ways to address such challenges laid the foundation for the emergence of operational research.

Almost any decision-making problem can be categorized as an operational research issue. Operational research pertains to critical aspects of managerial decision-making. It comprises a collection of techniques and methodologies drawn from mathematics and other scientific disciplines, proving profoundly influential in enhancing management decisions.

This section introduces a proposed multi-objective, multi-period optimization model for the design of crude oil supply chains. In this model, the assumption is that crude oil travels from production wells to oil/gas separators and then to crude oil storage units, before making its way to processing centers and demand terminals. The model further assumes that the capacity of oil/gas separators and processing facilities is predetermined. Likewise, the number and size of demands are known, with the imperative that all demands must be fully met. Pipelines facilitate the transmission of oil between different components of the supply chain. The model's primary objectives encompass determining optimal flow rates between these components, deciding whether to expand the capacity of separation and processing facilities, ascertaining the optimal capacities of storage units and demand terminals, and defining the output of each production well throughout the planning period. To incorporate the principles of sustainable development into the model, the objective function is formulated as a blend of terms that represent economic, social, and environmental dimensions.

Sets

W	Set of production wells
J	Set of oil/gas separators
K	Set of storage units
M	Set of processing facilities
D	Set of demand terminals
T	Set of time periods
DR	Set of crude oil production technologies

Parameters

p_j	Efficiency of oil/gas separator j
p_m	Efficiency of processing facility m
c_j	Capacity of oil/gas separator j
cp_m	Capacity of processing facility m
ce_j	Expansion capacity of oil/gas separator j
ce_m	Expansion capacity of processing facility m
iv_{kt}	Inventory of storage unit k at the beginning of period t
iv_{dt}	Inventory of demand terminal d at the beginning of period t
ec_{wt}	Unit cost of crude oil production in production well w in period t

pc_{jt}	Unit cost of separation in oil/gas separator j in period t
tc_{wjt}	Unit cost of oil transmission from production well w to oil/gas separator j in period t
tk_{jkt}	Unit cost of oil transmission from oil/gas separator j to storage unit k in period t
tm_{kmt}	Unit cost of oil transmission from storage unit k to processing facility m in period t
td_{mdt}	Unit cost of oil transmission from processing facility m to demand terminal d in period t
cr_{wj}	Capacity for oil transmission from production well w to oil/gas separator j
cd_{jk}	Capacity of oil transmission line from oil/gas separator j to storage unit k
ck_{km}	Capacity of oil transmission line from storage unit k to processing facility m
cm_{md}	Capacity of oil transmission line from processing facility m to demand terminal d
d_{dt}	Demand of terminal d in period t
coj	Cost of capacity expansion of oil/gas separator j
com	Cost of capacity expansion of processing facility m
pu_w	Greenhouse gas emission per unit of crude oil produced in production well w
pu_j	Greenhouse gas emission due to capacity expansion of oil/gas separator j
pu_m	Greenhouse gas emission due to capacity expansion of processing facility m
job_w	Number of job opportunities created per unit of crude oil produced in production well w
job_j	Number of job opportunities created due to capacity expansion of oil/gas separator j
job_m	Number of job opportunities created due to capacity expansion of processing facility m
CAP_w	Maximum exploitation capacity of production well w
CAP_{dr}	Maximum production capacity of crude oil production technology dr

Variables

$caps_k$	Capacity of storage unit k
$caps_d$	Capacity of terminal d
Tx_{wjt}	The total amount of crude oil transferred from production well w to oil/gas separator j over the entire planning period
xw_{wjt}	The amount of crude oil transferred from production well w to oil/gas separator j in period t
xk_{jkt}	The amount of crude oil transferred from oil/gas separator j to storage unit k in period t
Xm_{kmt}	The amount of crude oil transferred from storage unit k to processing facility m in period t
xd_{mdt}	The amount of crude oil units transferred from processing facility m to terminal d in period t
y_j	=1 if the capacity of oil/gas separator j is expanded, =0 otherwise
y_m	=1 if the capacity of processing facility m is expanded, =0 otherwise

Objective function and problem constraints

$$\min z_1 = \sum_w \sum_j \sum_t ec_{wt} x_{wjt} + \sum_w \sum_j \sum_t pc_{jt} x_{wjt} + \sum_j \sum_k \sum_t tk_{jkt} x_{jkt} + \sum_w \sum_j \sum_t tc_{wjt} x_{wjt} + \sum_k \sum_m \sum_t tm_{kmt} xm_{kmt} + \sum_m \sum_d \sum_t td_{mdt} xd_{mdt} + \sum_j cojy_j + \sum_m com\, y_m \quad (1)$$

$$min\ z_2 \sum_w \sum_j \sum_t xw_{wjt} pu_w + \sum_j pu_i y_j + \sum_m pu_m y_m \quad (2)$$

$$min\ z_3 \sum_w \sum_j \sum_t job_w x_{wjt} + \sum_j job_j \times y_j + \sum_m job_m y_m \quad (3)$$

subject to

$$Tx_{wjt} = Tx_{wjt-1} + x_{wjt} \qquad \forall w, j, t \quad (4)$$

$$x_{wjt} \leq CAP_w \qquad \forall w, j, t \quad (5)$$

$$\sum_w xw_{wjt} \leq CAP_{dr} \qquad \forall dr, j, t \quad (6)$$

$$\sum_w p_j\, xw_{wjt} = \sum_k xk_{jkt} \qquad \forall j, t \quad (7)$$

$$\sum_k xk_{jkt} = \sum_k xm_{kmt} \qquad \forall j, m, t \quad (8)$$

$$\sum_k p_m\, xm_{kmt} = \sum_d xd_{mdt} \qquad \forall m, t \quad (9)$$

$$\sum_w xw_{wjt} \leq c_j + ce_j \times y_j \qquad \forall j, t \quad (10)$$

$$\sum_k xm_{kmt} \leq cp_m + ce_m \times y_m \qquad \forall m, t \quad (11)$$

$$\sum_k xk_{jkt} + iv_{kt} \leq caps_k \qquad \forall k, t \quad (12)$$

$$\sum_m xmd_{mdt} + iv_{dt} \leq capd_d \qquad \forall d, t \quad (13)$$

$$xw_{wjt} \leq cr_{wj} \qquad \forall m, j, t \quad (14)$$

$$xk_{jkt} \leq cd_{jk} \qquad \forall j, k, t \quad (15)$$

$$xm_{kmt} \leq ck_{km} \qquad \forall k, m, t \quad (16)$$

$$xd_{mdt} \leq cm_{md} \qquad \forall m, d, t \quad (17)$$

$$\sum_m xmd_{mdt} = d_{dt} \qquad \forall d, t \quad (18)$$

$$xw_{wjt} \geq 0, xk_{jkt} \geq 0, xd_{mdt} \geq 0, xm_{kmt} \geq 0 \quad (19)$$

$$Tx_{wjt} \geq 0, caps_k \geq 0, caps_k \geq 0, y_m, y_j \in \{0,1\} \quad (20)$$

The objective function (1) serves to minimize the overall network cost throughout the entire planning horizon. This encompasses the costs associated with crude oil production, the expenses incurred in transporting oil between facilities, and the outlays linked to expanding the capacities of oil/gas separators and processing facilities. The objective function (2) is geared toward the minimization of greenhouse gas emissions stemming from both production operations and the capacity expansion of oil/gas separators and processing facilities. Meanwhile, the objective function (3) seeks to maximize the generation of employment opportunities across the network.

Constraint (4) calculates the cumulative volume of oil transferred from wells to separators over the entire planning period. Constraints (5) and (6) set limits on the volume of oil transferred from wells to oil/gas separators in period t, based on the well's exploitation capacity and the capacity of the production technology (equipment), respectively. Constraints (7), (8), and (9) ensure the equilibrium of flow between oil/gas separators, storage units, processing facilities, and terminals.

Constraints (10) and (11) impose constraints on the inflow to oil/gas separators and processing facilities, respectively. Similarly, constraints (12) and (13) restrict the inflows to storage units and terminals, respectively. Constraints (14) through (17) impose limitations on the flow between wells, oil/gas separators, storage units, processing facilities, and terminals in accordance with the capacities of transmission lines.

Constraint (18) guarantees the complete satisfaction of the entire demand. Inequalities (19) and (20) define the boundaries and limitations of the variables involved in the model.

3. Solution Method

In today's landscape, optimization challenges manifest themselves effectively across various domains, encompassing transportation, investments, location selection, network design, planning, and scheduling (Babaeinesami et al. 2022, Pourhassan et al. 2023). Typically, the initial description of practical problems relies on articulating a set of logical propositions and translating them into a mathematical model (Daneshvar et al. 2023). Consequently, expressing a problem in the form of a mathematical model stands as a pivotal step in the practical application of optimization techniques (Ghasemi et al. 2023).

Complex, large-scale problems often necessitate a collaborative effort by a team of experts possessing a diverse array of skills (Ghasemi et al. 2022, Momenitabar et al. 2022). Many organizational predicaments, for instance, encompass economic, social, political, engineering, natural, biological, and psychological dimensions (Ghasemi et al. 2021). While it is impractical for an individual to specialize in all these disciplines, the presence of a diverse group enables a comprehensive examination and analysis of the problem from various angles, each scrutinized by experts in their respective fields (Goodarzian et al. 2023, Momenitabar et al. 2023). This multifaceted approach enhances the likelihood of finding optimal solutions to the problem at hand.

The formulated model is tackled using the fuzzy solution method developed by Torabi and Hassini (2008). This approach involves transforming the multi-objective problem into a single-objective one by defining membership functions for each objective. The method encompasses the following sequential steps.

Within this model, various metrics are applicable, such as the Lp metric where $1 \leq p \leq \infty$. Another method categorized as a fuzzy interactive approach is highly effective, as it allows for the consideration of decision-maker preferences interactively. Torabi and Hassini (2008) introduced an enhanced aggregation function designed to convert a multi-objective model into a single objective, thereby ensuring the identification of only Pareto-optimal (i.e., efficient) solutions.

Step 1: Obtaining the positive ideal solution (PIS) and negative ideal solution (NIS) for each objective function.

$$Z_1^{PIS} = \min \ Z_1, Z_1^{NIS} = \max \ Z_1 \tag{21}$$

$$Z_2^{PIS} = \min \ Z_2, Z_2^{NIS} = \max \ Z_2 \tag{22}$$

$$Z_3^{PIS} = \max \ Z_3, Z_3^{NIS} = \min Z_1 \tag{23}$$

Step 2: Determining the membership function of each objective function.

$$\mu_1(f) = \begin{cases} 1 & if \ Z_1 \leq Z_1^{PIS} \\ \dfrac{Z_1^{NIS} - Z_1}{Z_1^{NIS} - Z_1^{PIS}} & Z_1^{PIS} \leq Z_1 \leq Z_1^{NIS} \\ 0 & Z_1 \geq Z_1^{PIS} \end{cases} \tag{24}$$

$$\mu_2(f) = \begin{cases} 1 & if \ Z_2 \leq Z_2^{PIS} \\ \dfrac{Z_2^{NIS} - Z_2}{Z_2^{NIS} - Z_2^{PIS}} & Z_2^{PIS} \leq Z_2 \leq Z_2^{NIS} \\ 0 & Z_2 \geq Z_2^{PIS} \end{cases} \tag{25}$$

$$\mu_3(f) = \begin{cases} 1 & if \ Z_3^{PIS} \leq Z_3 \\ \dfrac{Z_3 - Z_3^{NIS}}{Z_3^{PIS} - Z_3^{NIS}} & Z_3^{NIS} \leq Z_3 \leq Z_3^{PIS} \\ 0 & Z_3^{PIS} \geq Z_3 \end{cases} \tag{26}$$

Step 3: Integrating the objective functions based on the following model

$$max\lambda(f) = \gamma\lambda_e + (1 - \gamma) \sum_n w_n \, \mu_n(f) \tag{27}$$

$$\lambda_e \leq \mu_n(f) \; n = 1,2,3 \tag{28}$$

$$f \in F(f); \; \lambda_e \& \gamma \in [0,1] \tag{29}$$

In these equations, $\mu_n(f)$ is the membership degree of each objective function, λ_e is the minimum membership degree of the objective function, w_n is the relative weight of each objective function, and γ is the compensation coefficient. The above problem is solved by determining the compensation coefficient γ and the relative weights w_n for each objective function.

4. Numerical Results

This section presents the results obtained by solving the model with GAMS. The model was solved for three problems of different sizes, which are shown in Table 1. It should be noted that these problems were generated by picking random values from reasonable ranges for the parameters.

Table 1. Problem instances were generated with the relative weights (0.3, 0.35, 0.35) and the compensation coefficient $\gamma = 0.3$.

Problem	$\|W\|$	$\|J\|$	$\|K\|$	$\|M\|$	$\|D\|$	$\|T\|$	$\|DR\|$	Z_1	Z_2	Z_3
1	2	3	3	3	3	2	2	3331070.791	366046.322	544114.278
2	3	3	4	3	2	2	2	2153713.759	314595.168	444037.839
3	5	3	3	3	5	2	2	2480187.750	294428.624	439279.720

Figure 1 illustrates the set of Pareto solutions for Problem No.3, as detailed in Table 1. This figure has been generated by varying the parameter γ for Problem No.3. Within this visual representation, and it becomes evident that the point at which the current supply chain offers the greatest number of job opportunities coincides with the highest costs and environmental pollution. This observation implies that maximizing job opportunities cannot be achieved without accounting for the impacts of the other two factors, aligning with the fundamental concept of a Pareto optimal solution.

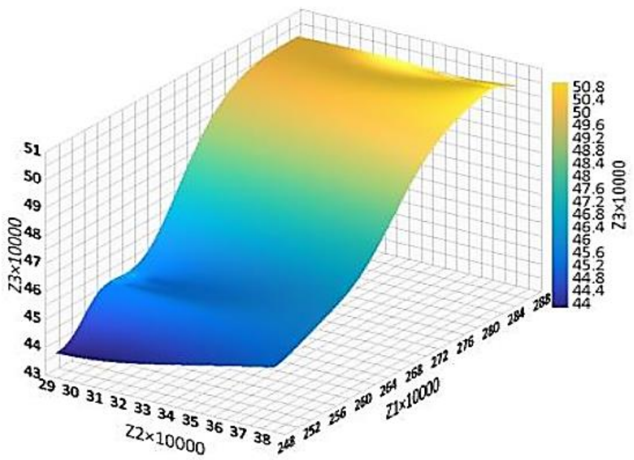

Fig. 1. Pareto optimal front.

The upsurge in total costs is a consequence of the endeavors involved in job creation. This endeavor necessitates infrastructure development, facility expansion, and meticulous planning to enhance production capacity, all of which contribute to elevated costs and increased environmental repercussions. In essence, the results depicted in the figure emphasize the feasibility of augmenting job opportunities while minimizing environmental pollution by investing in advanced technologies. However, this pursuit of advanced technology invariably incurs higher capital costs, which, regrettably, run counter to the objective of minimizing the cost component within the objective function.

Table 2 shows the changes in the objective function values following a change in relative weights at γ=0.3. From Table 2, it can be concluded that any change in the values assigned to relative weights will have a great impact on the objective function and solution. Therefore, these values must be chosen with great care.

Table 2. Changes in the objective function values following a change in relative weights at γ=0.3.

w_n	Z_1	Z_2	Z_3	$\mu_1(f)$	$\mu_2(f)$	$\mu_3(f)$
(0.9, 0.05, 0.05)	2191124.038	363669.621	410153.958	0.580	0.708	0.197
(0.7, 0.2, 0.1)	2393345.645	306007.572	433490.246	0.519	0.960	0.242
(0.45, 0.25, 0.3)	2480187.750	294428.624	439279.720	0.492	1	0.253

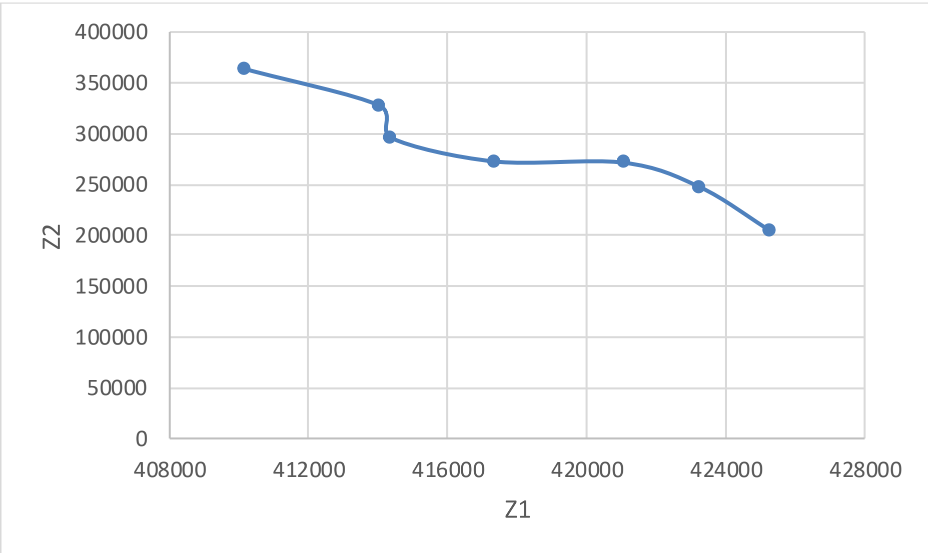

Fig. 2. Comparison of values of the first and second objective functions in Pareto solutions.

In Figure 2, it is evident that an increase in the value of the first objective function corresponds to a decrease in the value of the second objective function. In simpler terms, to achieve better outcomes regarding the second objective, we must be willing to tolerate a certain level of sub-optimality concerning the first objective.

Similarly, as illustrated in Figure 3, the same holds true for the first and third objectives. In this context, pursuing the first objective would compromise the third objective and vice versa. Consequently, these figures underscore that the defined objective functions are in conflict with each other, necessitating optimization through multi-objective optimization methods, much like the approach employed in this paper.

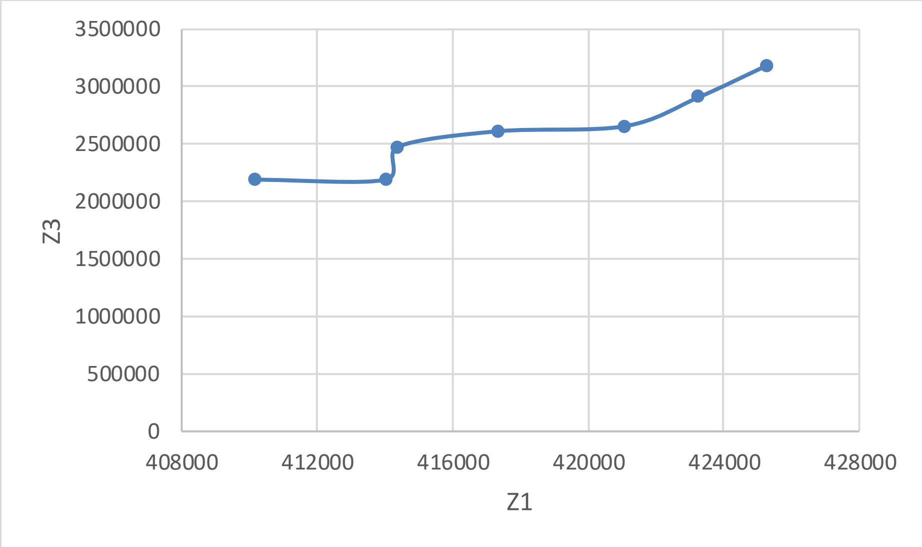

Fig. 3. Comparison of values of the first and third objective functions in Pareto solutions.

5. Conclusion

In the downstream industries of crude oil and gas condensate, a primary objective is to maximize the added value within the product portfolio. Attaining this goal, which ultimately translates to maximizing profits through the sale of the product portfolio, necessitates a shift away from the traditional and one-dimensional perspective of simply increasing refining or petrochemical capacity across all countries. It's important to emphasize that creating a value chain extends beyond the construction of new refining and petrochemical units. Prior to embarking on the construction of such units, thorough consideration should be given to the existing product portfolio within the region. This includes assessing raw materials, intermediate products, and final products. By cultivating a more diverse product portfolio in the market, updating existing units, and, where necessary, constructing new units, we can move closer to the goal of optimizing profit.

The purpose of establishing an oil and petrochemical supply chain, in addition to producing strategic products, should revolve around the creation of higher added value. Traditionally, there's been a belief that the closer one gets to the end products in the chain, the higher the value of the final products. In essence, it's presumed that selling raw materials with higher added value is the key.

However, in the oil and petroleum product market, a critical consideration revolves around the seller's flexibility in offering a range of products. This flexibility entails ensuring the availability of a diverse basket of products, including crude oil, natural gas, gas condensate, refinery products, and petrochemical products. This diverse product array should always be at the supplier's disposal, enabling them to respond to varying market conditions throughout the year or under different circumstances. By adjusting their product offerings, suppliers can secure maximum profit in any market situation.

This paper has introduced a comprehensive multi-level, multi-period, multi-objective mathematical model aimed at optimizing the design of the crude oil supply chain while aligning with the principles of sustainable development. The proposed model serves to minimize both the costs and environmental impacts stemming from supply chain operations while concurrently maximizing the generation of job opportunities.

The multifaceted, multi-objective model was effectively addressed using the methodology developed by Torabi and Hassini (2008). This approach leverages the principles of fuzzy programming coupled with the definition of membership degrees for objective functions. The model was put to the test across various problem instances, allowing for an exploration of how changes in relative weights and the compensation coefficient would impact the results. This investigation underscored that any adjustments in these parameters invariably influence the values of all three objective functions. Consequently, it becomes imperative for decision-makers to exercise caution in selecting these parameters to avert unwarranted consequences on the optimal values of the objective functions.

The proposed model, in conjunction with the derived Pareto optimal front, equips decision-makers with a valuable tool for striking a harmonious balance between environmental preservation, job creation, and cost-efficiency objectives throughout the process of optimizing the crude oil supply chain design. Future research endeavors may extend the applicability of this model to the optimization of oil field development while incorporating considerations for parameter uncertainties.

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