Designing a multi-objective supply chain model for the oil industry in conditions of uncertainty and solving it by meta-heuristic algorithms

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Abstract.

In today's highly competitive environment, the high speed of evolutions has increased the uncertainty of decisions, which creates a high level of uncertainty in the supply chain and impairs its ability to predict future conditions. To plan better and more accurately, reliable planning should be performed. One of the reliable approaches is robust optimization. In this study, a forward oil supply chain is considered to minimize the shipping costs as well as the number of loads under certain and uncertain conditions. To solve the model under certain conditions, two meta-heuristic algorithms, including PSO and MOPSO, are used, and in the uncertain condition, the Mulvey approach is implemented. The result shows the efficiency of proposed models under both conditions.

Keywords: Oil Supply Chain, Robust Optimization, Uncertainty, Multi-Objective Optimization, Meta-heuristic Algorithms

1 Introduction

These days, supply chain management is considered one of the fundamental business issues, affecting all organization activities in terms of providing service to customers [1,17,18,19,20]. Therefore, paying attention to opportunities and threats in business and assessing the organization's ability to deal with uncertainty is highly essential. One of the most significant factors for survival in today's competitive environment is reducing transportation, maintenance, and other costs, as well as reducing the purchasing costs under uncertainty [2,21,22,23,24]. According to several researches, uncertainty is considered a critical factor in the decision-making process, especially for supply chain planning, which has high uncertainty in demand, costs, and lead time [3, 4]. In this paper, a bi-objective mathematical model for the oil supply chain is developed to minimize the transportation costs of oil and petroleum products and minimize their loads in the large scale problem.

The remained of this paper is as follows: the literature review is presented in Section 2. The mathematical model is described and formulated in Section 3 and 4. The robust model is presented in Section 5. The proposed solution method is introduced in Section 6. The numerical example and comparisons of the proposed solution methods are shown in Section 7. Finally, conclusions and future research are demonstrated in Section 8.

2 Literature Review

The design of supply chain network is one of the most important strategic decisions that has been considered by many researchers and decision makers. It includes a set of problems such as the organization of facilities and their capacity levels, transportation of raw materials and products, distribution of products and services, meeting customer demand and the like. Several exact, heuristic and meta-heuristic approaches have been introduced to optimize the supply chain in terms of the total cost. Among the exact methods for multi-objective models, the weighted sum method and e-constraints are used mostly [5]. For example, [6] proposed a multi-objective model to minimize the total costs as well as environmental impacts. They used the weighted sum method and e-constraint to solve the model. Among the heuristic and meta-heuristic methods for the multi-objective models, the MOPSO is considered one of the most useful methods. In one case, [7] designed a closed-loop supply chain to maximize the total profit and minimize the total risks and product shortages. They used NSGA-II, MOSA, and MOPSO algorithm to solve the problem. However, to provide more realistic results, the innate uncertainty in the supply chain network should be considered. The uncertainty in the oil and petroleum supply chain usually arises from the crude availability, processing capacities, demand, and market prices [8].

Although there is great literature on oil supply chains, few researches have been included overcoming the uncertainty in addition to other economic aspects [9]. Different approaches that can be implemented to deal with uncertainty are scenario-based [10], stochastic programming [11], supply chain dynamics [12], and fuzzy decision making [13]. [14] presented a multi-period stochastic approach to overcome the demand and supply cost uncertainty in a consortium of oil operators. [15] considered the uncertainty in operating and economic condition for the petrochemical supply chain. In this paper by developing a new mathematical model based on supply chain model and transportation problem, the distribution of petroleum products has been studied.

3 Model Description

Figure 1 shows suppliers on the left, this *M* suppliers includes crude oil refineries and product import terminals. *N* warehouses are also considered in the center of the chain, which includes strategic and non-strategic warehouses. The products first enter one of the warehouses from the starting point of production, from there they can be transferred to another warehouse or go directly to the consumption area. *K* fuel receiving area is also shown to the right of Figure 1, each of which has a specific demand (uncertain demand) for each of the products. Transfers between centers (refineries, warehouses, and fuel receiving areas) are done by different transportation methods, in each of the stages of transfer, each product can use one of these means. But there are also some limitations according to transportation methods and other factors that will be explained in the model introduction.

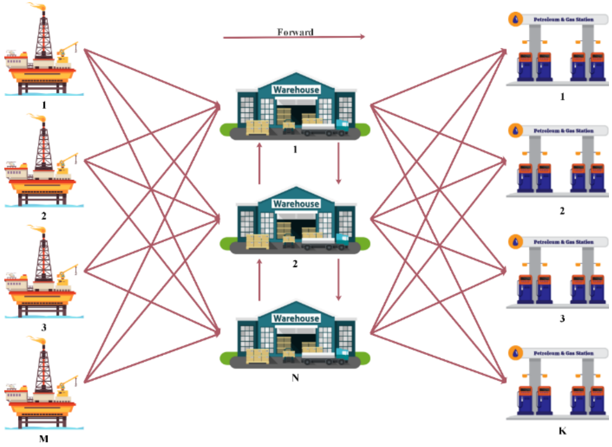

Figure 1. Fuel supply chain network during a period

The purpose is to formulate the problem and determine the optimal amount of each product that is transferred from any production source to any warehouse, and then to any shipping area. Also, the optimal transportation methods at each stage of product transfer along the chain should be specified. Likewise, the amount of each product that is stored in each warehouse in each time period to be used in later periods must be determined.

4 Proposed Mathematical Model

Considering the previous section, a mix integer non-linear programming (MINLP) model is presented. The sets, parameters, and decision variables of the proposed mathematical model are as follows:

4.1 Sets

i Types of products
m The sources of product supply (refineries and import terminals)
n Warehouses
k Consumption areas
l Types of product shipping methods

4.2 Parameter

D_{ik} Demand of area k for product i
F_{im} Maximum production capacity of supply m for product i
P^1_{mn} Maximum capacity of pipeline in transporting products from supply m to warehouse n
$P^2_{nn'}$ Maximum capacity of pipeline in transporting products from warehouse n to warehouse n'
P^3_{nk} Maximum capacity of pipeline in transporting products from warehouse n to consumption area k

Cap_{in}	Maximum capacity of warehouse *n* for product *i*
h_n	Holding cost of warehouse *n* per unit of stored product
c^1_{lmn}	Transportation cost of each batch of products by transportation method *l* per unit route from supplier *m* to warehouse *n*
$c^2_{lnn'}$	Transportation cost of each batch of products by transportation method *l* per unit of route from warehouse *n* to warehouse *n'*
c^3_{lnk}	Transportation cost of each batch of products by transportation method *l* per unit of route from warehouse *n* to consumption area *k*
d^1_{lmn}	Distance between supplier *m* to warehouse *n* by transportation method *l*
$d^2_{lnn'}$	Distance between warehouse *n* to warehouse *n'* by transportation method *l*
d^3_{lnk}	Distance between warehouse *n* to consumption area *k* by transportation method *l*
b_{il}	The minimum amount of shipping product *i* per each transfer in transportation method *l*
x^1_{lmn}	1 If it is possible to transfer the product from supply *m* to warehouse *n* by the transfer method *l*, otherwise 0
$x^2_{lnn'}$	1 If it is possible to transfer the product from warehouse *n* to warehouse *n'* by transportation method *l*, otherwise 0
x^3_{lnk}	1 If it is possible to transfer the product from warehouse *n* to consumption area *k* by transportation method *l*, otherwise 0
BN	Big positive number

4.3 Decision Variable

S^1_{ilmn}	The amount of product *i* that is transferred from supply *m* to warehouse *n* by transportation method *l*
$S^2_{ilnn'}$	The amount of product *i* that is transferred from warehouse *n* to warehouse *n'* by transportation method *l*
S^3_{ilnk}	The amount of product *i* that is transferred from warehouse *n* to consumption area *k* by transportation method *l*
I^0_{in}	Inventory of warehouse *n* for each product *i* at the beginning of the period
I^1_{in}	Inventory of warehouse *n* for each product *i* at the end of the period
U^1_{ilmn}	1 If product *i* is delivered from supplier *m* to warehouse *n* by transportation method *l*, otherwise 0
$U^2_{ilnn'}$	1 If product *i* is delivered from warehouse *n* to warehouse *n'* by transportation method l, otherwise 0
U^3_{ilnk}	1 If product *i* is delivered from warehouse *n* to consumption area *k* by transportation method *l*, otherwise 0

$$Min\ Z_1 = \sum_i \sum_l \sum_m \sum_n \left(\left(\frac{Sx^1_{ilmn}}{b_{il}} \right) d^1_{lmn} c^1_{lmn} \right) + \sum_i \sum_l \sum_n \sum_{n'} \left(\left(\frac{Sx^2_{ilnn'}}{b_{il}} \right) d^2_{lnn'} c^2_{lnn'} \right) + \sum_i \sum_l \sum_n \sum_k \left(\left(\frac{Sx^3_{ilnk}}{b_{il}} \right) d^3_{lnk} c^3_{lnk} \right) + \sum_i \sum_n (h_n I_{in}) \quad (1)$$

$$Min\ Z_2 = \sum_i \sum_l \sum_m \sum_n \sum_{n'} \sum_k U^1_{ilmn} + U^2_{ilnn'} + U^3_{ilnk} \quad (2)$$

The first objective function (Equation 1) minimizes the transportation costs of products along the supply chain. This objective function consists of four separate parts, namely, the transportation cost from supplier to warehouse, the transportation cost from one warehouse to another, the transportation cost from one warehouse to consumer area, and finally holding cost of products in warehouses at the end of the current period. It should be noted that b_{il} is considered only for transportation method by fuel trucks to calculate transportation cost of each truck regardless of the amount of their products (therefore, the result of the division is rounded up). For other ways of transportation, this parameter is considered 1.

The second objective function (Equation 2) minimizes the total number of transfers by a particular transportation mode which causes the reduction of road transportation to increase the safety in transporting products.

4.4. Constraint

$$Sx^{1}_{ilmn} = S^{1}_{ilmn} x^{1}_{lmn} \qquad \forall i,l,m,n \tag{3}$$

$$Sx^{2}_{ilnn'} = S^{2}_{ilnn'} x^{2}_{lnn'} \qquad \forall i,l,n,n' \tag{4}$$

$$Sx^{3}_{ilnk} = S^{3}_{ilnk} x^{3}_{lnk} \qquad \forall i,l,n,k \tag{5}$$

$$I^{0}_{int} + \sum_{l}\sum_{m} Sx^{1}_{ilmn} + \sum_{l}\sum_{n'} Sx^{2}_{ilnn'} = \sum_{l}\sum_{n'} Sx^{2}_{ilnn'} + \sum_{l}\sum_{k} Sx^{3}_{ilnk} + I^{1}_{int} \qquad \forall i,n \tag{6}$$

$$\sum_{l}\sum_{n} Sx^{3}_{ilnk} \ge D_{ik} \qquad \forall i,k \tag{7}$$

$$\sum_{l}\sum_{n} Sx^{1}_{ilmn} \le F^{max}_{im} \qquad \forall i,m \tag{8}$$

$$\sum_{l=2}^{L}\sum_{m}^{M} Sx^{1}_{ilmn} + \sum_{l=2}^{L}\sum_{n}^{N} Sx^{2}_{ilnn'} \le Cap_{in} \qquad \forall i,n \tag{9}$$

$$\sum_{i} Sx^{1}_{ilmn} \le P^{1}_{mn} \qquad \forall m,n \tag{10}$$

$$\sum_{i} Sx^{2}_{ilnn'} \le P^{2}_{nn'} \qquad \forall n,n' \tag{11}$$

$$\sum_{i} Sx^{3}_{ilnk} \le P^{3}_{nk} \qquad \forall n,k \tag{12}$$

$$Sx^{1}_{ilmn} \ge U^{1}_{ilmn} \qquad \forall i,l,m,n \tag{13}$$

$$Sx^{1}_{ilmn} \le BN \times U^{1}_{ilmn} \qquad \forall i,l,m,n \tag{14}$$

$$Sx^{2}_{ilnn'} \ge U^{2}_{ilnn'} \qquad \forall i,l,n,n' \tag{15}$$

$$Sx^{2}_{ilnn'} \le BN \times U^{2}_{ilnn'} \qquad \forall i,l,n,n' \tag{16}$$

$$Sx^{3}_{ilnk} \ge U^{3}_{ilnk} \qquad \forall i,l,n,k \tag{17}$$

$$Sx^{3}_{ilnk} \le BN \times U^{3}_{ilnk} \qquad \forall i,l,n,k \tag{18}$$

$$\sum_{l} U^{1}_{1lnk} \times \sum_{l} U^{1}_{2lnk} \le \sum_{l} U^{1}_{3lnk} \qquad \forall m,n \tag{19}$$

$$\sum_{l} U^{2}_{1lnn'} \times \sum_{l} U^{2}_{2lnn'} \le \sum_{l} U^{2}_{3lnn'} \qquad \forall n,n' \tag{20}$$

$$\sum_l U^3_{1lnk} \times \sum_l U^3_{2lnk} \leq \sum_l U^3_{3lnk} \qquad \forall n,k \tag{21}$$

$$\sum_l S^1_{4lmn} = 0 \qquad \forall m,n \tag{22}$$

$$\sum_l S^2_{4lnn'} = 0 \qquad \forall n,n' \tag{23}$$

$$\sum_l S^3_{4lnk} = 0 \qquad \forall n,k \tag{24}$$

$$U^1_{ilmn}, U^2_{ilnn'}, U^3_{ilnk} \in \{0,1\} \tag{25}$$

$$S^1_{ilmn}, S^2_{ilnn'}, S^3_{ilnk}, I^0_{in}, I^1_{in} \geq 0 \tag{26}$$

Constraint 3, 4, and 5 guarantees that products can be transported only in some routes and transportation modes. Constraint 6 is an equilibrium constraint and logically indicates that for each product in each warehouse the amount of inventory at the beginning of the period plus the amount of transferred product from supplier, and the amount of product transferred to it from other warehouses, should be equal to the amount of product that is transferred from the mentioned warehouse to customer areas, plus the amount of product that is transferred to other warehouses, plus the inventory at the end of the period. Constraint 7 indicates that the minimum quantity of each product that must reach to each customer is equal to demands of customer. Constraint 8 guarantees that the maximum amount produced from each product at each supplier is equal to its capacity. Constraint 9 states that for each warehouse and each type of product, total entered products to warehouse, from supplier and other warehouses, should not exceed its capacity. Constraints 10, 11, and 12 are related to the capacity of pipelines. The sum of all quantities of transported products through the first transportation method (by pipeline) should not exceed the maximum capacity of transport by that pipeline in determined route. Constraints 13 and 14 are for obtaining the value of U^1_{ilmn}. By these two constraints, when Sx^1_{ilmn}takes a non-zero value, U^1_{ilmn} assigns 1, and when Sx^1_{ilmn}accepts a zero value, U^1_{ilmn} assigns 0. Likewise, constraints 15 and 16 and constraints 17 and 18 are for obtaining the values of $U^2_{ilnn'}$ and U^3_{ilnk}, each.

Constraints 19, 20, and 21 are technical constraints in the transportation method by the pipeline. These constraints guarantee that if in the planning period by the first transportation method (by pipe), product *i1* (e.g., gasoline) is transferred from one source to a destination and in the same period, product *i2* (e.g., kerosene) is transported in the same direction by the same pipeline, so, product *i3* (e.g., gas oil) must also be transported by pipeline in that direction to be placed between the first two products in the pipelines. These constraints are designed so that in transportation method by pipeline, due to technical limitations and different types of products, petrol product cannot be loaded on the pipeline immediately after the gasoline product and a minimum amount of another product, such as gas oil, needs to be loaded on the pipeline and then kerosene loaded. Constraints 22, 23, and 24 state that the fourth product (furnace oil) cannot be transported in the first transportation method. Finally, constraints 25 and 26 are related to the decision variables of the proposed model.

5 Robust Model

In this part, the first objective function is stabilized and assuming that the demand for fuel products is not reliable and is considered an uncertain parameter; hence, the result of this objective function relative to the changes is based on this parameter. Accordingly, different scenarios are considered for the demand, and then the robust optimization model of Mulvey et al. [16] is applied.

6 Solution Method

Due to the computational complexity of the problem and the high number of variables and parameters in the proposed model (especially in robust mode), we cannot find the optimal solution through linear optimization software and through exact solution methods. In this paper, to deal with this problem, PSO and MOPSO meta-heuristic algorithms are employed to solve the model. The PSO and MOPSO algorithms are used to solve the model in a single objective and multi-objective mode, respectively.

7 Numerical Examples

Initially, the problem was solved in the single-objective mode for simple and robust modes by the PSO algorithm, and its results were compared on a small scale with exact methods by GAMS software. Then, in the next part, the model was solved in multi-objective mode by the MOPSO algorithm, and an optimal Pareto level was obtained. Finally, the original model's solutions are compared in normal and robust modes and in small and large sizes. A computer with a Core i7 6700 HQ processor and 16GB of RAM was used to run the numerical examples. GAMS linear optimization software is our criterion for measuring the proximity of the obtained answers compared to reality. For this software, a 3 hours' time limit is considered. If an optimal solution for the desired sample is not obtained at the end of this time, the proposed model is recognized as unsolvable by exact solution methods. Since both algorithms (both single-objective and multi-objective) are random in nature, each numerical example is executed ten times by MATLAB R2015b software. In the following, the numerical examples calculated for the proposed model are given as a single objective for the first objective function in simple and robust modes.

Size	Indicates the number of products (*i*), the number of transportation methods (*l*), the supplier (*m*), the number of warehouses (*n*), and the number of customer areas (*k*)
$F_{Optimal}^{Normal/Robust}$	Indicates the value of the first optimal objective function of a linear problem using GAMS software
$F_{Best}^{Normal/Robust}$	Indicates the best value of the first objective function, which is obtained by means of 10 times the execution of the algorithm
$Gap_{Optimal-Best}^{Normal/Robust}$	Indicates difference percentage between the value of the optimal objective function and the best value of the objective function obtained by each algorithm and it is based on equation 59.
$NFE^{Normal/Robust}$	Indicates the number of times that the objective function is called in best mood

$t_{Optimal}^{Normal/Robust}$ Problem solving time by GAMS software in seconds

$$Gap_{Optimal\text{-}Best}^{Normal/Robust} = \frac{(F_{Best}^{Normal/Robust} - F_{Optimal}^{Normal/Robust})}{F_{Optimal}^{Normal/Robust}} \times 100 \qquad (59)$$

7.1. The results of the PSO algorithm in single-objective mode in normal and robust model

As can be seen the results of the PSO algorithm for the normal and robust model is according to Table 3.

Table 3. Numerical values obtained for normal and robust model

	Small Size (I×L×M×N×K)			Big Size Model
	2×1×3×2×3	2×3×4×5×7	3×4×5×9×12	4×4×11×86×229
$F_{Optimal}^{Normal}$	645712	8586550	68543897	39104906330
F_{Best}^{Normal}	660772	8704667	70857699	40346816221
$F_{Average}^{Normal}$	661430	8801123	74332567	43568867927
$Gap_{Optimal-Best}^{Normal}$	2.3245	1.3756	3.3756	3.1758
NFE^{Normal}	1034	4238	32548	16254389
$t_{Optimal}^{Normal}$	1.43	3.24	25.30	12873
$F_{Optimal}^{Robust}$	845457	12009346	90112340	-
F_{Best}^{Robust}	856926	12488171	93154082	50765234347
$F_{Average}^{Robust}$	89768	13543009	964576651	55385098322
$Gap_{Optimal-Best}^{Robust}$	1.35	3.98	3.37	-
NFE^{Robust}	3625	15828	88243	45654904
$t_{Optimal}^{Robust}$	5.30	12.50	110.30	35987

7.2 The results of the MOPSO algorithm in multi-objective mode in normal and robust model

In order to evaluate the efficiency of the MOPSO algorithm by combining different parameters, the following two efficiency scales have been used [6].

NPS This index calculates the number of non-dominated solutions which are obtained each time by applying the algorithm. The higher NPS is, the better algorithm works.

MID The value of this criterion equals to the distance of the Pareto points from the ideal point and can be calculated based on equation 60. The lower value of MID indicates the excellence of the algorithm.

$$c_i = \sqrt{\left(\frac{f_{1i} - f_1^{best}}{f_{1,total}^{\max} - f_{1,total}^{\min}}\right)^2 + \left(\frac{f_{2i} - f_2^{best}}{f_{2,total}^{\max} - f_{2,total}^{\min}}\right)^2}$$

$$MID = \frac{\sum_{i=1}^{n} c_i}{n} \qquad (60)$$

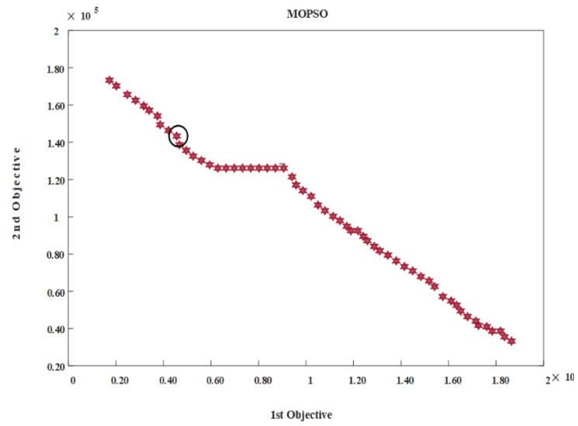

Figure 2. The results of MOPSO algorithm

After solving the single-objective model for each of the PSO algorithm's objective functions, the proposed model was solved in the two-objective model by the MOPSO algorithm with the same parameters defined in the previous numerical examples. In this case, the number of non-dominated solutions (NPS) was 59. In each of these solutions, each value of the two objective functions was determined. For the MID criteria, its value was 0.8645. As shown in Figure 2, the calculated value for the first objective function in a robust model, obtained by the PSO algorithm, is also part of the Pareto solutions set, which indicates the reliability of the Pareto solution. Furthermore, according to one of the answers specified in Figure 2, Table 4 shows its costs, according to various transportation methods.

Table 4. Costs for the specified point based on various means of transportation

Transportation Mode	**Cost (MU)**
The total cost of moving in robust mood for the highlighted point from the Pareto level by rail	101458789
The total cost of moving in robust mood for the highlighted point from the Pareto level by ship	2154586458
The total cost of moving in robust mood for the highlighted point from the Pareto level through the pipelines	16526145365
The total cost of moving in robust mood for the highlighted point from the Pareto level by fuel tankers	31983043735

8 Conclusion

Due to the high costs of refining and distribution of petroleum products and on the other hand, the growing need to reduce the massive costs of governments and maximize the use of resources, the need to have a comprehensive plan for the refueling process, taking into account all the variables for future, is urgent and undeniable. In this study, a novel two-objective model was designed. The proposed model mainly covers structural and operational constraints. This model has several advantages; first, the proposed model adequately covers all operational constraints, including holding costs. Second, planning is inherently a long-term process, and many costs are overlooked in planning for separate periods. Third, the proposed model is capable of multi-period programming. Fourth, the most crucial advantage is the robustness of the model. Given the very high involving costs in the refueling process, it becomes clear the importance of the model's output information on the basis of determined decisions. Without designing such a model in the form of a supply chain, with the smallest mistake in entering data into the model or an incorrect or even slightly unrealistic estimate for the demand of different areas for different types of petroleum products, the whole calculation will be problematic. Besides, there is no alternative decision if the estimates are made correctly, but any of the refineries or warehouses fail to meet their obligations for technical reasons. But in the proposed model, with the cost that we initially pay as a robust cost and is much less than the mentioned consequences, the obtained program is guaranteed over time. The fifth advantage is related to the goals being considered; as everyone knows, human lives are not comparable to any other currency. In the proposed model, in addition to reducing costs, the use of fuel tanks that reduce the risk to people by being on the road goes down as much as possible. This reduction risk is precious, although it somewhat does increase costs.

Some suggestion that can be considered as a future recommendation for this study are as follow: a) pipeline planning can be done on a daily basis to control changes due to operational reasons, b) planning can be done periodically, c) the proposed model can be provided as a kind of software under internal network, d) compare the performance of the proposed algorithms with similar algorithms, e) the production of refineries and the capacity volume of products in tanks can also be considered with uncertainty, and f) the economic feasibility of adding pipelines in specific areas can be done.

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