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Article

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Developing benders decomposition algorithm for a green supply chain network of mine industry: Case of Iranian mine industry



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ABSTRACT

This paper attempts to design a three-echelon supply chain network for mine industry considering suppliers, manufacturing centers and distributors with different kinds of vehicles. A multi-objective mixed integer programming model is proposed to minimize transportation costs, shortage costs, purchase costs, production costs and CO₂ emissions of vehicles with fuzzy demand values. ϵ -constraint method is used in order to convert multiple objective functions to a single objective function. Benders decomposition algorithm is applied to solve the model under three demand-based scenarios. A case study is done on Iranian mine industry to present the significance and applicability of the proposed model in a real-life case problem as well as the efficiency of Benders decomposition.

1. Introduction

Over the recent decades with rapid industrialization and expansion in production, consumption and trading levels in the world, the necessity for supply chain management (SCM) in several industries has increased. Manifold factors influence the necessity to utilize SCM, importantly costs and environmental issues. Firms face challenges related to costs, competition and environmental problems configure their supply chain design and logistics systems continuously. Depletion of natural resources, climatic problems, gas emissions, natural and technical disruptions are the major environmental factors acting as an indispensable challenge for all industries, which can be dealt with green supply chain management. Green supply chain management (GSCM) is an important trend among most of the industrial activities which enables managers to address the adverse impacts of traditional supply chain [44]. GSCM is applied within two procedures: first, it is used to integrate the environmental management principal; second, with a prevention or preservation policy to put an end for the further depletion. Hervani et al. [29] stated that GSCM minimize all types of wastes such as emissions, chemical, hazardous and solid waste. Another advantage of GSCM is that this concept considers the all phases of a good's life cycle, beginning from the extraction of raw material phase, design phase, production phase and distribution phase, to the good's use by costumers, and finally its final disposal [18,41,69]. Supply chain of mining includes several activities that are tightly related to each other

such as operations, logistics and marketing functions that needs to be addressed in an appropriate way to for ensuring the high efficiency and profit. Mining industry is one of the important industries that can afford jobs for hundreds of people directly and indirectly.

Mining activities mainly consist of extraction, processing, and transportation of minerals from mining sites to market place [41]. Over the years, arbitrary and unregulated mining activities have significantly contributed to environmental degradation. Consequently, a number of environmental issues such as disturbance of top soil, contamination of water bodies which stems from acid mine drainage, the release of cyanide and other toxic chemicals, atmospheric pollution, global warming with increasing emissions from greenhouse gases, visual intrusion, dust, vibrations, traffic, and noise may occur [9,30]. Besides, low investment capacity, the use of traditional technologies, the poor working conditions of unskilled manpower lead to poor productivity and maintenance of equipment [46] which both can contribute greatly to several health and economic problems. Exploring mining supply chain reveals more details about the different parts of its network. In recent years, supply chain of mining has gotten some advances into considering not only the production process, but also the condition influencing the material to be delivered to markets. Following these improvements, mining sector has focused more on concepts such as environmental management, sustainable development and corporate social responsibility (see, [30,31,34,61,66]).

This paper aims to investigate a multi-objective green supply chain of mining industry with fuzzy demand values. The objectives are to

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minimize costs and emission, besides maximize customer satisfaction. The rest of the paper is organized as follows. In [Section 2](#), we review the related studies in literature. Problem description is presented in [Section 3](#). Next, we propose multi-objective mixed integer programming. We devise benders decomposition to solve the model. In [Section 4](#), a case study of Iranian mining industry is studied and evaluated by model. Finally, we conclude in [Section 5](#).

2. Literature

The mining industry in Iran has been a significant economic activity for centuries and surprisingly contribute greatly to economic growth annually. Government of Iran highly support activities which led to extraction of material such as gold, metal, copper, bronze and so on. Mining companies in Iran are exclusively supported by Ministry of Industry & Mining politically, technically and financially. Iran is a country, rich in materials with manifold grand mines, dispersed all over the country. However, the processing and consuming centers for mineral materials have brought some challenges which have to be dealt appropriately to ensure the maximum efficiency and profit. Although some of these challenges have to do with technical part, a large proportion is happening outside the mines through their supply chain that influence profit and environmental conditions.

One of the important challenges has to do with the uncertainty in the demand and supply values. Uncertainties in both supplier and demand sides are very common in literature. Several optimization methods are proposed to solve the supply chain problems under uncertainty such as mixed integer programming, stochastic programming, dynamic programming, exact methods and also meta-heuristics (see, [\[63\]](#); Shen and Pang [\[57\]](#); [\[58\]](#); Shen and Qi [\[50\]](#); [\[53\]](#); [\[10,47\]](#); Baghalian, et al. [\[5\]](#); [\[3,11,22–24,36,71\]](#)). Govindan et al. [\[28\]](#) comprehensively reviewed and categorized the studies associated to supply chain network design under uncertainty. Investigating the studies in two steps, they reviewed the research articles first considering the supply chain design and planning and then went through the optimization tools that are used in literature for the networks under uncertainty sets such as fuzzy sets.

These challenges have notoriously affected the economic benefits of mine industry so the necessity of addressing problem is needless to mention. In this part, we categorize literature on Mining in Iran, GSCM in mining industry and studies related to benders decomposition.

2.1. Mining in Iran

Mining sector in Iran plays an undisputable role in the growth of economy and is one of the important infrastructures in the country. The dispersion of many diverse mineral resources such as iron, coal, oil, gas, chromite, copper, lead and zinc and manganese, and their sub-materials have made this industry, more reliable and profitable. Although Iran produces more than 68 types of materials and having a total 84 billion tons of proven and potential mineral reserves, its mining industry in not developed technically and most of the processes are done traditionally. However, Iranian mine industry has undergone a decline in growth and do not place among top 10 countries concerning capacity and production in the recent. A possible answer to this can be find in the traditional mechanism and the machinery that are used in Iranian mines.

2.2. Green supply chain management

By the increase in the social and political pressure, sensitivity around end-of-life goods, transportation risks, environmental issues have led the field of the supply chain management to more focused on making a change on supply chain performances toward natural environment [\[41\]](#), changing the traditional strategy of supply chain to a more environment-oriented strategy [\[60\]](#). Integrating internal and

external resources of organizations, green supply chain management has become more interested to industry and academia (Govindan et al. [\[27\]](#)). There are number of different definition of GSCM in the literature. Zsidisin and Siferd, [\[77\]](#) and Diabat and Govindan [\[18\]](#) defined green supply chain as “the set of the set of supply chain management policies held, actions taken and relationships formed in response to concerns related to the natural environment with regard to the design, acquisition, production, distribution, use, re-use and disposal of the firm's goods and services”. GSCM is also defined as sustainable supply chain [\[33,37,48,55\]](#). Amalnick and Saffar [\[2\]](#) designed green supply chain network considering environmental issues as CO₂ emissions. They proposed fuzzy mathematical model with an aim on minimizing costs and environmental impacts. Recently, GSCM has been noticed in several sectors such as manufacturing, electrical, automotive, mobile phone, etc. (see, [\[32,65,72\]](#); Eltayeb et al. [\[20\]](#); [\[12,13,17,73–75\]](#)).

2.3. Green supply chain management in mining industry

Addressing environmental issues related to mining industries in the literature and industry shows the attentions to adopting the cleaner production, environmental management and policies, parallel to GSCM [\[76\]](#), adhering to governmental regulations ([\[25\]](#)a), obtaining social license to operate [\[30,45\]](#), attracting financial groups [\[4\]](#) and increasing their eco-efficiency [\[66\]](#). Ghose [\[25\]](#) explored techno-economic and socioeconomic factors that inhibit environmental management practices in Indian small-scale mining industries. Ghose [\[25\]](#) examined the schematics of environmental management plans adopted by small scale mines in India. Berkel [\[66\]](#) introduced a framework for eco-efficiency in Australian mineral processing industries. Nikolaou and Evangelinos [\[45\]](#) utilized SWOT analysis to analyze challenges in Greek mining industries to adopt environmental management practices. Examination of key mega trends and potential challenges of environmental sustainability in mining industries of Australia, Catalonia and Tanzania is conducted by [\[42,43,68\]](#). Muduli et al. [\[41\]](#) examined the qualification of the barriers to GSCM implementation using graph theoretic and matrix approach. Sivakumar et al. [\[59\]](#) used AHP, a decision-making method, and Taguchi loss functions to the evaluation and selection of green vendor. Govindan et al. [\[27\]](#) investigated the influential strength of factors on adoption of green supply chain management practices in Indian mine industries.

It can be inferred from [Table 1](#) that all the studies performed in field of mine supply chain networks can be categorized by following research areas:

- *Modeling approaches.* Different types of models are applied for mine supply chain network. Most of these methods are qualitative models such Environment management system (EMS), Eco-efficiency (EE), SWOT, Interpretive structural modelling (ISM), Taguchi loss (TL), DEMATEL. Mixed integer programming (MIP) is presented for first time for this problem.
- *Solution methods.* Exact solution (E) and heuristics algorithms are normally applied for large supply chain networks.
- *Objective functions.* Different mathematical formulation developed for modeling supply chain networks are presented in context of single objective and multi-objective models.
- *Objective function types.* Objective functions of mathematical models in supply chain networks mostly represent most three common types such cost function (Cost), CO₂ reduction function (CO₂) and Customer satisfaction function (CS).
- *Research scopes.* Most of the scopes have been considered in literature for studying mine supply chain were restricted to supplier (s) and manufacturer (M), distributor (Di) and environmental and ecological issues (EN).
- *Demand points.* Demand points in supply chain networks usually are out of two types: crisp number (CR) and fuzzy number (FU)

Table 1
Literature of mine supply chain.

| References | Model | Solution method | Objective function | Demand points | | Research scope | Case Study | | | | | | | | | |
|---------------------------|---------|-----------------|--------------------|---------------|-------|----------------|-----------------|----|----|----|---|---|----|----|---|--------------------|
| | | | | Single | Multi | | CO ₂ | CS | CR | Fu | S | M | Di | EN | | |
| [30] | EMS | – | – | – | – | – | – | – | – | – | – | ● | – | – | ● | Australia & Canada |
| ([25]b) | – | – | – | – | – | – | – | – | – | – | – | ● | – | – | ● | India |
| [45] | EE | – | – | – | – | – | – | – | – | – | – | ● | – | – | ● | Australia |
| ([41]b) | SWOT | – | – | – | – | – | – | – | ● | – | – | ● | – | – | ● | Greece |
| (R.Sivakumar et al. 2014) | ISM | – | – | – | – | – | – | – | – | – | – | ● | – | – | ● | India |
| [27] | TL | – | – | – | – | – | – | – | ● | – | – | ● | – | – | – | India |
| ([25]b) | DEMATEL | – | – | – | – | – | – | – | ● | – | – | ● | – | – | – | India |
| Our work | MIP | ● | ● | – | ● | ● | ● | ● | – | ● | ● | ● | ● | – | – | Iran |

2.4. Benders decomposition review

Benders, [6] developed procedures for solving large-scaled mixed variable programming problems, specially dealing with complicated variables. Rahmaniani et al. [51] presented a survey of benders decomposition algorithm with the application in the optimization. Besides, the algorithm has been applied in wide areas such as facility location, scheduling, mixed integer programming, distribution systems design, network design and optimization, (see, [1,8,14,16,38–40,62,67]; Bertsimas [7]; Ciré [15]; [19, 26]).

Benders decomposition is widely used in the supply chain management. Keyvanshokoo et al. [35] proposed an accelerated stochastic benders decomposition algorithm to solve a profit maximization model for closed-loop supply chain network. They proposed a hybrid robust-stochastic programming approach which includes stochastic scenarios for transportation costs and polyhedral uncertainties for demands.

Santoso et al. [54] presented a solution method with combining the sample average approximation scheme and an accelerated benders decomposition algorithm to solve large-scaled stochastic supply chain managements. Pishvae et al. [49] used an accelerated benders decomposition algorithm with three efficient acceleration mechanisms to solve a sustainable medical supply chain network under uncertainty. Zarrinpoor [70] used accelerated benders decomposition to solve location-allocation model addressing a real-world health service network design problem and for the design of integrated water supply and wastewater collection systems.

Uster et al. [64] develop a dual solution approach to generate strong benders cuts by introducing three new approaches for adding benders cuts, to solve a multi-product closed-loop supply chain network. In comparison to branch-and-cut algorithm, their solution method works better in generating lower and bounds to find optimal solution and amount of the time needed to obtain the optimal solution. Easwaran and Uster (2009) proposed a bender decomposition algorithm including benders cuts and tabu search heuristics to determine optimal locations of collection centers and remanufacturing facilities in a multi-product closed-loop supply chain of remanufacturing facilities, finite-capacity manufacturing, distribution and collection facilities that works with number of retailers.

Roni et al. [52] presented a mixed integer programming of biomass co-firing in coal-fired power plants supply chain within a hub-and-spoke network. They used benders decomposition to evaluate their model with numerical data.

Shaw et al. [56] considered bender decomposition to solve chance-constrained a green supply chain which addresses carbon emissions and carbon trading issues by taking into account uncertainties in capacity of suppliers, plants and warehouses, and demand.

As we noted earlier, only a few studies have been done on modeling the mine green supply chain. Here, we design the mine green supply chain with its most important contents including suppliers, manufacturing centers, distribution centers and vehicles with considering the

emissions. Then, we proposed the mathematical formulations for the green supply chain of mine industry. Benders decomposition algorithm is developed to solve the model. For the first time in the literature, we also investigated our model for the case of mine industry in Iran.

3. Problem description and model formulation

In this section, a multi-objective mixed integer programming model is developed for three-echelons Iranian mine supply chain (IMSC) including: supplier, manufacturer, distributor with multi-type vehicles. Schematic view of the model including suppliers, manufacturers and distributors are shown in Fig 1. Suppliers potentially provide the raw material. Being transported from supply centers to manufacturing centers, manufacturers can produce several new products. Products are transmitted to distributors who directly sent them to markets. Our proposed model aims to reduce costs, increase customer's satisfaction and decrease the vehicle emissions. Followings are considered as innovations in this paper, since they are not considered in the literature. We used fuzzy set for demand values in order to consider the uncertainties and fluctuations in real-life problems. As much as we want to make our problem closer to a real-life problem, specific types of vehicles with different capacities are considered. In reality, most of the time suppliers, manufacturing centers and distribution centers purchase or rent vehicles for the shipments. We consider this in our model because their costs are different and noticeably effect the final cost of the network. In order to reduce extra costs in terms of distance, we take into account the possibility of coalition in same-type centers. Innovations in this paper try to fulfill the gaps in the literature of supply chain network of mine industry.

The model has been proposed based on the following assumptions:

- Only the emission of the vehicle carrying loads in ongoing route is considered.
- Customers can demand and receive goods with no limitation.
- We did not consider assignment problem for landfills.
- Costs related to carrying of goods are considered fixed for different periods.
- Suppliers have the adequate raw material to deliver to manufacturers.
- Inventory cost for suppliers is not considered in our model.
- Inventory strategies differ in each manufacturing center.
- Manufacturers, suppliers and distributors can utilize both purchased and rented vehicles simultaneously.
- Coalition of the same type centers, for reducing costs in distance, is only considered for purchased vehicles, carrying from suppliers to manufacturers.

Sets

- s Suppliers $s = 1, \dots, S$
- m Manufacturer $m = 1, \dots, M$

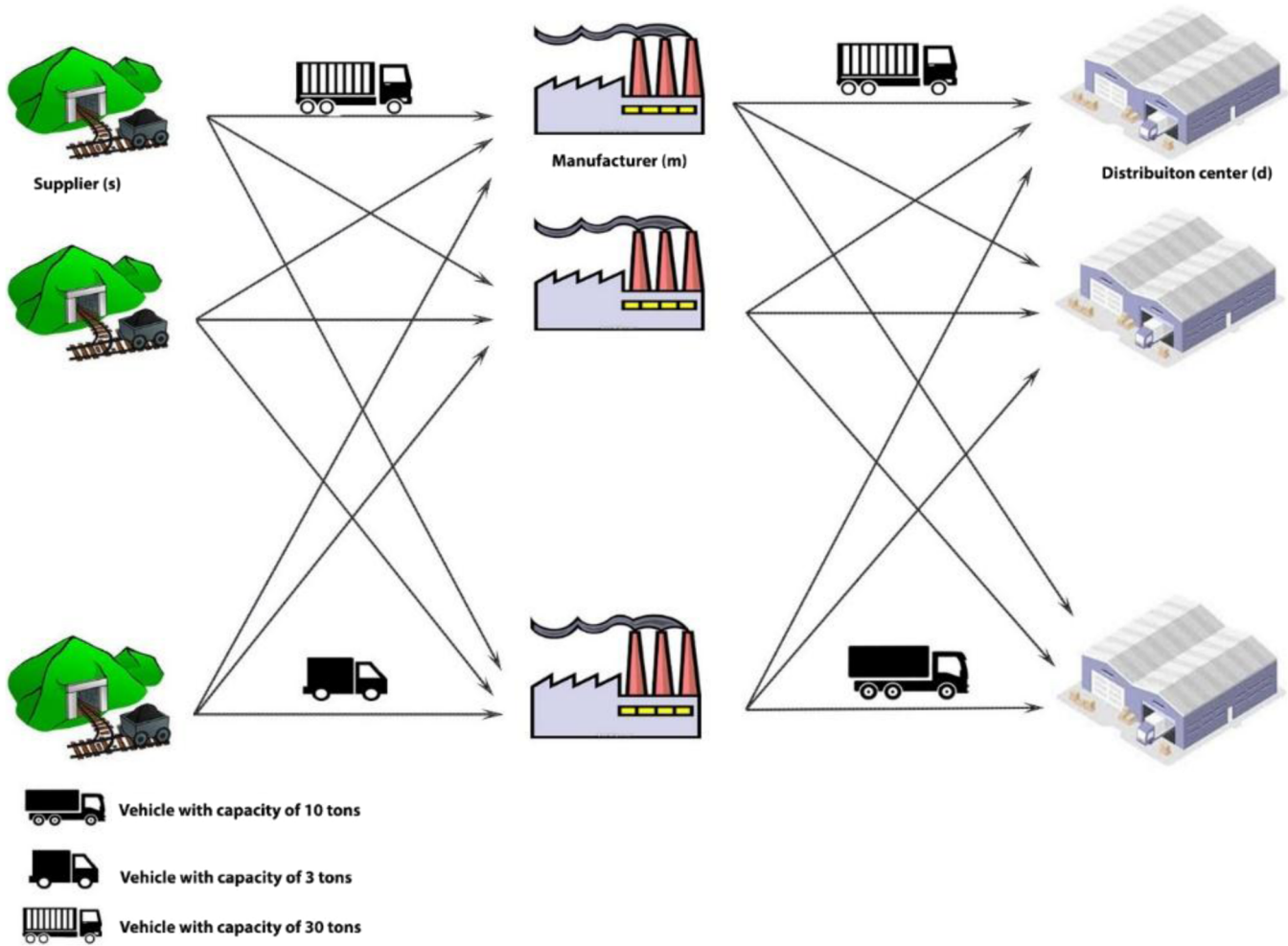


Fig 1. Mine industry networks.

| | | | |
|--|--|-------------|--|
| d | Distributor $d = 1, \dots, D$ | $v2_m$ | Weight capacity of manufacturing center m for holding raw material |
| v | Vehicles $v = 1, \dots, V$ | $v3_m$ | Weight capacity of manufacturing center m for holding the product |
| i | Manufacturing locations $i = 1, \dots, I$ | $v4_d$ | Weight capacity of distribution center d for holding the product |
| j | Distribution locations $j = 1, \dots, J$ | $g1$ | Unit weight of raw material |
| t | Time periods $t = 1, \dots, T$ | $g2$ | Unit weight of the product |
| Parameters and decision variables | | TT_t | Available time for manufacturing in period t |
| $C1_{smv}$ | Unit transportation cost from supplier s to manufacturing center m with purchased vehicle v | $R1$ | Number of distribution centers needed to be established |
| $C2_{mdv}$ | Unit transportation cost from manufacturing center m to distribution center d with purchased vehicle v | $R2$ | Number of Manufacturing centers needed to be established |
| $f1_{mi}$ | Fixed establishment cost of manufacturing center m at i | $\pi1_d$ | Unit shortage cost in distribution center d |
| $f2_{dj}$ | Fixed establishment cost of distribution center d at j | $\pi2_m$ | Unit shortage cost in manufacturing center m |
| PT_m | Time for producing a product in manufacturing center m | LN | Large number |
| ST_m | Installation time for producing a product in manufacturing center m | $q1_{smtv}$ | Number of raw material units transported from supplier s to manufacturing center m in period t with vehicle v |
| $p1_{sm}$ | Unit purchasing cost of raw material from supplier s by manufacturing center m | $q2_{mdtv}$ | Number of products transported from manufacturing center m to distribution center d in period t with vehicle v |
| $p2_{md}$ | Unit purchasing cost of product from manufacturing center m by distribution center d | $q4_{mt}$ | Number of produced products in manufacturing center m in period t |
| $l1_{sm}$ | Distance between supplier s and manufacturing center m | $b2_{mt}$ | Amount of shortage in manufacturing center m in period t |
| $l2_{md}$ | Distance between manufacturing center m and distribution center d | $b1_{dt}$ | Amount of shortage in distribution center d in period t |
| e_m | Producing cost of a product in manufacturing center m | $x0_{mt}$ | 1 if manufacturing center m produce product in period t , otherwise 0 |
| TD_t | Demand in period t | $x1_{mi}$ | 1 if manufacturing center m is established in i , otherwise 0 |
| $a1_v$ | CO2 emission from unloading vehicle v | $x2_{dj}$ | 1 if distribution center d is established in j , otherwise 0 |
| $a2_v$ | CO2 emission from loading vehicle v | $x3_{smtv}$ | 1 if raw material k is transported from supplier s to |
| $v1_v$ | Weight capacity of vehicle v | | |

$x4_{mdtv}$ manufacturing center m in period t with purchased vehicle v , otherwise 0
 1 if product p is transported from manufacturing center m to distribution center d in period t with vehicle v , otherwise 0

$$TTC = \sum_{s=1}^S \sum_{m=1}^M \sum_{v=1}^V \sum_{t=1}^T C1_{smv} q1_{smtv} + \sum_{m=1}^M \sum_{d=1}^D \sum_{v=1}^V \sum_{t=1}^T C2_{mdv} q2_{mdtv} \quad (1)$$

$$TSC = \sum_{m=1}^M \sum_{t=1}^T \pi 2_m b2_{mt} + \sum_{d=1}^D \sum_{t=1}^T \pi 1_d b1_{dt} \quad (2)$$

$$TOC = \sum_{m=1}^M \sum_{i=1}^I f1_{mi} x1_{mi} + \sum_{d=1}^D \sum_{j=1}^J f2_{dj} x2_{dj} \quad (3)$$

$$TPC = \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V p1_{sm} q1_{smtv} + \sum_{m=1}^M \sum_{d=1}^D \sum_{t=1}^T \sum_{v=1}^V p2_{md} q2_{mdtv} \quad (4)$$

$$TPM = \sum_{m=1}^M \sum_{t=1}^T e_m q4_{mt} \quad (5)$$

$$\text{Min } zz1 = TTC + TSC + TOC + TRC + TPC + TPM \quad (6)$$

$$PP_1 = \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V \frac{q1_{smtv}}{v1_v} (\alpha 2_v - \alpha 1_v) l1_{sm} \quad (7)$$

$$PP_2 = \sum_{d=1}^D \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V \frac{q2_{mdtv}}{v1_v} (\alpha 2_v - \alpha 1_v) l2_{md} \quad (8)$$

$$\text{Min } zz2 = PP_1 + PP_2 \quad (9)$$

$$\sum_{m=1}^M \sum_{d=1}^D \sum_{v=1}^V q2_{mdtv} \geq TD_t \quad \forall t \quad (10)$$

$$\sum_{d=1}^D \sum_{v=1}^V q2_{mdtv} = \sum_{s=1}^S \sum_{v=1}^V q1_{smtv} \quad \forall m, t \quad (11)$$

$$\sum_{m=1}^M PT_m q4_{mt} + \sum_{m=1}^M ST_m x0_{mt} \leq TT_t \quad \forall t \quad (12)$$

$$q4_{mt} g2 \leq v3_m x1_{mi} \quad \forall m, i, t \quad (13)$$

$$q1_{smtv} g1 \leq v2_m x1_{mi} \quad \forall s, m, i, t, v \quad (14)$$

$$q2_{mdtv} g2 \leq v4_d x2_{dj} \quad \forall d, m, t, j, v \quad (15)$$

$$q1_{smtv} g1 \leq v1_v \quad \forall t, v, s, m \quad (16)$$

$$q2_{mdtv} g2 \leq v1_v \quad \forall t, m, v, d \quad (17)$$

$$\sum_{d=1}^D \sum_{j=1}^J x2_{dj} = R1 \quad (18)$$

$$\sum_{d=1}^D x2_{dj} \leq 1 \quad \forall j \quad (19)$$

$$\sum_{i=1}^I \sum_{m=1}^M x1_{mi} = R2 \quad (20)$$

$$\sum_{m=1}^M x1_{mi} \leq 1 \quad \forall i \quad (21)$$

$$\sum_{v=1}^V x3_{smtv} \leq 1 \quad \forall s, m, t \quad (22)$$

$$\sum_{v=1}^V x4_{mdtv} \leq 1 \quad \forall d, m, t \quad (23)$$

$$\sum_{v=1}^V \sum_{d=1}^D q2_{mdtv} = q4_{mt} \quad \forall m, t \quad (24)$$

$$q1_{smtv} \leq LN. x3_{smtv} \quad \forall s, m, v, t \quad (25)$$

$$q2_{mdtv} \leq LN. x4_{mdtv} \quad \forall d, m, t, v \quad (26)$$

$$q1_{smtv}, q2_{mdtv}, q4_{mt}, q5_{dvt}, i1_{mt}, i2_{dt}, b2_{mt}, b1_{dt} \in z^+ \\ x1_{mi}, x2_{dj}, x3_{smtv}, x4_{mdtv} \in \{0, 1\} \quad (27)$$

Transportation costs, shortage costs, locating costs, purchase costs and production costs are minimized by objective functions (1–5) and (6), respectively. Objective functions (7) and (8) minimize the CO₂ emissions of vehicles. Eq. (10) ensures that number of products sent to distribution centers is more than their demand. Eq. (11) makes the balance in inventory of raw materials in the supplier and products sent to distribution centers from manufacturing centers. Eq. (12) ensures the production time. Eq. (13) ensures the production capacity of the product. Eq. (14) show the capacity limitation for raw materials in manufacturing center. Eq. (15) show the capacity limitation for the products in distribution center. Eq. (16) represents the capacity limitation for vehicles transporting goods from supplier to manufacturing center. Eq. (17) represents the capacity limitation for vehicles transporting goods from manufacturing center to distribution center. Eqs. (18) and (19) shows the establishment of distribution centers. Eqs. (20) and (21) shows the establishment of manufacturing centers. Available numbers of vehicles from supplier to manufacturing center is ensured in Eq. (22). Available numbers of vehicles from manufacturing center to distribution center is ensured in Eq. (23). Eq. (24) ensures that suppliers send out raw materials.

Eqs. (25) and (26) guarantee the usage of vehicles in respect to demand.

Eq. (27) assures that $q1_{smtv}$, $q2_{mdtv}$, $q4_{mt}$, $q5_{dvt}$, $i1_{mt}$, $i2_{dt}$, $b2_{mt}$, $b1_{dt}$ are non-negative variables, and $x1_{mi}$, $x2_{dj}$, $x3_r$, $x4_{smtv}$, $x5_{mdtv}$, $x6_{dctv}$ are binary variables.

Due to nonlinear terms in Eqs. (7) and (8), a linearization technique is used on ceil function in order to convert them to linear equations. For this, we introduce two new integer variables defined as $\frac{q1_{smtv}}{v1_v} = y$, $\frac{q2_{mdtv}}{v1_v} = z$. Using these, both of the objective functions changes to the Eqs. (28) and (29). In new constraints (31)–(34), both of new variables should be greater or equal to the terms of ceil function. On the other hand, they should also be smaller than the terms of ceil function plus one. Since ceil function gives the value for the bigger amount and that's the reason why the variables should be smaller in (31) and (33).

$$PP_1 = \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V y (\alpha 2_v - \alpha 1_v) l1_{sm} \quad (28)$$

$$PP_2 = \sum_{d=1}^D \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V z (\alpha 2_v - \alpha 1_v) l2_{md} \quad (29)$$

$$\text{Min } zz2 = PP_1 + PP_2 \quad (30)$$

$$y < \frac{q1_{smtv}}{v1_v} + 1 \quad \forall s, m, t, v \quad (31)$$

$$y \geq \frac{q1_{smtv}}{v1_v} \quad \forall s, m, t, v \quad (32)$$

$$z < \frac{q2_{mdtv}}{v1_v} + 1 \quad \forall m, d, t, v \quad (33)$$

$$z \geq \frac{q2_{mdtv}}{v1_v} \quad \forall m, d, t, v \quad (34)$$

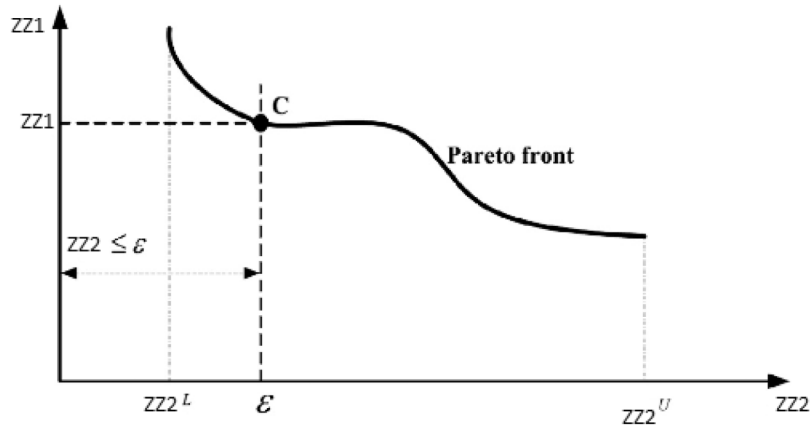


Fig 2. Solutions of ϵ -constraint method.

3.1. ϵ -constraint method

To solve the proposed model, first a method should be provided to deal with multiple objectives of the model. The ϵ -constraint method is used to convert our multi-objective model to a single objective model. In this method, one of the objective functions is chosen as main objective (ZZ1) to be optimized and the other objective function (ZZ2) is supposed to be constraint Ehrhoff [21]. Final form of model is represented as:

$$ZZ3 = \min(ZZ1) \tag{35}$$

$$ZZ2 \leq \epsilon \tag{36}$$

Eqs. (11)-(27) and (28)-(34)

Eq. (35) shows total objective function. The second objective function (ZZ2) is restricted by ϵ which is variable between $ZZ2^{min}$ and $ZZ2^{max}$. In each iteration, the single objective is solved for each value of ϵ . The series of solutions obtained are pareto optimal front of multi-objective problem that are shown in Fig 2.

It is shown in Fig 2 that solutions for first objective function and second objective function are in contradiction. In other words, an increase in one of the objective functions lead to the decrease in the other one.

4. Solution methodology

Benders decomposition algorithm, introduced by Benders [6], is one of the efficient and exact algorithms to solve large scale MIP problems. Benders decomposition instead of solving the original large model, reformulate the model by decomposing it to a pure integer programming, namely master problem (MP), and a linear programming called sub-problem (SP). Then the model is solved with cutting plane method by using the solution of one in the other until the optimal solution is achieved. Steps of Benders decomposition algorithm are described in Fig 3. As illustrated in the Fig. 3, a series of projections, outer linearization and relaxations are the main components of the Benders. In the first step, by having the set of complicated variables, the primal model is projected onto the subspaces. Then, the dual model is formulated for the obtained result, where extreme rays and points define the feasibility cuts and optimality cuts of those variables. Next, by enumeration of all the extreme rays and points, a new equivalent model is formulated. Solving this model by relaxation strategy considering feasibility cuts and optimality cuts lead to MP and SP. Then, the problem is solved iteratively to reach the optimal solution [51]. In other words, both MP and DSP are solved iteratively until they satisfy the convergence condition. Advantages of benders decomposition algorithm outweigh those of other algorithms like meta-heuristics or heuristics, used for solving problems with large sizes such as: (1) it relies on strong algebra

concepts, (2) the convergence of this algorithm and achievement of optimal solution is analytically proven, (3) the DM can adjust the optimality gap precisely when it is needed and (4) other efficient solution methods can be employed while solving the decomposed problems within a BDA [49]. So, we implement Benders decomposition for the concerned model. Sub-problem (SP), MP and Dual-sub problem (DSP) are formulated in this part.

For multi-objective model provided in previous section, MP model becomes:

$$\text{Min MP} = \sum_{i=1}^I \sum_{m=1}^M f1_{mi}x1_{mi} + \sum_{d=1}^D \sum_{j=1}^J f2_{dj}x2_{dj} + \xi \tag{37}$$

s.t.

$$\sum_{d=1}^D \sum_{j=1}^J x2_{dj} = R1 \tag{38}$$

$$\sum_{d=1}^D x2_{dj} \leq 1 \quad \forall j \tag{39}$$

$$\sum_{i=1}^I \sum_{m=1}^M x1_{mi} = R2 \tag{40}$$

$$\sum_{m=1}^M x1_{mi} \leq 1 \quad \forall i \tag{41}$$

$$\sum_{v=1}^V x3_{smtv} \leq 1 \quad \forall s, m, t \tag{42}$$

$$\sum_{v=1}^V xd_{mdtv} \leq 1 \quad \forall m, d, t \tag{43}$$

$$\begin{aligned} &Sub^v + \sum_{i=1}^I \sum_{m=1}^M \theta1_{mi}(x1_{mi} - x1_{mi}^\varphi) \quad \forall \varphi = 1, 2, \dots, rep \\ &+ \sum_{d=1}^D \sum_{j=1}^J \theta2_{dj}(x2_{dj} - x2_{dj}^\varphi) \\ &+ \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V \theta3_{smtv}(x3_{smtv} - x3_{smtv}^\varphi) \\ &+ \sum_{m=1}^M \sum_{d=1}^D \sum_{t=1}^T \sum_{v=1}^V \theta4_{mdtv}(x4_{mdtv} - x4_{mdtv}^\varphi) \leq \xi \end{aligned} \tag{44}$$

$\theta1_{mi}$, $\theta2_{dj}$, $\theta3_{smtv}$ and $\theta4_{mdtv}$ are dual variables to constraints. We fix following variables $x1_{mi} = \bar{x1}_{mi}$, $x2_{dj} = \bar{x2}_{dj}$, $x3_{smtv} = \bar{x3}_{smtv}$, $x4_{mdtv} = \bar{x4}_{mdtv}$. The primal sub-problem (PSP) can be defined as follows:

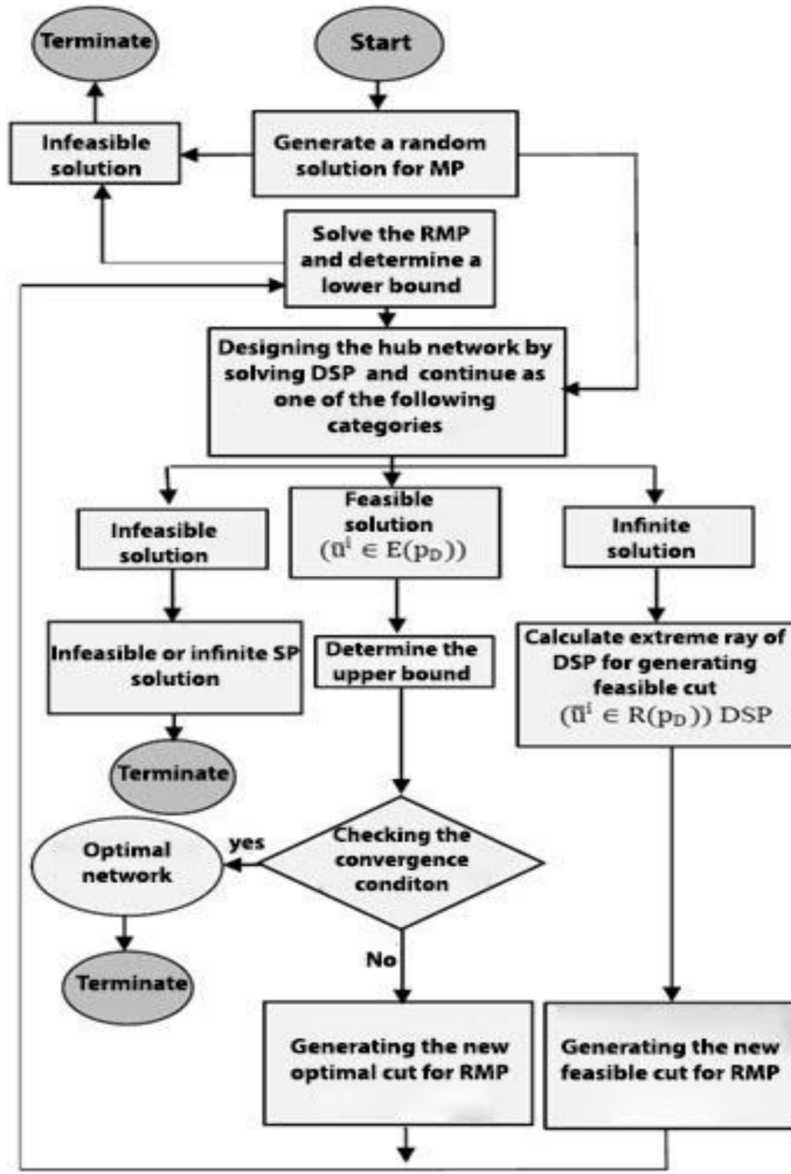


Fig 3. Benders decomposition algorithm.

$$\begin{aligned}
 \text{Min } PSP &= \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V C1_{smtv} q1_{smtv} & - q4_{mt} g2 + v3_m x1_{mi} &\geq 0 & \forall m, t, i & (51) \\
 &+ \sum_{m=1}^M \sum_{d=1}^D \sum_{t=1}^T \sum_{v=1}^V C2_{mdtv} q2_{mdtv} & - q1_{smtv} g1 &\geq -v1_v & \forall s, m, t, v & (52) \\
 &+ \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V p1_{smtv} q1_{smtv} & - q2_{mdtv} g2 &\geq -v1_v & \forall m, d, t, v & (53) \\
 &+ \sum_{m=1}^M \sum_{d=1}^D \sum_{t=1}^T \sum_{v=1}^V p2_{mdtv} q2_{mdtv} + \sum_{m=1}^M \sum_{t=1}^T e_m q4_{mt} & (45) & - \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V y(a2_v - a1_v) l1_{sm} - \sum_{d=1}^D \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V z(a2_v - a1_v) l2_{md} & \geq -\epsilon & (54) \\
 \text{s.t.} & & (46) & \sum_{v=1}^V \sum_{d=1}^D q2_{mdtv} - q4_{mt} = 0 & \forall m, t & (55) \\
 \sum_{m=1}^M \sum_{d=1}^D \sum_{v=1}^V q2_{mdtv} &\geq TD_t & \forall t & & & \\
 \sum_{d=1}^D \sum_{v=1}^V q2_{mdtv} - \sum_{s=1}^S \sum_{v=1}^V q1_{smtv} &= 0 & \forall m, t & & & (56) \\
 \sum_{m=1}^M PT_m q4_{mt} + \sum_{m=1}^M ST_m \overline{x0_{mt}} &\leq TT_t & \forall t & & & (48) \\
 q2_{mdtv} g2 &\leq v4_d x2_{dj} & \forall m, d, t, v, j & & & (49) \\
 -q1_{smtv} g1 + v2_m x1_{mi} &\geq 0 & \forall s, m, t, v, i & & & (50) \\
 & & & & & (47) & - q1_{smtv} \geq -LN. \overline{x3_{smtv}} & \forall s, m, t, v & (56) \\
 & & & & & & - q2_{mdtv} \geq -LN. \overline{x4_{mdtv}} & \forall m, d, t, v & (57) \\
 & & & & & & - y + \frac{q1_{smtv}}{v1_v} + 1 \geq 0 & \forall s, m, t, v & (58) \\
 & & & & & & - z + \frac{q2_{mdtv}}{v1_v} + 1 \geq 0 & \forall m, d, t, v & (59)
 \end{aligned}$$

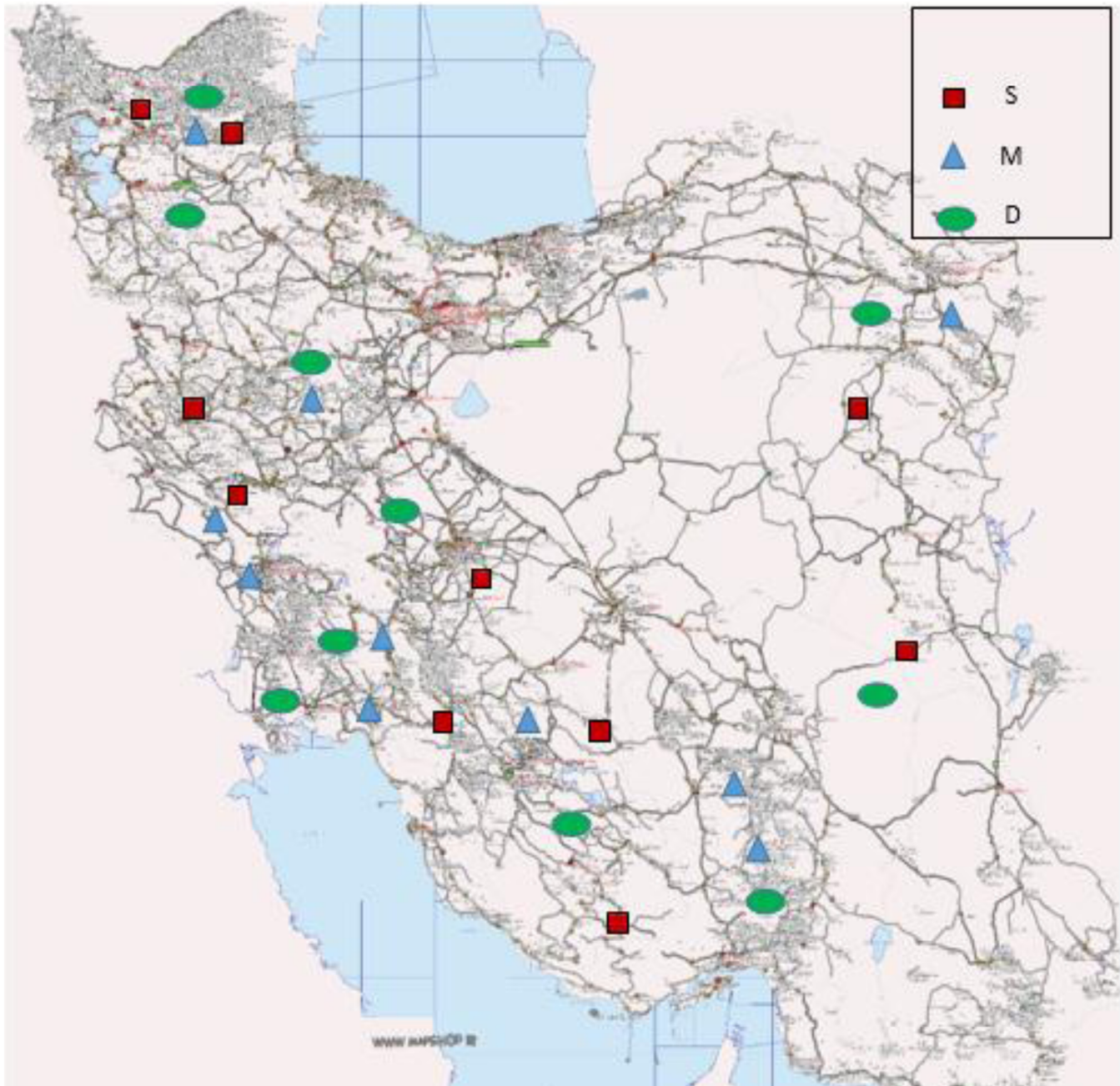


Fig 4. Suppliers (s), Manufacturing centers (m) and distributors (d) in Iran.

Table 2
Transportation cost between mines and manufacturing centers.

| | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | M10 |
|-----|------|------|------|------|------|------|------|------|------|------|
| S1 | 61 | 720 | 1134 | 1839 | 1575 | 1908 | 831 | 694 | 1313 | 1292 |
| S2 | 166 | 833 | 1080 | 2126 | 1681 | 1964 | 911 | 1007 | 1247 | 1307 |
| S3 | 1100 | 525 | 265 | 498 | 980 | 840 | 444 | 499 | 520 | 80 |
| S4 | 1545 | 987 | 698 | 189 | 1095 | 308 | 1063 | 1054 | 300 | 405 |
| S5 | 1504 | 913 | 915 | 778 | 300 | 1650 | 1027 | 1420 | 904 | 655 |
| S6 | 1892 | 1374 | 1098 | 550 | 682 | 878 | 1260 | 1467 | 1070 | 821 |
| S7 | 941 | 238 | 221 | 1046 | 1088 | 1149 | 11 | 253 | 530 | 487 |
| S8 | 792 | 367 | 285 | 1162 | 1214 | 1324 | 189 | 85 | 602 | 619 |
| S9 | 1425 | 782 | 329 | 680 | 1302 | 747 | 701 | 1120 | 10 | 381 |
| S10 | 1263 | 707 | 471 | 425 | 989 | 745 | 619 | 827 | 390 | 125 |

Table 3
Transportation cost between distribution centers and manufacturing centers.

| | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 |
|-----|------|------|------|------|------|------|------|------|------|------|
| M1 | 10 | 630 | 905 | 1515 | 1520 | 1810 | 1130 | 720 | 1390 | 500 |
| M2 | 690 | 60 | 400 | 930 | 890 | 1270 | 780 | 550 | 790 | 380 |
| M3 | 935 | 470 | 30 | 725 | 1160 | 1000 | 550 | 600 | 430 | 480 |
| M4 | 1515 | 990 | 700 | 10 | 910 | 490 | 1090 | 1290 | 560 | 1315 |
| M5 | 1520 | 890 | 1160 | 910 | 10 | 1400 | 1630 | 1430 | 1350 | 1225 |
| M6 | 1810 | 1320 | 980 | 490 | 1400 | 10 | 1140 | 1620 | 600 | 1550 |
| M7 | 750 | 280 | 210 | 1000 | 1100 | 1300 | 600 | 340 | 690 | 500 |
| M8 | 800 | 490 | 280 | 1070 | 1300 | 1300 | 340 | 200 | 840 | 650 |
| M9 | 1290 | 750 | 300 | 660 | 1245 | 700 | 640 | 980 | 100 | 1050 |
| M10 | 1145 | 630 | 325 | 365 | 920 | 660 | 850 | 930 | 450 | 950 |

Table 4
IMSC case study results.

| Scenarios | Demand | S | M | D | ZZ3 | Time (benders) | Time (GAMS) | Improvement (%) |
|-----------|--------|----|----|----|---------------|----------------|-------------|-----------------|
| 1 | – | 10 | 10 | 10 | 1550652913.65 | 10.20 | 23.023 | +55.69% |
| 2 | +15% | 10 | 10 | 10 | 1814263908.97 | 11.65 | 21.536 | +45.87% |
| 3 | –15% | 10 | 10 | 10 | 1364574564.01 | 4.05 | 15.854 | +74.40% |
| 4 | +20% | 10 | 10 | 10 | 2051282426.11 | 10.68 | 12.01 | +11.07% |
| 5 | –20% | 10 | 10 | 10 | 1128351001.55 | 5.8 | 5.06 | –13.21% |
| 6 | +40% | 10 | 10 | 10 | 2400928861.47 | 13.42 | 11.29 | +18.86% |
| 7 | –40% | 10 | 10 | 10 | 9203039402.82 | 9.55 | 9.18 | –04.03% |

Table 5
IMSC problem cases.

| Class | S | M | D | V |
|-------|----|----|----|---|
| C1 | 10 | 10 | 10 | 3 |
| C2 | 10 | 5 | 8 | 3 |
| C3 | 8 | 10 | 12 | 4 |
| C4 | 13 | 15 | 17 | 5 |
| C5 | 13 | 11 | 19 | 3 |
| C6 | 8 | 14 | 14 | 4 |

Table 6
Computational results on problem cases.

| Class | Benders decomposition Objective functions value | CPLEX | | | |
|-------|--|-----------|--------|---------------------------|--------|
| | | Iteration | CPU(s) | Objective functions value | CPU(s) |
| C1 | 1,160,285,000.00 | 12 | 5.1 | 1,160,240,000.00 | 4.2 |
| C2 | 8,564,320,000.00 | 15 | 6.9 | 8,564,320,000.00 | 9.2 |
| C3 | 1,487,957,664.67 | 14 | 5.5 | 1,487,787,664.67 | 5.3 |
| C4 | 5,071,507,579.38 | 29 | 14.7 | 5,069,507,579.38 | 9.6 |
| C5 | 2,302,581,821.50 | 22 | 8.0 | 2,302,281,821.50 | 10.4 |
| C6 | 3,931,226,286.77 | 19 | 10.8 | 3,931,226,286.77 | 16.3 |

$$z - \frac{q2_{mdtv}}{v1_v} \geq 0 \quad \forall m, d, t, v \quad (60)$$

The Dual sub-problem (DSP) can be defined as follows:

$$\begin{aligned}
 \text{Max DSP} = & \sum_{t=1}^T TD_t \theta5_t + \sum_{t=1}^T (TT_t + \sum_{m=1}^M ST_m \bar{x0}_{mt}) \theta7_t \\
 & + \sum_{d=1}^D \sum_{j=1}^J v4_d \bar{x2}_{dj} \theta8_{dj} \\
 & - \sum_{v=1}^V v1_v \theta11_v - \sum_{v=1}^V v1_v \theta12_v - \epsilon \theta13 \\
 & - \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V LN. \bar{x3}_{smtv} \theta15_{smtv} \\
 & - \sum_{m=1}^M \sum_{d=1}^D \sum_{t=1}^T \sum_{v=1}^V LN. \bar{x4}_{mdtv} \theta16_{smtv}
 \end{aligned} \quad (61)$$

s.t.

$$\begin{aligned}
 \theta5_t + \theta6_{mdtv} - g2\theta8_{dj} - g2\theta12_v - \theta16_{mdtv} + \frac{1}{v1_v} \theta18_{mdtv} - \frac{1}{v1_v} \theta19_{mdtv} \\
 \leq C2_{mdtv} + p2_{mdtv} \quad \forall m, d, t, v \quad (62)
 \end{aligned}$$

$$\begin{aligned}
 -\theta6_{mdtv} - g1\theta9_{smtv} - \theta15_{smtv} - \frac{1}{v1_v} \theta17_{smtv} \\
 \leq p1_{smtv} + C1_{smtv} \quad \forall s, m, t, v \quad (63)
 \end{aligned}$$

$$PT_m \theta7_t - g2\theta10_{mti} \leq e_m \quad \forall m, t, i \quad (64)$$

$$\sum_{m=1}^M \sum_{d=1}^D \sum_{v=1}^V q2_{mdtv} \geq TD_t \quad \forall m, d, t, v \quad (65)$$

$$\sum_{d=1}^D \sum_{v=1}^V q2_{mdtv} - \sum_{s=1}^S \sum_{v=1}^V q1_{smtv} = 0 \quad \forall m, d, t, v \quad (66)$$

$$- \sum_{m=1}^M PT_m q4_{mt} \geq TT_t + \sum_{m=1}^M ST_m \bar{x0}_{mt} \quad \forall t \quad (67)$$

$$- q2_{mdtv} g2 \geq v4_d \bar{x2}_{dj} \quad \forall m, d, t, v \quad (68)$$

$$- q1_{smtv} g1 + v2_m x1_{mi} \geq 0 \quad \forall s, m, t, v, i \quad (69)$$

$$- q4_{mt} g2 + v3_m x1_{mi} \geq 0 \quad \forall m, t, i \quad (70)$$

$$- q1_{smtv} g1 \geq -v1_v \quad \forall s, m, t, v \quad (71)$$

$$- q2_{mdtv} g2 \geq -v1_v \quad \forall m, d, t, v \quad (72)$$

$$\begin{aligned}
 - \sum_{s=1}^S \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V y(a2_v - a1_v) l1_{sm} - \sum_{d=1}^D \sum_{m=1}^M \sum_{t=1}^T \sum_{v=1}^V z(a2_v - a1_v) l2_{md} \\
 \geq -\epsilon \quad \forall d \quad (73)
 \end{aligned}$$

$$\sum_{v=1}^V \sum_{d=1}^D q2_{mdtv} - q4_{mt} = 0 \quad \forall m, t \quad (74)$$

$$- q1_{smtv} \geq -LN. \bar{x3}_{smtv} \quad \forall s, m, t, v \quad (75)$$

$$- q2_{mdtv} \geq -LN. \bar{x4}_{mdtv} \quad \forall m, d, t, v \quad (76)$$

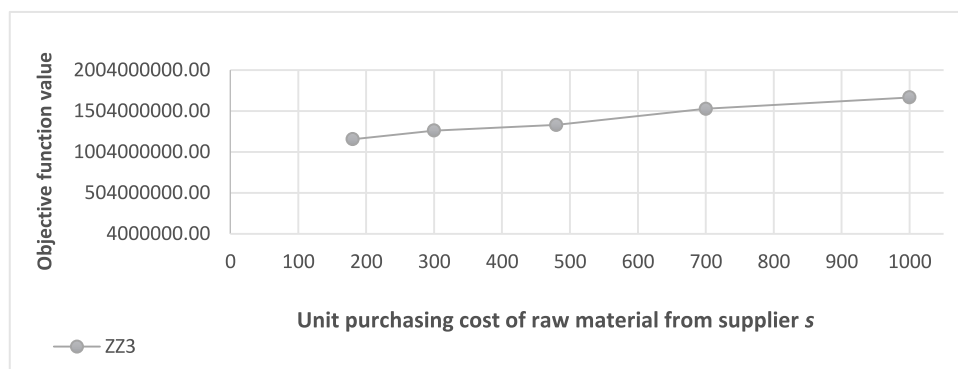


Fig 5. Objective function vs. unit purchasing cost of raw material.

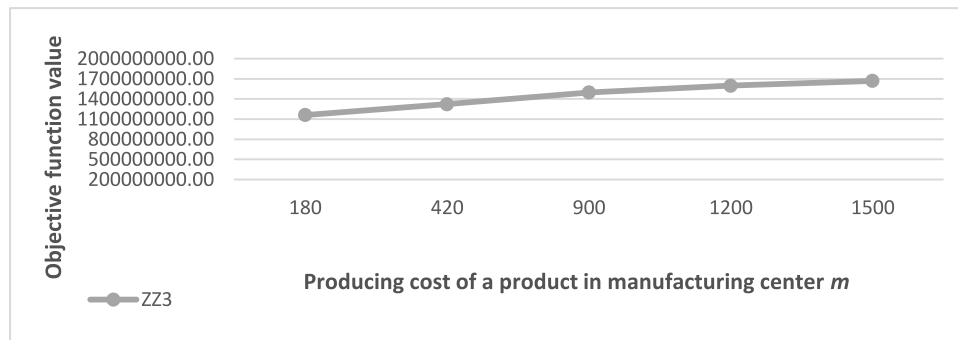


Fig 6. Objective function vs. producing cost of product.

$$-y + \frac{q1_{smtv}}{v1_v} + 1 \geq 0 \quad \forall s, m, t, v \tag{77}$$

$$-z + \frac{q2_{mdtv}}{v1_v} + 1 \geq 0 \quad \forall m, d, t, v \tag{78}$$

$$z - \frac{q2_{mdtv}}{v1_v} \geq 0 \quad \forall m, d, t, v \tag{79}$$

5. Case study

In this section, the proposed model and solution algorithm is applied for a real-life case of IMSC and the corresponding results are represented and analyzed. In this stage, Iran currently has ten active mines spread in different geographical parts of the country. Likely one manufacturing center and one distribution center exist near each mine in Iran. Considered mines, manufacturing centers and distribution centers in this paper are illustrated in Fig 4. Transportation cost between three parts of IMSC are represented in Tables 2 and 3.

Most important issue of mine supply chain in Iran has to do with the policy taken by private corporations extracting material from mines. Main policy of these corporation is to plan manually for their orders from manufacturing centers. Next, manufacturing centers do not consider costs related to transportation of material from supplier. Their only criterion to choose to buy material has to do with the suppliers' sale cost. They rarely consider criteria such as distance, vehicle type, emissions of the vehicle and etc. The aim of investigating green supply chain of mine industry in Iran is to reduce extra costs, increase the profit for suppliers, manufacturing centers and distribution centers and decrease emissions based on the vehicles that are used in transportation. Therefore, managers could make better decisions on productivity of the mine industry in Iran.

As stated in problem description section, we consider demands as triangular fuzzy number (Q_1, Q_2, Q_3). Q_2 represents the determined demand value. For Q_1 and Q_3 , we consider six demand-based scenarios in such a way that for Q_1 we consider demands as -15%, -20% and -40% of the deterministic demand; and for Q_3 we choose positive values +15%, 20% and 40% of deterministic demand. Then, we solve the model under seven scenarios based on the fuzzy demand. We ran our model seven times with deterministic demand values, and defined scenarios for demand values. Both R1 and R2 which respectively represent number of distribution centers needed to be established and number of manufacturing centers needed to be established are considered to be two. GAMS 24.9.1 optimization software is used to implement the model and the solution method and all the other experimental are carried out by an Intel Core i7, 2.4 GHz computer with 8 GB RAM. The reason that GAMS 24.9.1 optimization solver and CPLEX solver is used to solve the model has to do with the medium size of our linear programming model.

In Table 4, number of suppliers, manufacturing centers, distributors, optimal objective value, computational time using Benders

decomposition and computational time using GAMS 24.9.1 software are presented. As it is shown in Table 4, Benders decomposition solution approach effectively decrease the computational time of solving the case problem at most by 74.4% in scenario 3. While GAMS software solves the model in not a long time, there may be an argument about the necessity of Benders decomposition in such situations. However, it is needless to say that Benders decompositions will be more valuable when the size of problem grow in future.

Then, we employ five classes of problems in which test instances, sets and parameters, are generated randomly. Generated values for sets are shown in Table 5. Class 1 represents the original values for case of Iran.

As far as the results shown in Table 6 are concerned, it is visible that unlike the CPLEX that solves the test instances in very long time, not only benders decomposition algorithm solves all the test instances of different size to optimality with iota gaps, but also it solves them in more reasonable amount of time. In addition, CPLEX solver may solve the instances with small size in good time but running time will increase exponentially as the size of problem increases.

We did a series of sensitivity analysis to see how changes in parameters effects objective function value. Fig 5 shows the results of objective function with respect to changes in unit purchasing cost of raw material from supplier s by manufacturing center m . By increasing the purchasing value, objective function value increases, too. Furthermore, the increase in purchasing cost of raw material will also change objective function vale more, as purchasing cost of product from manufacturing center by distributor would probably increase, too.

Manufacturing centers are of great importance in determining the price of a product which surely has to do with producing cost of that product. Hence, little changes in producing costs of a product will strongly influence the price of final product. Here, we analyze our model with respect to increase in producing cost of a product in manufacturing center. The results in Fig 6 illustrates that increase in unit producing cost of product in manufacturing center will worsen objective function value.

6. Conclusion

In this paper, we developed multi-objective mixed integer programming models in order to minimize the transportation costs, shortage costs, purchase costs, production costs and CO₂ emissions of vehicles. In order to consider uncertainty in our model, demand values were chosen as a triangular fuzzy number. Then we evaluated our models with a real-life case problem related to Iranian mine industry. Providing a large employment opportunity and also producing a great mass of mineral products such as gold, metal and copper, mines are of great significance to the economy of the Iran. Most of the manufacturing centers and distributors are established randomly based on their close distance to the mines and other factors such environmental, economic, geographical criteria are not taken into account. With taking these factors, mine industry can easily prevent many unnecessary costs.

Besides, mines are always under pressure of environmental activists since mine industry is one of the major causes that cause air pollution in Iran.

For future studies, our model can be extended into taking into account more environmental factors based on mining activities. In addition, a location-allocation problem can be formulated for choosing the optimal manufacturing and distribution centers location and mines allocation to those centers. Also, a robust model can be formulated by considering uncertainty in flow among suppliers-manufacturing centers-distribution centers or disruption in any echelon of the supply chain.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.orp.2018.11.002](https://doi.org/10.1016/j.orp.2018.11.002).

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