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RESEARCH PAPER

Sustainable Supply Chain Network Design with Price-Based Demand Considering Sound and Dust Pollutions: A Case Study

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Abstract

The mining industry is taken into consideration due to its significant role in the economic growth of developing countries. Moreover, stone quarries have great effects on other industry sectors such as building and production. Thus, this research presents a three-objective multi-period multi-product mixed-integer quadratic programming problem to optimize a sustainable stone supply chain network design. Maximizing total profit as an economic aspect, minimizing sound pollution as a social aspect, and minimizing dust pollution as an environmental aspect of sustainability are considered simultaneously in this paper for the first time. Furthermore, stone pricing is considered in this paper through a price-based demand. An ε-constraint approach is utilized to solve the multi-objective model and achieve the non-dominated solutions. A real case study on Iranian stone quarries is analyzed to show the applicability of the addressed model. Finally, the managerial insights are presented as guidance to the government and managers for better decisions in the mentioned supply chain. The results show the great potential of installing quarries in the center of Iran geographically and that Razavi Khorasan is the best area for exporting stones.

Keywords:
Stone Supply Chain Network Design;
Sustainable Development;
E-Constraint Approach;
Pricing

Introduction

Mining is a significant section of many countries' economics all over the world which contributes 4-7% of greenhouse gas emissions and 0.5% of global gross domestic product [1]. The mining industry is an important infrastructure in Iran due to the scattering of mineral resources in the country. Also, this industry has an undeniable and significant role in the financial improvement of developing countries [2,3].

There are some basic activities in the mining supply chain such as mineral resources extraction, processing, and shipping the minerals from mining locations to markets [4]. Uncontrolled and arbitrary mining operations have considerably caused environmental degradation over the years. Thus, the main challenge of this industry is sustainability matters [5]. Some of the environmental issues that can happen in the mining industry are greenhouse gas emissions and global warming because of the transportations, utilization of different devices for extracting, and mineral processing [6]. There are also other environmental issues such as visual intrusion, noise, traffic, vibrations, and dust pollutions [7,8].

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Mining is an industry in which social, environmental, and economic decisions are interdependent [9]. Thus, this industry has to consider the significance of social responsibility, environmental management, and sustainable development throughout the past two decades [6]. Considering the aforementioned points, the sustainability concept would require more effective attention in terms of deposits with non-renewable resources like stones that will be proposed in this paper. Moreover, the tendency of stone importation is an important challenge in Iran, despite the abundant mineral resources. Therefore, the important issue is considering the price of local stone through a price-based demand to make a competition in local stone and imported stone prices.

Since the literature about mining supply chain network design is rare [10] and to the best of our knowledge, it has been neglected to investigate a stone supply chain network design (SSND) by considering sound and dust pollutions along with economic aspects, this study proposes a multi-objective sustainable SSND. The objective functions of this study are maximizing total profit, minimizing sound pollution, and minimizing dust pollution, simultaneously.

The rest of this paper is prepared as follows. A literature review in the mining area is presented in Section 2. In Section 3, the problem statement and ε-constraint method are explained. The presented model is applied in a real-world case study in Section 4. Also, managerial insights and computational results are proposed in this section. Finally, the conclusion and future research directions are presented in Section 5.

Literature review

The mining industry helps to economic growth in Iran annually and this industry is an important economic activity for centuries [2]. Therefore, there are various challenges in designing a mining supply chain network. Some relevant studies will be reviewed concisely in the next paragraphs.

There are some researches considering the sustainable aspect of mining supply chain network design. Phillips [11] has evaluated the environmental impacts in two diverse open cast iron ore mines through a sustainable mathematical model. He also showed the importance of sustainability in two considered mines in Iran. Zohal and Soleimani [12] have proposed a green closed-loop supply chain network design through a multi-objective mathematical model to optimize this supply chain in the gold industry. Carbon and cost minimization in addition to revenue maximization are the three objective functions of their research. Also, they have developed an ant colony approach for solving their model. Canales-Bustos et al. [13] have developed a mathematical formulation to optimize a green mining supply chain network design. They have also presented an epsilon-constraint-based algorithm and a multi-objective particle swarm algorithm to solve the model and achieve Pareto optimal front. Fattahi et al. [14] have developed a stochastic mining supply chain network design addressing the uncertainty in renewable energy resources. Wind and solar generators are taken into account to achieve low carbon emissions in mining processes. Soleimani [15] has developed a sustainable closed-loop supply chain network design in mining for ornamental stone quarries. Moreover, profit maximization and energy minimization are two goals of this study. Also, service level and fixed-charged transportation are the considered concepts in the mentioned paper. Attari and Torkayesh [2] have proposed a multi-objective mathematical formulation to optimize the mining supply chain network design by minimizing cost and carbon emissions. Furthermore, the demand uncertainty is considered and the benders decomposition algorithm is applied to solve the model. Muchaendepi et al. [16] have investigated on Zimbabwe mining sector to illustrate an absence of organizational and structural alteration needed for supporting the implementation of sustainable supply chain management. Recently, Valderrama et al. [10] have developed a multi-product and multi-period model of mining supply chain network design that integrates environmental and economic issues. Also, the extracted ore grade and its quality are taken into account in their mathematical model.

Several articles have considered other aspects of mining (i.e. sustainability is not taken into account). For example, Pimentel et al. [17] have handled a capacity planning problem through multi-stage stochastic programming in the global mining supply chain. Also, some solution methods from exact to approximate approaches were examined through a software configuration. Fung et al. [18] have proposed a hybrid mixed-integer linear programming model solved by a simulated annealing algorithm and optimized the mineral resources capacity planning. Patterson et al. [19] have proposed a mathematical model to optimize the energy efficiency of a coal mine. Zhang et al. [20] have addressed a mineral value chain mathematical model by a benders decomposition-based approach. Indeed, the related down and upstream operations are optimized in this value chain. They have also addressed the market uncertainty in the mentioned value chain and illustrated that neglecting this uncertainty causes an underestimation in total profit. Hosseini et al. [21] have proposed the development of Lane's model to define the optimal production plan and stockpile in mining operation of oil sands. Moreover, Azzamouri et al. [22] have developed a quadratic mathematical model to optimize the employed source ores quantities in the factory, transported source ores amount from the mines, and the safety stocks optimization to face the unexpected change in the merchantable ores book order. Haonan et al. [23] have addressed heuristics to solve the integrated mining supply chain and mine production scheduling. The difference of this study compared with the most important previous studies of the literature was presented in Table 1.

It is obtained from the following Table that previous studies in mining supply chain network design have not considered mineral products pricing. So, this research considers competition between local and abroad stone suppliers for the first time. Moreover, sound and dust pollutions are not taken into account in the literature.

Table 1. Literature review of mining supply chain

References		Products		Network sections				Decision type						Time period		Objective function					Considering elastic demand	Case study
Number	Year	Single-product	Multi-product	Mine	Factory	Distribution center	Customer	Location	Product flow	Inventory	Pricing	Capacity planning	Allocation	Single-period	Multi-period	Cost /Profit	Carbon emission	Sound pollution	Dust pollutions	Other		
Pimentel et al. [17]	2011		*	*	*		*	*	*			*	*	*		*						
Fung et al. [18]	2015	*		*		*			*			*			*	*						
Zohal and Soleimani [12]	2016	*		*	*	*	*	*	*				*	*		*	*					Gold
Canales-Bustos et al. [13]	2017		*					*					*	*		*	*			*		
Soleimani [15]	2018		*	*	*		*	*	*	*			*		*	*				*		Decorative stone
Fattahi et al. [14]	2018		*	*			*	*	*				*		*	*						Zink
Attari and Torkayesh [2]	2018	*		*	*	*		*	*				*		*	*	*					Iranian mines
Zhang et al. [20]	2019		*	*			*	*	*	*		*	*		*					*		
Valderrama et al. [10]	2020		*					*	*	*			*		*	*	*					Iron ore
This study	2021		*	*	*	*	*	*	*	*	*		*		*	*		*	*		*	Stone quarries

Considering the aforementioned points, most of the sustainable models in mining supply chain network design represent common types of goals such as maximizing profit or minimizing costs or carbon emissions. Furthermore, the non-sustainable mathematical models in the mining supply chain are generally developed for capacity planning and the mineral value chain.

The researches on sustainable supply chain network design by considering environmental aspects is rare [13]. However, according to the literature review, despite the importance of considering sound and dust pollution in mining supply chain network design, there is no article devoted to it. It should be noted that due to the cities development, mines have approached them which has caused sound and dust pollutions in many cities. Furthermore, despite the equipment to protect miners' health against sound pollution, they are not adequate. Since drilling and blasting activities take place in mining areas with sequent dust and noise, silicosis and hearing loss are usually happened in mining operations [24]. Thus, it is important to consider these issues.

This paper presents a multi-objective multi-product multi-period mixed-integer quadratic model for SSND on research gaps. The first objective function as an economic goal aims to maximize the total profit of the mentioned supply chain. The second one minimizes dust pollution as an environmental goal. Finally, the third objective function minimizes sound pollution as a social goal based on the EN16309 standard [25] which Dolezal and Spitzbart-Glasl [26] have also utilized in their work to illustrate the sound as a social aspect because of its impact on the neighborhood.

The main contributions of this study that make it different from other papers in mining supply chain network design are as follow:

- A multi-objective multi-product mixed-integer quadratic problem over a multi-period time horizon is introduced for optimizing the planning and design of the SSND model.
- According to the variety of pollutions in mining industries, this paper considers sound and dust pollutions through an optimization mathematical model for the first time.
- Despite the abundance of stone quarries in Iran, the stone is imported from other countries. In other words, there is competition between local and abroad suppliers. Thus, a price-based demand is considered in this research to take into account the competition in local and imported stones prices.

In more detail, Fig. 1 illustrates the main research gaps in mining supply chain network design. According to the literature review, all previous researches have considered the demand of mineral products as a parameter. This paper considers a price-based demand according to the country's situation (stone importations) and takes into account competition between local and abroad suppliers in the mining industry for the first time.

Furthermore, all sustainable researches in the mining supply chain have considered the minimization of carbon emissions as the environmental aspect of sustainability. This research tries to minimize dust and sound pollutions of mining locations for the first time and considers penalties and rewards for redundant and saved pollutions.

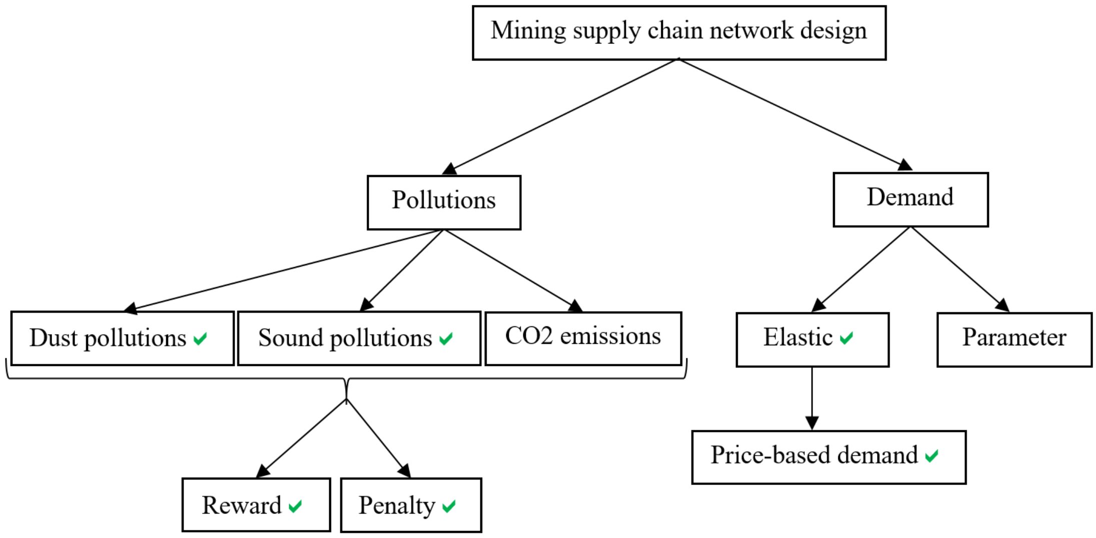

Fig. 1. A framework of main research gaps.

Problem statement

As mentioned before, the mining industry has an undeniable role in the financial growth of countries. Moreover, there are a few researches that have considered sustainability aspects in the mining supply chain and specifically, manpower health has not been taken into account.

Pollutants can shut down different parts of the country and damage the economy, severely. Moreover, it is necessary to consider the environment, the vegetation, the miners' health and some of their problems such as silicosis and hearing loss, and also residential areas that are impacted by mining activities due to producing sound and dust pollutants in the mining industry. Unfortunately, there is no study devoted to the relevant pollutions in the mining supply chain. Thus, it is important to address the practical gaps through designing a mining supply chain network design.

Therefore, a multi-objective multi-level multi-product model is proposed to optimize the planning of SSND in multi-periods. The stone supply chain encompasses four levels illustrated in Fig. 2. In the first level, the dimension stones are extracted from the quarries. Then, the extracted stones are sent to stone-cutting factories after cutting into blocks. In the next stage, the blocks pass different processes and they are cut into slabs matching to the customer demands in the factory. Then, the slabs are delivered to the distribution centers. Finally, the stones with different types are transported to customers.

The presented model aims to reduce sound and dust pollutions and maximize the total profit of the SSND model. Moreover, there is competition between local and imported stone prices due to the abundant stone importation. So, the local stone pricing is investigated in the proposed model.

It determines the optimum locations for quarries, cutting factories, and stone distribution centers. Also, the level of inventory in distribution centers and cutting factories, the stone price, the flow amount allocation between facilities (considering stone waste percentage), pollution values, and the optimal value of customer requests are the decision targets of the proposed model. The declared decisions decide about the values which are serious for decision-makers and managers. Also, these values practically exist in the real world.

Moreover, the assumptions of the proposed mathematical model are described as follows:

- The model is considered multi-period and multi-product.
- There is limited capacity for the facilities.
- The customer demand must be satisfied by stone extraction.

- Lateral transportation is not allowed.
- The locations of customers' locations are known.
- Sound and dust pollutions of quarry locations are taken into account.
- The preliminary inventory is considered zero.

Fig. 2. Stone supply chain network design.

Formulation of the SSND model is presented in this section. Besides, the employed notations in the SSND model is described below.

Indices

i	Index of candidate locations for quarries (i= 1,…, I)
j	Index of candidate locations for stone cutting factories (j= 1,…, J)
k	Index of candidate locations for distribution centers (k = 1,…, K)
l	Index of stone customers (l= 1,…, L)
s	Index of stone types (s= 1,…, S)
t	Index of periods (t= 1,…, T)

Parameters

fix_{is}^1	Fixed cost of installing quarry location i for stone type s
fix_{js}^2	Fixed cost of opening stone cutting factory j for stone type s
fix_{ks}^3	Fixed cost of opening distribution center k for stone type s
op_{is}^1	Operational cost of mining at quarry i for stone type s
op_{js}^2	Operational cost at cutting factory j for stone type s
op_{ks}^3	Operational cost at distribution center k for stone type s
sh_{ij}^1	Transport cost from quarry i to cutting factory j
sh_{jk}^2	Transport cost from cutting factory j to distribution center k
sh_{kl}^3	Transport cost from distribution center k to customer l
CP_s^1	Quarry extraction capacity for stone type s
CP_s^2	Capacity of factory for stone type s
CP_s^3	Capacity of distribution center for stone type s
p_{st}^0	Substitute (imported) stone price for Iranian stone s in period t
α_{lst}	Potential demand for local stone s related to the customer l in period t
hc_j^2	Holding cost of stones in suggested stone cutting factory j
hc_k^3	Holding cost of stones in suggested distribution center k
ν	Price elasticity coefficient for substitute stone
η	Price elasticity coefficient for Iranian stone
θ	The tolerance percentage that the price of local stone (Iranian) can vary from substitute stone price
sp_{it}	Amount of released sound pollution in quarry i per ton of stone in period t
dp_{it}	Amount of produced dust pollution in quarry i per ton of stone in period t
sp^{max}	Permited max sound level

dp^{max}	Permited max dust level
sc^{+}	Sound pollution penalty for redundant sound
sc^{-}	Sound pollution reward for saved sound
dc^{+}	Dust pollution penalty for redundant dust
dc^{-}	Dust pollution reward for saved dust
ξ	Stone waste precentage (during blocks production) in the quarry
φ	Stone waste percentage(during slabs production) in the factory

Variables

w_{is}^{1}	$\begin{cases}1 & \text{If a quarry is opened at location i for stone type s}\\ 0 & \text{Otherwise}\end{cases}$
w_{js}^{2}	$\begin{cases}1 & \text{If a stone cutting factory is opened at location j for stone type s}\\ 0 & \text{Otherwise}\end{cases}$
w_{ks}^{3}	$\begin{cases}1 & \text{If a distribution center is opened at location k for stone type s}\\ 0 & \text{Otherwise}\end{cases}$
Qt_{ijst}^{1}	Amount of shipped block from quarry i to cutting factory j for stone type s in period t
Qt_{jkst}^{2}	Amount of shipped slab from factory j to distribution center k for stone type s in period t
Qt_{klst}^{3}	Amount of shipped stone from distribution center k to customer l for stone type s in period t
I_{jst}^{2}	Inventory level in stone cutting factory j for stone type s in period t
I_{kst}^{3}	Inventory level in stone distribution center k for stone type s in period t
D_{lst}	Request amount (elastic demand) of customer l for local stone s in period t
p_{st}^{1}	Local stone s price in period t
se_{t}^{+}	Amount of redundant sound emission in period t
se_{t}^{-}	Amount of saved sound emission in period t
de_{t}^{+}	Amount of redundant dust pollution in period t
de_{t}^{-}	Amount of saved dust pollution in period t

The goals of this paper are considered in three aspects of sustainability issues:

- The first objective function: it considers economic aspects and aims to maximize the total profit of the SSND model.
- The second objective function: it considers the environmental aspects by minimizing the dust pollution of mining.
- The third objective function: it considers the social aspects through minimizing the sound pollution of mining.

It is noteworthy to mention that the stone demand is considered as an elastic demand which is influenced by the local stone price and imported stone price. Eq. 1 shows that by increasing the local stone price (p_{st}^{1}) the elastic demand (D_{lst}) decreases because the customers prefer to fulfill their demand by imported stones. On the other hand, the elastic demand for local stone increases by increasing the imported stone price (p_{st}^{0}). It is noteworthy that the index t for capacities is neglected in this research because the capacity is considered the same in all periods.

$$D_{lst} = \alpha_{lst} - \eta\, p_{st}^{1} + \nu p_{st}^{0} \qquad \forall l, s, t \qquad (1)$$

Therefore, Eq. 2 shows the total income which is equal to multiplying the local stone price (p_{st}^{1}) and the elastic demand.

$$Z_{1}^{income} = \sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{t=1}^{T} p_{st}^{1}(\alpha_{lst} - \eta\, p_{st}^{1} + \nu p_{st}^{0}) \qquad (2)$$

Now, Eq. 3 illustrates the first objective function which maximizes the total profit of SSND.

$$Z_1 = Z_1^{income} + Z_1^{fix} + Z_1^{sh} + Z_1^{op} + Z_1^{hc} + Z_1^{rp} \tag{3}$$

This equation includes, respectively: Eq. 2 total income; Eq. 3-1 fixed cost of opening quarries, stone cutting factories, and distribution centers; Eq. 3-2 transportation costs of the quarry, factory, and distribution center; Eq. 3-3 operational costs of the quarry, factory, and distribution center; Eq. 3-4 holding costs of inventory in the stone cutting factory and distribution center; Eq. 3-5 the saved ($\sum_{t=1}^{T} se_t^- sc^-$) and redundant ($\sum_{t=1}^{T} se_t^+ sc^+$) sound pollution rewards and penalties. Likewise, the last two sections ($\sum_{t=1}^{T} de_t^- dc^-$ and $\sum_{t=1}^{T} de_t^+ dc^+$) which are saved and redundant dust pollution rewards and penalties. Indeed, the penalty and reward are positive/negative allowances for the miners, if there are saved and excess pollutants, respectively.

$$Z_1^{fix} = \sum_{s=1}^{S}\sum_{i=1}^{I} fix_{is}^1 w_{is}^1 + \sum_{s=1}^{S}\sum_{j=1}^{J} fix_{js}^2 w_{js}^2 + \sum_{s=1}^{S}\sum_{k=1}^{K} fix_{ks}^3 w_{ks}^3 \tag{3-1}$$

$$Z_1^{sh} = \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{j=1}^{J}\sum_{i=1}^{I} sh_{ij}^1\, Qt_{ijst}^1 + \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{j=1}^{J} sh_{jk}^2\, Qt_{jkst}^2 + \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{l=1}^{L}\sum_{k=1}^{K} sh_{kl}^3\, Qt_{klst}^3 \tag{3-2}$$

$$Z_1^{op} = \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{j=1}^{J}\sum_{i=1}^{I} op_{is}^1\, Qt_{ijst}^1 + \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{j=1}^{J} op_{js}^2\, Qt_{jkst}^2 + \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{l=1}^{L}\sum_{k=1}^{K} op_{ks}^3\, Qt_{klst}^3 \tag{3-3}$$

$$Z_1^{hc} = \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{t=1}^{T} hc_j^2\, I_{jst}^2 + \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{t=1}^{T} hc_k^3\, I_{kst}^3 \tag{3-4}$$

$$Z_1^{rp} = \sum_{t=1}^{T} se_t^- sc^- - \sum_{t=1}^{T} se_t^+ sc^+ + \sum_{t=1}^{T} de_t^- dc^- - \sum_{t=1}^{T} de_t^+ dc^+ \tag{3-5}$$

It should be noted that there are several studies in which authors have used the structure of cap & trade for topics other than carbon emission. For example, Canales-Bustos et al. [13] have utilized these relations in their work about the quality deviation of the final product instead of carbon. Likewise in this study, the penalty and reward were considered as the allowance for miners in a way similar to cap & trade. In fact, the pollutants will not be sold or bought but the miners will be rewarded (for less amount of pollutants) and penalized (for the excess amount of pollutants) in the form of working allowance.

Eq. 4 elaborates the second objective function which minimizes the dust pollution.

$$Z_2 = min \sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{t=1}^{T} dp_{it} w_{is}^1 \tag{4}$$

Eq. 5 is the third goal of this study which minimizes the sound pollution.

$$Z_3 = min \sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{t=1}^{T} sp_{it} w_{is}^{1} \tag{5}$$

Constraint (6) illustrates that the stone inventory level in factory (I_{jst}^{2}) is equivalent to the $(1-\xi)$ fold of transported block from quarreis to each factory ($\sum_{i=1}^{I} Qt_{ijst}^{1}$), subtracting slab flow from factory to the distribution centers ($\sum_{k=1}^{K} Qt_{jkst}^{2}$), plus the stone inventory level at time $t-1$ ($I_{j,s,t-1}^{2}$). It is noteworthy to mention that the inventory level at time $t=1$ is considered zero in this model. Similarly, Constraint (7) shows the stone inventory level in distribution center k.

$$I_{jst}^{2} = \sum_{i=1}^{I} Qt_{ijst}^{1}(1-\xi) - \sum_{k=1}^{K} Qt_{jkst}^{2} + I_{j,s,t-1}^{2} \qquad \forall j,s,t \tag{6}$$

$$I_{kst}^{3} = \sum_{j=1}^{J} Qt_{jkst}^{2}(1-\varphi) - \sum_{l=1}^{L} Qt_{klst}^{3} + I_{k,s,t-1}^{3} \qquad \forall k,s,t \tag{7}$$

Constraints (8-10) show the extraction, cutting factory, and distribution center capacity.

$$\sum_{j=1}^{J} Qt_{ijst}^{1} \le CP_{s}^{1} w_{is}^{1} \qquad \forall i,s,t \tag{8}$$

$$\sum_{k=1}^{K} Qt_{jkst}^{2} \le CP_{s}^{2} w_{js}^{2} + I_{j,s,t-1}^{2} \qquad \forall j,s,t \tag{9}$$

$$\sum_{l=1}^{L} Qt_{klst}^{3} \le CP_{s}^{3} w_{ks}^{3} + I_{k,s,t-1}^{3} \qquad \forall k,s,t \tag{10}$$

Constraint (11) shows that all transported stone from distribution centers ($\sum_{l=1}^{L} Qt_{klst}^{3}$) must satisfy each customer demand.

$$\sum_{k=1}^{K} Qt_{klst}^{3} = \alpha_{lst} - \eta\, p_{st}^{1} + \nu p_{st}^{0} \qquad \forall l,s,t \tag{11}$$

Constraint (12) guarantees that in every quarry i in period t for stone type s, the released sound pollution by extracting the stones ($\sum_{j=1}^{J} sp_{it}\, Qt_{ijst}^{1}$) does not exceed the permitted maximum sound level (sp^{max}), subtracting the amount of saved sound emission (se_t^{-}), plus the amount of redundant sound emission (se_t^{+}). Similarly, Constraint (13) assures the allowed maximum dust level.

$$\sum_{j=1}^{J} sp_{it}\, Qt_{ijst}^{1} \le sp^{max} - se_t^{-} + se_t^{+} \qquad \forall i,s,t \tag{12}$$

$$\sum_{j=1}^{J} dp_{it}\, Qt_{ijst}^{1} \le dp^{max} - de_t^{-} + de_t^{+} \qquad \forall i,s,t \tag{13}$$

Constraint sets (14-16) guarantee to assign one type of extracted stone at each location based on specific soil of that location, one type of stone cutting factory at each location to consider environmental issues, and one type of distribution center at each location to create a sales hub for each type of stone.

$$\sum_{s=1}^{S} w_{is}^{1} \leq 1 \qquad \forall i \qquad (14)$$

$$\sum_{s=1}^{S} w_{js}^{2} \leq 1 \qquad \forall j \qquad (15)$$

$$\sum_{s=1}^{S} w_{ks}^{3} \leq 1 \qquad \forall k \qquad (16)$$

Constraints (17) and (18) show that the stone inventory level in cutting factory j and distribution center k will exist only if these facilities are constructed.

$$I_{jst}^{2} \leq M w_{js}^{2} \qquad \forall j, s, t \qquad (17)$$

$$I_{kst}^{3} \leq M w_{ks}^{3} \qquad \forall k, s, t \qquad (18)$$

Constraint (19) illustrates the feasible interval for the local stone price for stone type s in period t (p_{st}^{1}).

$$(1-\theta) p_{st}^{0} \leq p_{st}^{1} \leq (1+\theta) p_{st}^{0} \qquad \forall s, t \qquad (19)$$

$$w_{is}^{1}, w_{js}^{2}, w_{ks}^{3} \in \{0,1\} \qquad (20)$$

$$p_{st}^{1}, I_{jst}^{2}, I_{kst}^{3}, se_{t}^{-}, se_{t}^{+}, de_{t}^{-}, de_{t}^{+}, Qt_{ijst}^{1}, Qt_{jkst}^{2}, Qt_{klst}^{3} \geq 0 \qquad (21)$$

ε-constraint method

The ε-constraint method is utilized to solve the multi-objective model proposed in this paper. This is a popular method for multi-objective approaches presented by Hwang and Masud [27]. There are different methods to solve multi-objective optimization problems. The ε-constraint method is utilized in this paper by virtue of its advantages over other approaches, which are explained as follows:

- This approach is utilized to deal with multi-objective problems, widely [28, 29].
- Non-convex Pareto sets can be handled by the ε-constraint approach [30].
- Decision-makers are allowed to put the threshold levels for some goals by this method [28].
- A different efficient solution is produced at each run, therefore the efficient set with a more rich demonstration can be obtained [31].

In the ε-constraint method, one of the objective functions is chosen ordinary to remain while others are added into constraints [32]. Then, the problem is solved by considering different ε-cuts on objective functions in constraints each time and gaining the optimal solutions of the resulted single objective model. To this end, the optimum interval of each objective function in constraints is divided into pre-determined amounts and the values for ε_k are achieved. The general formulation (for a minimization problem) for the ε-constraint method is as follow:

$$Min_{x \in X} f_j(x) \qquad (22)$$

s.t:

$$f_k(x) \leq \varepsilon_k \quad k \neq j \qquad (23)$$

and other constraints (24)

Case study

There is a high variety of stone mines in Iran which makes it a paradise of stone quarries[†]. Thus, there are different potential research chances to develop sustainability aspects of mining in Iran. To assess the applicability of the addressed model a real case study is employed in the developed SSND model.

Considerations and parameters

- Porcelain, travertine, granite, and marble stones are chosen for this case study by virtue of their redundancy in Iran[‡].
- Respectively, 18 areas are considered for quarries, cutting factories, and distribution centers to gain the best areas (in Table 2).
- Also, 10 areas are chosen for demand zones (in Table 3).
- The utilized vehicles in this case study are the 22-ton trailer (for delivering the extracted stones to the factory, 10-ton truck (for delivering the slabs to the distribution center), and 2-ton Nissan (for transporting the final stones to customers). The transportation information is utilized to calculate the shipping costs in each phase.
- The utilized data are achieved from websites[§], authoritative references, miners and expert officials, field researches, and some papers like Álvarez-Fernández et al. [33]. Some parameter values are demonstrated in Table 4. Besides, other important parameters such as the amount of released sound pollution and permitted max sound level ranges have been earned from the field researches and relevant working papers such as Noise pollution and its control methods with emphasis on green space design work report[**], sound pollution standard[††], and investigation of noise pollution in open stone mines in Harsin region of Kermanshah province working paper[‡‡]. Some of these parameters are demonstrated in Appendix (in Tables A1-A5).
- Also, the definition of pollution parameters has been inspirited from Paksoy and Özceylan [34]. They have considered a penalty cost for the sound pollution in their objective function and defined the permitted max sound level in their mathematical model.
- There is a two-year planning horizon which is separated into four-month periods.
- The costs are proposed in million Toman and stone weight is considered in Ton.
- Finally, the unit of sound and dust parameters are considered in Decibel and Ton, respectively.

Table 2. Candidate areas for installing facilities.

Sign	Area	Sign	Area	Sign	Area	Sign	Area	Sign	Area
1	Isfahan	5	Yazd	9	Ardabil	13	South Khorasan	17	Qazvin
2	Markazi	6	Zanjan	10	Kurdistan	14	Fars	18	Kerman
3	West Azerbaijan	7	Hamedan	11	Tehran	15	Qom		
4	East Azerbaijan	8	Razavi Khorasan	12	Sistan and Baluchestan	16	Gilan		

[†] http://www.alvanstone.com/fa/post-17071.html
[‡] https://fararu.com/fa/news/403445
[§] www.bahesab.ir, https://web.bar1.ir/, https://sangevazin.com/stones/, and https://en.doe.ir/portal/home/
[**] https://www.doe.ir/Portal/file/?181200/1_1.pdf
https://fars.doe.ir/portal/file/?188442/%D8%A7%D8%B3%D8%AA%D8%A7%D9%86%D8%AF%D8%A7%D8%B1%D8%AF-%D8%A7%D9%84%D9%88%D8%AF%DA%AF%D9%8A-%D8%B5%D9%88%D8%AA%D9%8A.pdf
[‡‡] https://www.civilica.com/Paper-SHEMRI05-SHEMRI05_022.html

Table 3. Customers' area.

Sign	Area	Sign	Area
1	Isfahan	6	Zanjan
2	Markazi	7	Hamedan
3	West Azerbaijan	8	Razavi Khorasan
4	East Azerbaijan	9	Ardabil
5	Yazd	10	Kurdistan

Table 4. Parameter values.

Parameter	Value	Parameter	Value
ν	0.000001	dc^{+} (Tm)	1500
η	0.000001	dc^{-} (Tm)	10
θ	0.2	ξ	0.2
sc^{+} (Tm§§)	1500	φ	0.35
sc^{-} (Tm)	10		

Validation

To validate the introduced model, the results of the unsustainable problem are utilized as a benchmark for the sustainable model. Thus, it becomes clear what happens if the proposed model is not sustainable. To do this, all three objectives of the sustainable model are considered as three indices for measuring economic, environmental, and social aspects of sustainability in the models. The results of both sustainable and unsustainable models are placed in these indices as illustrated in Fig. 3. It shows that the unsustainable mathematical model is naturally more beneficial than the sustainable one, because of considering some social and environmental constraints in the sustainable model; however, sound and dust pollutions are less in the sustainable model.

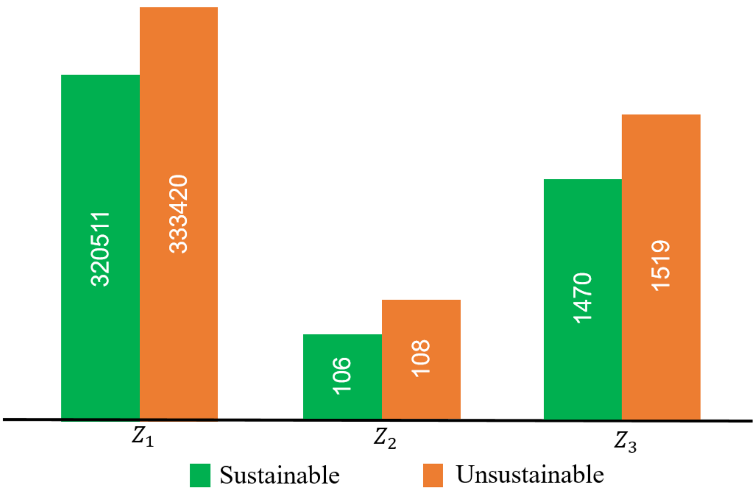

Fig. 3. The results of sustainable and unsustainable models.

The mathematical model is solved utilizing CPLEX solver in GAMS® Optimization Software in about 25 minutes. A laptop with Intel Core i7-6700HQ @ 2.60 GHz (8 GB memory) is utilized to implement the mathematical model.

The optimal results of opening quarries, cutting factories, and distribution centers are demonstrated in Fig. 4. As shown, 4 quarries are installed in Hamedan, Razavi Khorasan, Tehran, and Kurdistan. Besides, 4 cutting factories are constructed in East Azerbaijan, Yazd,

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§§ Toman

Razavi Khorasan, and Qom. The results show that the cutting factory and quarry are established in the same location, only in Razavi Khorasan. Also, the other factories are constructed near quarry locations. Therefore, it can cause low transportation costs.

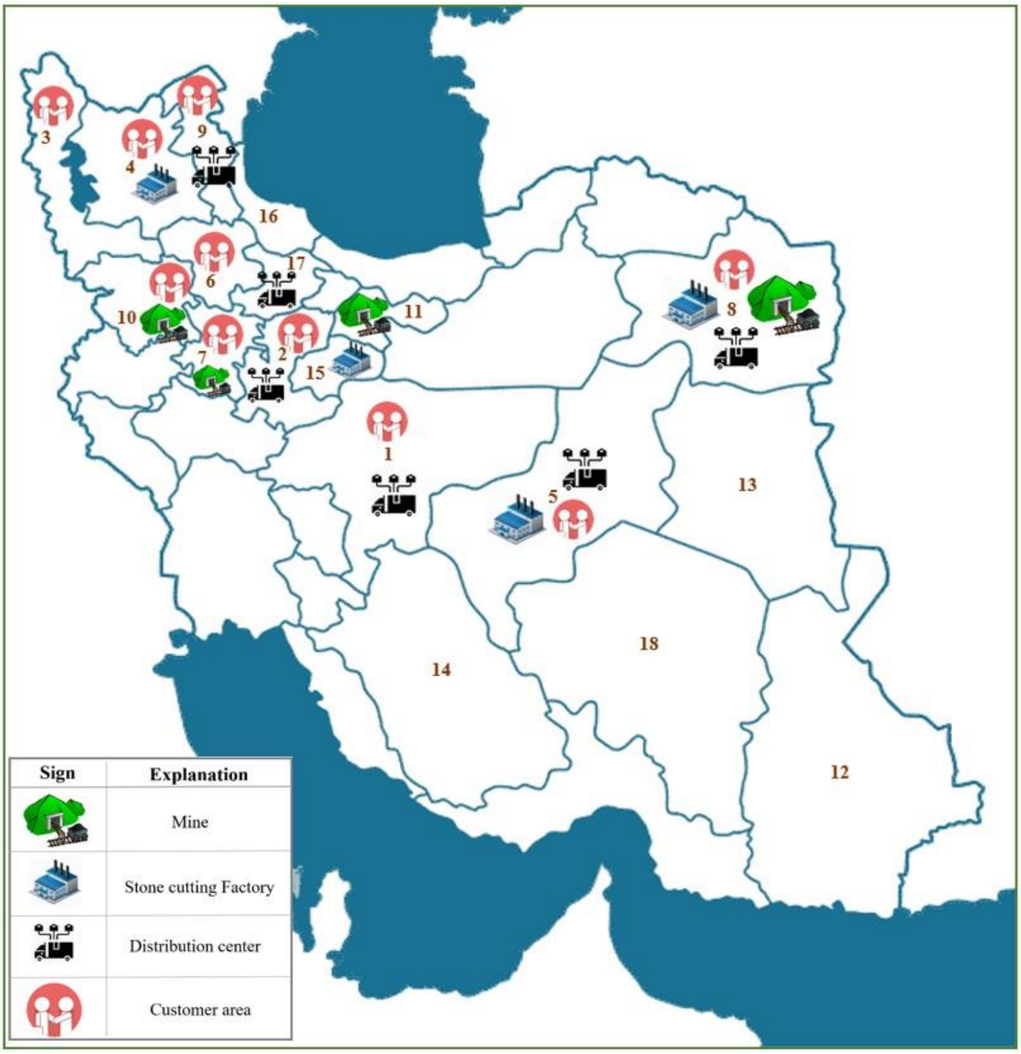


Fig. 4. Selected zones for quarry, cutting factory, and distribution centers.

Tables 5 shows the selected stone types which are assigned to selected quarries, stone cutting factories, and distribution centers.

Table 6 shows the Pareto solutions in 21 iterations by the ε-constraint method. It is clear that by decreasing the profit, the sound and dust pollution goals are improved. The non-dominated solutions related to profit and sound pollution objective functions, and profit and dust pollution goals are illustrated in Fig. 5 and Fig. 6, respectively. The question is that why there are not abundant Pareto solutions? The answer is that, since the value of social and environmental goals are related to the quarry installations (according to Eqs. 4 and 5), their values are produced in a low variety.

Table 5. Selected provinces and stone types for installing quarries, cutting factories, and distribution centers

Sign	Province	Stone type in quarry			
		Marble	Granite	Travertine	porcelain
7	Hamedan				*
8	Razavi Khorasan	*			
10	Kurdistan		*		
11	Tehran			*	
Sign	Province	Stone type in stone cutting factory			
4	East Azerbaijan		*		
5	Yazd			*	
8	Razavi Khorasan	*			
15	Qom				*
Sign	Province	Stone type in distribution centers			
1	Isfahan			*	
2	Markazi				*
5	Yazd			*	
8	Razavi Khorasan	*			
9	Ardabil		*		
17	Qazvin	*			

Table 6. Non-dominated solutions.

Iteration	Z_1	Z_2	Z_3	ε1	ε2	Iteration	Z_1	Z_2	Z_3	ε1	ε2
1	331,866	108	1519	117	1581	12	308,821	106	1424	107.1	1464.95
2	331,470	108	1519	116.1	1570.45	13	308,821	106	1424	106.2	1454.4
3	331,746	108	1519	115.2	1559.9	14	308,821	106	1424	105.3	1443.85
4	332,091	108	1519	114.3	1549.35	15	308,821	106	1424	104.4	1433.3
5	331,866	108	1519	113.4	1538.8	16	308,821	106	1424	103.5	1422.75
6	332,076	108	1519	112.5	1528.25	17	308,821	106	1424	102.6	1412.2
7	325,571	107	1517	111.6	1517.7	18	308,821	106	1424	101.7	1401.65
8	320,649	106	1470	110.7	1507.15	19	308,821	106	1424	100.8	1391.1
9	320,315	106	1470	109.8	1496.6	20	308,821	106	1424	99.9	1380.55
10	320,511	106	1470	108.9	1486.05	21	308,821	106	1424	99	1370
11	320,511	106	1470	108	1475.5						

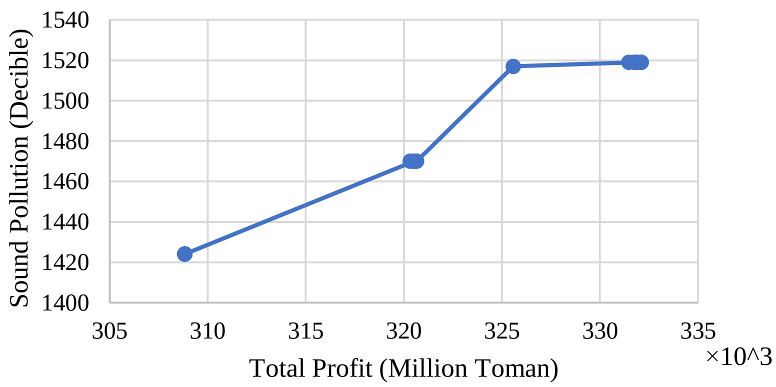


Fig. 5. Pareto front of total profit and sound pollution goals.

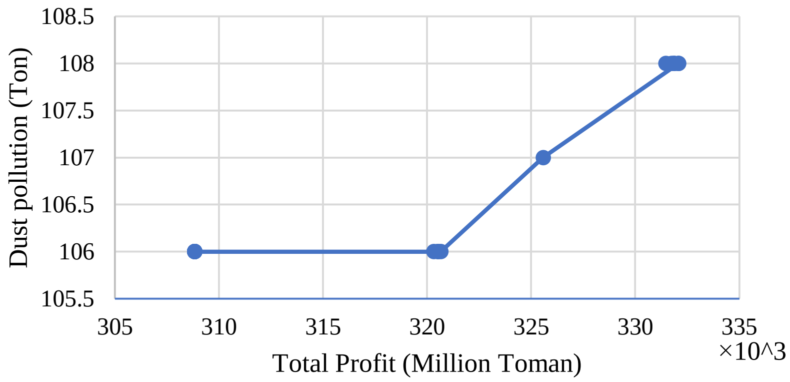


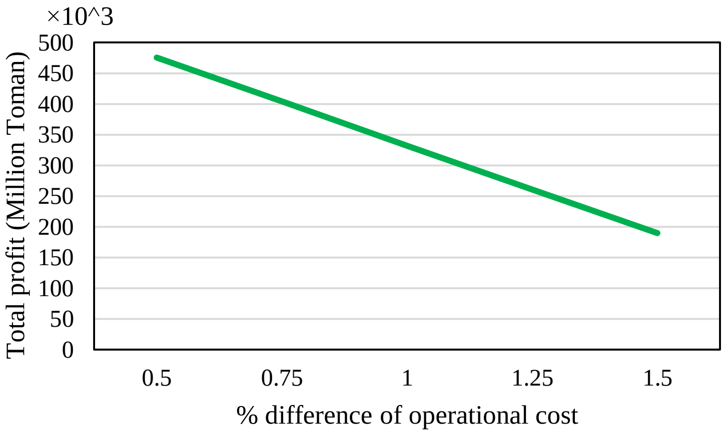
Fig. 6. Pareto front of total profit and dust pollution goals.

Sensitivity analysis

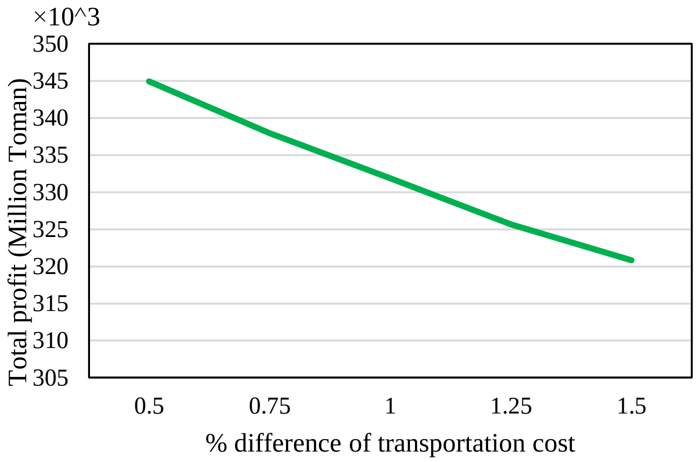
In this section, the performance of the addressed optimization model is evaluated in sustainable SSND.

It is essential to analyze the operational and transportation costs impacts on mentioned objective functions due to the Dollar fluctuations and their influences on economic issues in Iran. So, these cost parameters are evaluated in the interval of [-50%, +50%] to gain the greatest insight into the proposed problem.

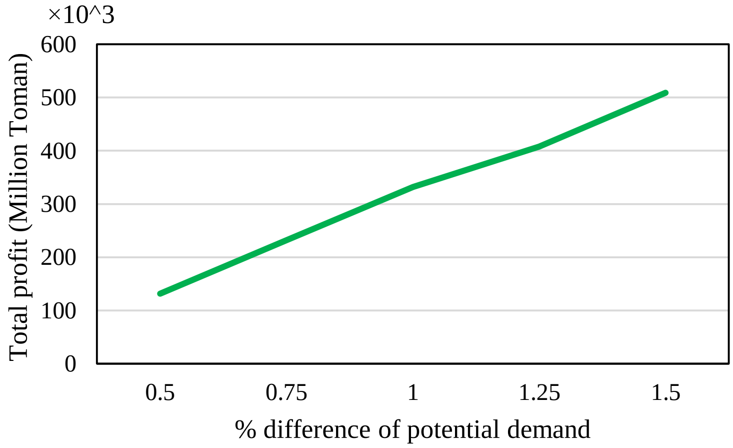
The results of operational costs and transportation costs are shown in Fig. 7 (a) and Fig. 7 (b), respectively. At first sight, the profit decreases by increasing shipping and operating costs. Furthermore, the operational cost has a significant effect on profit. Such that, by increasing the operational cost by 50%, the total profit is reduced by 43%. On the other hand, by increasing shipping costs to a similar size, the profit is reduced by only 3%. Low fuel prices in Iran, can justify this trivial effect.



a. Operational cost.



b. Transportation cost.



c. Potential demand.

Fig. 7. Impact of operational cost, transportation cost, and potential demand parameters on total profit.

As expected, the profit increases by rising potential demand in an interval of [-50%, +50%] shown in Fig. 7 (c).

Fig. 8 illustrates the effect of released sound pollution parameters on total profit and sound pollution goals. The sound pollution objective function increases by rising this parameter which is a tangible fact. By contrast, the total profit decreases in the mentioned interval. This reduction can be justified by the penalty imposition on total income.

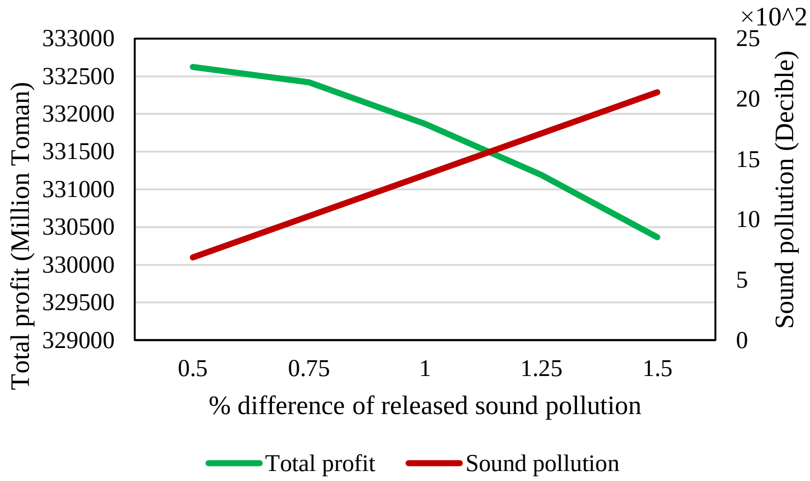


Fig. 8. Objective functions changes by altering released sound pollution.

Also, Fig. 9 shows the effect of produced dust pollution parameter on total profit and dust pollution goals. At first insight, it is obvious that the dust pollution objective function increases by rising the mentioned parameter in the interval of [-50%, +50%]. Total profit has different behavior in the interval of [-50%, +50%]. Such that, it increases in the interval of [-50%, -25%] because of installing more quarry locations to satisfy the stone customer demand. But the profit decreases in the interval of [-25%, +25%]. As mentioned, the presented model considers the capacity for each segment. Therefore, in the interval of [-25%, +25%], it is preferred to focus on capacity improvement instead of installing new quarry locations. Finally, by increasing the released dust pollution to more than 25%, it is decided to install quarry locations to meet the demands.

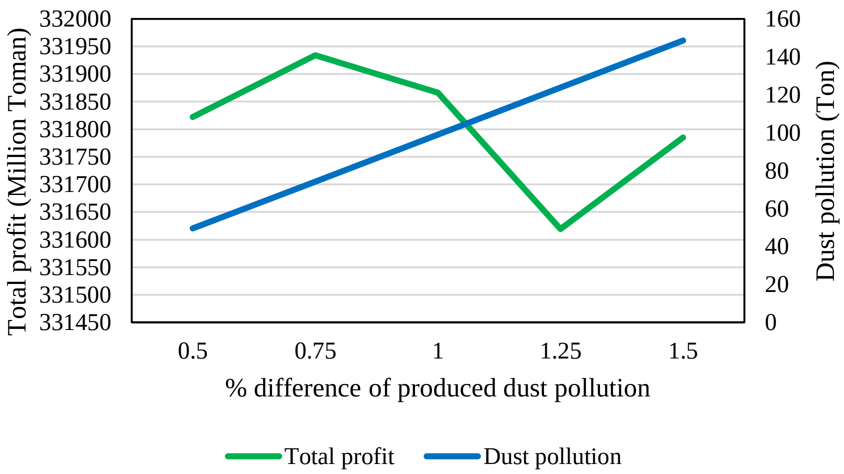


Fig. 9. Objective functions changes by altering produced dust pollution.

Finally, the effect of substitute stone price on total profit is evaluated in Fig. 10. It is clear that by increasing this parameter, total profit rises significantly according to the demand equation. Such that, by increasing the alternative stone price by 20%, the profit rises 43%. Due to the notable effect of alternative stone price on total profit, it is evaluated in an interval of [-20%, +20%] with a 10% difference.

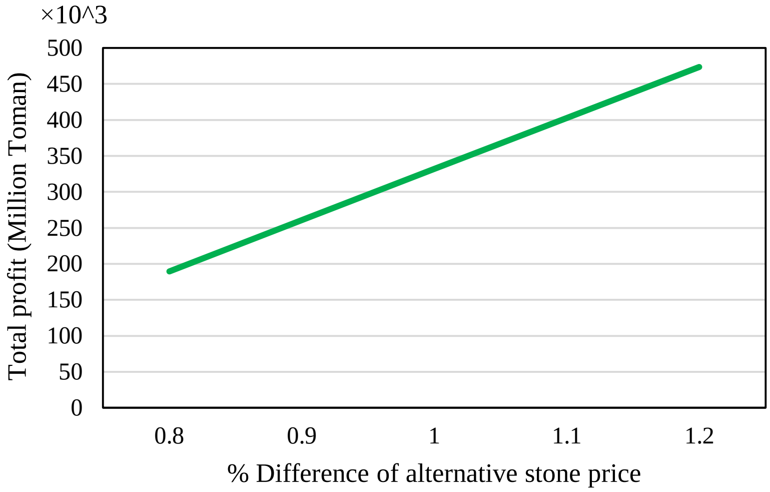


Fig. 10. Total profit changes by altering alternative stone price.

Managerial insights

Based on the above analyses and numerical results, the main benefits of this study can be summarized as below:

- The great potential of quarry installation in Iran has made it known as a stone quarry paradise. On the other hand, most of the installed quarries are in the center of Iran, geographically. Thus, based on the consequences of the mathematical model, the quarry installation in the north-western and south parts of Iran can be developed by government subsidization.
- According to the results, East Azerbaijan, Yazd, Razavi Khorasan, and Qom are appropriate provinces to construct stone factories. Therefore, essential incentives and facilities should be provided in these places.
- There are stone customers in West Azerbaijan and Zanjan, although none of the facilities is constructed there. These areas can be proposed for installing the mentioned facilities (quarry, cutting factory, and distribution center) to provide the neighboring provinces (such as West Azerbaijan and Ardabil) demand in addition to meeting the needs of its customers.
- Although it was shown in the sensitivity analysis that transportation cost does not have a significant impact on stone supply chain costs, applying other transportation modes such as rail transport can lessen the shipping costs.
- The relationship between the demand of stone and the stone price is considered in the proposed model. Thus, it can aid managers who try to maximize the total profit of the stone supply chain network.
- A sustainable stone supply chain considering the effect of the proposed problem on the total profit of the supply chain which provides the basis for the tactical and strategic decisions is developed in this research. It helps the managers to control their profit, environmental impacts, people's welfare, and miners' satisfaction.

Conclusion

In this paper, a multi-level, multi-objective, multi-period, and multi-product mixed-integer quadratic programming problem is investigated to optimize an SSND model in the mining industry. Maximizing the profit of the stone supply chain and minimizing the dust and sound pollution are three objective functions of this research that considers the economic, environmental, and social aspects of sustainability, respectively. Furthermore, a competition exists between the imported and local stone prices through a price-based (elastic) demand. A real-world case study is applied to evaluate the efficiency and applicability of the proposed model. Also, the profit of the unsustainable model is higher than the sustainable one due to the consideration of social and environmental constraints and it illustrates the validity of the proposed SSND model.

The results of this paper can help the managers and governments for taking suitable strategic decisions in the SSND of the mining industry. As it is shown in the case study, the majority of the selected provinces for installing quarries were expected to be chosen due to their mineral potential. By contrast, none of the facilities has been constructed in vast provinces with industrial importance such as Fars and Kerman, unexpectedly. Therefore, the difference between capital necessities per production unit in each province is one of the involved factors in this decision.

According to the results, it can be concluded that the operational costs are more effective on total profit compared to the transportation costs. Moreover, the sound and dust pollution objective functions are altered as same as each other by changing the released sound pollution and produced dust pollution parameters. On the other hand, altering these parameters in an interval of [-50%, +50%] has a different impact on the total profit. Such that, the profit reduces steadily by increasing the released sound pollution. In contrast, by raising the produced dust pollution in the mentioned interval the profit has irregular change due to the installation and capacity development decisions. The results illustrate the applicability and currency of the presented model. Therefore, it can be utilized in Iran successfully.

There are some limitations to this study. Different modes of transportation such as road and rail transportation are neglected in this paper. Besides, the focus was on stones in this research, whereas other mineral resources may be proposed by accordingly improving the addressed model. Moreover, sound and dust pollutions are neglected in the cutting factory locations. Finally, the uncertainty of parameters is not investigated in this research.

Some future research directions can be applied to develop the addressed model. For instance, demand and stone price uncertainties can be taken into account. According to the proposed problem complexity, Lagrangian relaxation, Bender's decomposition, and other approaches can be applied to reduce the solving time. Furthermore, the proposed model can be developed by considering several transportation modes. Moreover, dust and noise pollutions can also be considered in stone factories due to sawing and processing activities. Also, other green aspects (such as wastes, CO_2 emissions, etc.) and social approaches (such as maximizing job opportunities, safety, etc.) can be taken into account in this problem. Moreover, the quality of extracted and final stones can be considered in the mathematical model. Finally, a closed-loop supply chain network design can be developed for the stone industry.

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Appendix

Input parameters:

Table A.1. Considered values for capacity parameters (Ton)

capacity parameters	Value
CP_s^1	$CP_1^1 = 10000, CP_2^1 = 11000, CP_3^1 = 9000, CP_4^1 = 8000$
CP_s^2	$CP_1^2 = 3000, CP_2^2 = 4000, CP_3^2 = 5000, CP_4^2 = 3000$
CP_s^3	$CP_1^3 = 900, CP_2^3 = 850, CP_3^3 = 700, CP_4^3 = 1200$

Table A.2. Considered values for holding cost parameters (Toman)

hc_j^2 (j = 1, 2, ..., 18)				hc_k^3 (k = 1, 2, ..., 18)			
j	value	j	value	k	value	k	value
1	52902	10	48083	1	65827	10	76310
2	53963	11	55491	2	77438	11	76820
3	58523	12	54785	3	69455	12	68696
4	56166	13	48017	4	61764	13	74487
5	50829	14	51778	5	61777	14	61596
6	51181	15	54735	6	70231	15	63736
7	58373	16	50815	7	60612	16	78628
8	58455	17	50963	8	74756	17	76130
9	58373	18	51425	9	74814	18	65653

Table A.3. Considered values for sound pollution parameter (Decibel)

sp_{it} ($i = 1, 2, \dots, 18$ and $t = 1, 2, \dots, 6$)													
i \ t	1	2	3	4	5	6	i \ t	1	2	3	4	5	6
1	48	83	65	31	40	52	10	55	51	89	57	33	36
2	66	74	42	58	53	47	11	84	88	89	33	58	49
3	63	50	69	51	51	78	12	81	45	88	87	67	39
4	36	36	88	64	41	66	13	67	82	52	63	77	36
5	70	61	68	42	41	55	14	39	86	76	39	71	72
6	40	75	60	35	40	35	15	83	82	34	63	34	43
7	83	72	67	84	90	36	16	90	75	79	59	62	43
8	47	76	42	49	83	68	17	71	62	48	31	61	75
9	85	56	63	70	33	52	18	60	59	61	33	41	85

Table A.4. Considered values for dust pollution parameter (Ton)

dp_{it} ($i = 1, 2, \dots, 18$ and $t = 1, 2, \dots, 6$)													
i \ t	1	2	3	4	5	6	i \ t	1	2	3	4	5	6
1	5	3	3	6	3	5	10	3	8	4	4	2	8
2	7	6	2	3	7	3	11	4	5	6	7	4	4
3	3	6	4	3	7	6	12	3	7	6	4	8	7
4	5	3	5	8	6	8	13	4	5	6	8	5	8
5	8	5	4	4	2	5	14	2	2	6	2	3	5
6	5	6	8	8	5	3	15	3	4	2	8	4	3
7	6	2	3	5	4	2	16	7	3	3	8	8	2
8	4	4	4	7	2	6	17	7	6	4	3	5	2
9	7	8	8	3	5	6	18	3	8	2	4	5	2

Table A.5. Considered values for alternative stone price (Toman)

p^0_{st} ($s = 1, 2, \dots, 4$ and $t = 1, 2, \dots, 6$)						
s \ t	1	2	3	4	5	6
1	15000000	14850000	14700000	14550000	14400000	13800000
2	10000000	9900000	9800000	9700000	9600000	9200000
3	5000000	4950000	4900000	4850000	4800000	4600000
4	2900000	2871000	2842000	2813000	2784000	2668000