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Iron ore allocation model to feedstock concentrate plants from multiple sources to multiple destinations considering the uncertainty of grade, in iron ore mines: a case study in Sangan mine, Iran

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Original scientific paper

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Abstract
Operations research is a science that is used in various fields. This science is a set of quantitative techniques that help managers make decisions using scientific methods. This science is related to many axial decision-making issues of managers. For this reason, it is also called the science of management. This science is widely used in industries and mines. One of the most appropriate methods for solving research problems in operations is using linear programming in mining projects. This study was conducted in the Sangan iron ore mine in Iran. In this article, by using linear programming modeling and solving the transportation problem, the allocation of iron ore to feedstock concentrate plants from multiple sources to multiple destinations has been done considering the uncertainty of the grade. This paper is in the field of studying and identifying the quantitative and qualitative amount of extractable iron ore reserves in the mines, and on the other hand, the needs of concentrate plants concerning their feedstock supply by considering the uncertainty of iron ore grade in mines and deciding on their proper allocation. Mineral modeling and estimation of the amount of extractable minerals have been done using the block model. Uncertainty of iron ore grade in the block model is investigated using the sequential Gaussian simulation method. The amount of mining capacity and its sequence is planned considering the type of iron ore used in the plans during 5-year periods. In this article, the modeling of the problem has been done by considering the existing limitations in mines, such as the amount of supply, grade of iron ore, iron oxide and sulfur. On the other hand, the limitations in plants, such as demand, type and grade of iron ore, iron oxide and sulfur are considered in the modeling. In the end, the amount of iron ore tonnage sent from each mine to each plant during 5 years is presented by solving the problem.

Keywords:
open pit mining; iron ore mines; concentrate plants; operations research; allocation

1. Introduction

Uncertainty refers to a situation in which a person cannot accurately describe, determine, or predict a system's behavior and other characteristics from a quantitative and qualitative dimension with the information he has. Programs in the real world do not always follow information with certainty. Change is a well-known factor in most engineering and management activities. Uncertainty is an inherent characteristic of any project. Uncertainty is one of the design parameters that should always be considered as one of the critical criteria during the design process. Uncertainty is a parameter dependent on the measurement results (estimation), and it describes the dispersion of different measurement results. In other words, the estimation uncertainty is expressed by a range of possible values, which includes the actual value. We can conclude with the above definitions that uncertainty occurs when more than one result is obtained from a single activity. Uncertainty is essential because the risks related to the project usually come from the uncertainties in that project. Therefore, the uncertainty of grade in Sangan mine has been investigated. Risk can be defined as the uncertainty that affects the goals. Mining projects are usually hazardous due to volatility and inherent uncertainty in geological models. Uncertainty and risk in mining projects cannot be eliminated entirely. The best action is to minimize their effects on mining projects and processes. Uncertainty in mining projects originates from three sources, a) inherent uncertainties, b) technical and engineering uncertainties, and c) economic uncertainties (**Dimitrakopoulos et al., 2002**). The main uncertainty that affects the optimization is the uncertainty in the materials (resources) in the ground, which is an uncertain reserve for mining production planning (**Ramazan and Dimitrakopoulos, 2013**). The objective of the optimization process is usually to maximize the operation's net present value (NPV). In research conducted in a gold mine in Australia, considering technical uncertainty and using two approaches of stochastic integer production planning (SIP) and tradi-

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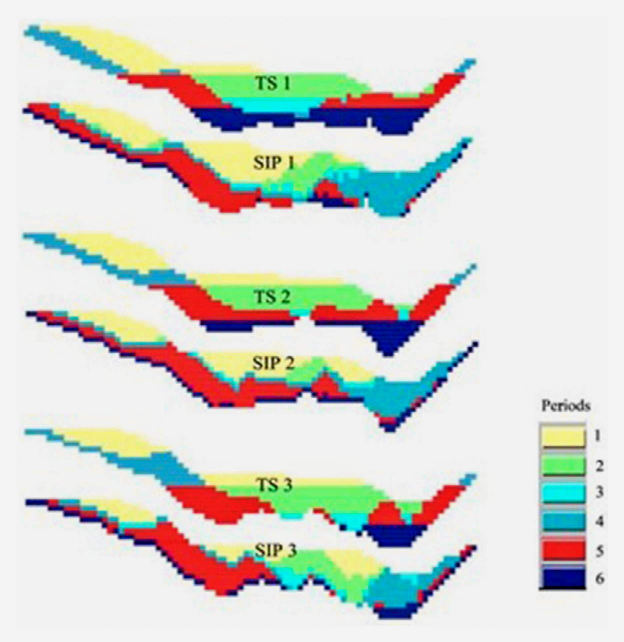

Figure 1: Three cross-sectional views of (TS) and SIP methods based on different extraction periods (**Ramazan and Dimitrakopoulos, 2013**).

tional production planning (TS), the results were compared and based on maximizing net present value, as shown in **Figure 1**. In the traditional production planning model, a scenario is used. The SIP model uses a set of multiple simulation scenarios of minerals in the ground.

This method describes a set of several scenarios equally, the possibility of uncertainty in mineral resources in the ground. The SIP method allows the proposed model to generate an optimal production schedule. The program produced using the proposed SIP model has resulted in approximately 10% higher NPV than the program resulting from the traditional approach (**Ramazan and Dimitrakopoulos, 2013**). **Zuckerberg et al. (2011)** introduced software called Bodor. This software, developed for a bauxite mine owned by Billiton BHP in Austria, aims to calculate and present possible production planning with some constraints. The constraints of this software are as follows: a) production of the desired product from the point of view of grade and tonnage; b) achieving the highest possible production rate for the mine. This software and model aims to minimize the net present value (NPV) of costs, and the logic used is based on solving a mixed integer mathematical model. This model has been used in bauxite mines and has been practically acceptable. **Benndorf and Dimitrakopoulos (2013)** have proposed another model for long-term production planning at Yandi iron ore mines in Australia. In this research, the long-term mine production planning is optimized using the random integer programming method. The objective function of this model is presented in a multi-objective manner and includes optimization of pit economic parameters, minimization of deviations from production goals, including mineral tonnage and quality, and mining costs. Constraints of this model include mineral storage limitations, meaning that each block must be harvested only once in all mining periods, stable slope limit, minimum and maximum allowable limits for the grade of different elements and production tonnage, capacity and availability of different machineries. **Smith and Wicks (2014)** have used a mixed integer programming model to maximize the amount of copper that can be mined from a deposit. In this model, it is assumed that the materials sent to the warehouse keep their quality characteristics, and at the time of exit, the quality characteristics are considered the same as at the time of arrival. One of the most critical problems of this model is not taking into account the uncertainty of the grade and quality of the mineral. **Monteil and Dimitrakopoulos (2015)** have presented a model with a meta-heuristic method. This model aims to maximize the net present value and minimize the deviation from the mining goals. In this model, if the capacity, transportation, and mixing constraints are not met, a parameter is considered a penalty in the objective function, reducing the net present value. In this study, only geological uncertainty is considered. **Mousavi et al. (2016)** have presented a mathematical model for short-term planning (short-term allocation) in an iron ore sense. They have used the combined method of branch and limit and refrigeration simulation to solve the model. In this model, the constraints of machine capacity and grade are considered. This model has been used for an iron ore mine, and the effect of the processing plant's capacity and stockpiles on the costs has been investigated. **Goodfellow and Dimitrakopoulos (2016**) presented a model to optimize planning in the conditions of uncertainty in the supply of salable mineral products using the meta-heuristic method. This model consists of two parts: in the first part, extraction scenarios are optimized, and in the second part, processing methods are optimized. The proposed model uses a combination of three meta-heuristic methods: particle swarm and differential evolution. **Matamoros and Dimitrakopoulos (2016)** presented a model for short-term planning based on stochastic integer programming. In the presented model, the uncertainty of the quantity and quality of the mineral is considered. The most critical issue in the presented model is not to include elements with mineral matter and a single destination. This model has been used in an iron ore mine, and the necessary planning for one year's extraction has been considered. **Rahmanpour and Osanloo (2016)** have conducted a study on a lime mine. This study aimed to plan the optimal production of five different mines to provide the feed required for a quality sodium carbonate plant. Optimal production planning envisages the possibility of access to production and the risk of this mine simultaneously. **Mohammadi et al. (2017)** represented a new approach for determining the optimum cut-off grade in multiproduct open pit mines using the imperial-

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ist competitive algorithm. This study uses the imperialist competitive algorithm to find the optimal cut-off grade. As a result, by storing low-grade ore, the concentrate plant can be fed at maximum capacity for one year in addition to the initial schedule**. Moreno et al. (2017)** have presented a non-linear planning model in production planning using an operational research model and examining different linear and non-linear planning models. The presented model considers the location of the reservoir in the mine. In the proposed model, the accumulation reserve is considered as a part of the strategic planning of the mine. The most important problem of the model is that no qualitative and quantitative uncertainty is considered. In order to design mining sequences in mines, **Kakha and Monjezi (2017)** has used the parameterization algorithm method of grade using variance. In this study, the main goal was to minimize the effect of grade uncertainty in the design of mining pushbacks. In this model, the economic value of the blocks is calculated by considering the grade of the elements in the block, and then the extraction pushbacks in the mine are designed. A hypothetical example in a lead and zinc mine is used to solve the model. **Tahernjad et al. (2018)** analyzed the effect of the uncertainty of mineral grade and price in the production planning of open pit mines. In this study, the uncertainty of mineral grade in the deposit is considered one of the most important parameters, and the comparative method using sequential Gaussian simulation (SGS) and ordinary kriging (OK) has been used in an iron mine. The comparison shows that the simulation method has less quantitative and qualitative deviation than the traditional kriging method in achieving production planning goals. **Jamshidi and Osanloo (2018a)** have studied the optimization of mining production planning for mineral blocks. **Jamshidi and Osanloo (2018b)** also examined multiple destinations' impact on multi-element mines' production planning. In this study, mixed integer programming is used for short-term production planning. In the model presented in multi-element mines, different blocks are mixed to obtain a product of a certain quality. Typically, the mixing of blocks is done to achieve a quality and quantity determined based on the needs of the processing plant and the consumer's needs. However, by mixing, different products can be produced according to the storage characteristics, and combining one block with other blocks can provide various products. This study considers different destinations for products and material blocks, each with defined characteristics. In this study, ten different scenarios have been considered. Only one destination is considered for mining products in four scenarios, and in six scenarios, multiple destinations are included in production planning. According to the results, the maximum net present value in multiple destinations is about 15% higher than the maximum net present value in the case of single products. **Liu et al. (2019)** investigated a problem of integrated production and distribution planning for iron ore and its concentrate in a research conducted at Northeastern Shenyang University in China. In this research, the problem of production and distribution planning faced by iron ore mining companies was discussed. The goal was minimization of the total costs of the iron ore concentrate production and its distribution system. In this study, a mixed integer programming model has been developed and then solved using the Lagrange method.

2. Iron ore mines and concentrate plants

Sangan iron ore mines and iron ore concentrate plants are studied in this article. The mines and plants are located in Razavi Khorasan Province, Khaf city, and 18 km northeast of Sangan city. The distance of these mines and plants from Mashhad is 300 km. The mines are located in a rectangular area of 208 square kilometers, and the iron ore extracted from these mines is used in concentrate plants. The location of the mines and plants is shown in **Figure 2**.

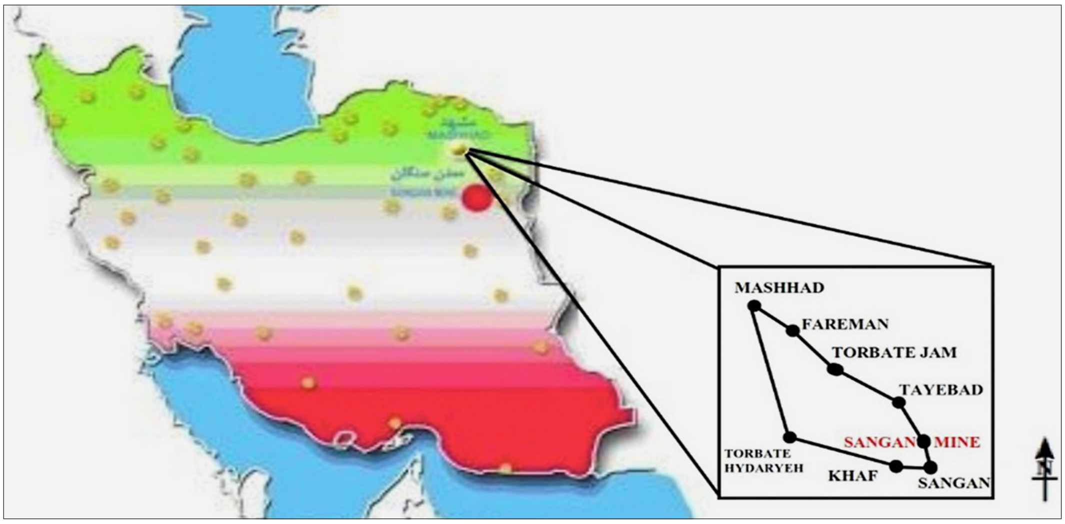

Figure 2: Location of iron ore mines and concentrate plants. Scale: 1/10000000

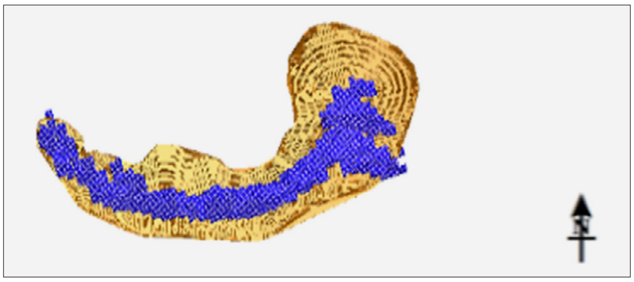

Figure 3: Final pit limit and block model of western mines. Scale: 1/300000

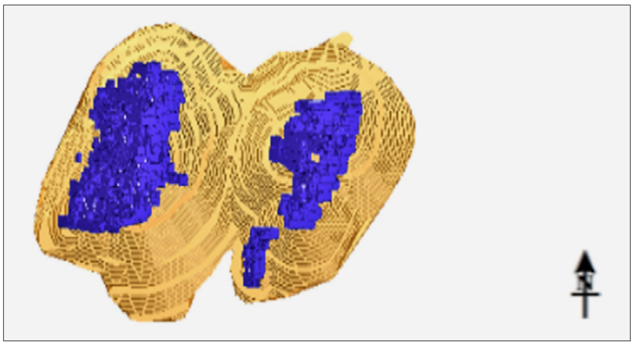

Figure 4: Final pit limit and block model of central mines. Scale: 1/300000

Iron ore mines include three main sections: western, central, and eastern. Western mines and central mines are in the extraction stage. Eastern mines are in the exploration stage. **Figure 3** and **Figure 4** show the final pit of the western and central mines and the mineral block model.

Iron ore concentrate is the primary raw material in the steel production and value chain. In recent years, the need for iron ore, concentrate and pellets has increased with the growth of investment in the steel sector. Accordingly, in this article, the demand assessment of 5 concentrate plants of model is examined and those plants are used in a proposed model as the demand destination. The iron ore extracted from these mines is used in 5 concentrate plants. Iron ore required by plants in 5 years is shown in **Table 1**. The conversion factor of iron ore to steel, which is defined in four stages (iron ore, concentrate, pellet, sponge iron and steel), is shown in **Table 2**.

3. Systematic literature review

In systematic literature reviews, existing studies are combined, the current state of knowledge in a given field is assessed, and research gaps are identified. To identify documents for inclusion in the review, this method uses a rigorous search strategy utilizing keywords (**Mallett et al., 2012**). Systematic approaches reduce biases in literature selection and provide reliable results for researchers in a particular field, since they are systematic in nature. As a result, this article features a systematic review based on the PRISMA standard that follows a specific procedure (**Snyder, 2019**).

Table 2 shows that the final conversion factor of iron ore to steel is 2.56. That means 2,560,000 tons of iron ore are needed to produce 1,000,000 tons of steel.

4. Investigation of grade uncertainty using sequential Gaussian simulation

One of the most important indicators in proper allocation are the quantity and quality of minerals. The mineral's qualitative characteristics based on the mineral's modeling have uncertainty. The block model in this research is prepared based on exploratory data in a 100m*100m exploratory drilling network. In this paper, grade uncertainty has been investigated as one of the most important influencing plants in the efficiency of iron ore concentrate plants. Sequential Gaussian simulation is one of the most suitable methods to investigate the uncertainty of minerals, which is a stochastic modeling algorithm for obtaining multiple realizations based on input data. In this simulation, each successive realization is simulated based on the normal cumulative distribution function. In using the sequential Gaussian simulation method, Node (grade points) randomly uses the original data, and the data simulated in the previous

Table 1: Iron concentrate plant requirements

Plants	Plant requirements during 5 years (tons)				
	First-year	Second-year	Third-year	Fourth-year	Fifth-year
Plant NO (1)	5,200,000	8,850,000	11,000,000	11,000,000	11,000,000
Plant NO (2)	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000
Plant NO (3)	10,000,000	11,000,000	11,000,000	11,000,000	11,000,000
Plant NO (4)	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000
Plant NO (5)	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000
Total	30,200,000	34,850,000	37,000,000	37,000,000	37,000,000

Table 2: Standard conversion factor of iron ore to steel

Stages	Iron ore	Concentrate	Pellet	Sponge iron	Steel
Stage 1	1.54	1			
Stage 2		1	1		
Stage 3			1.46	1	
Stage 4				1.14	1

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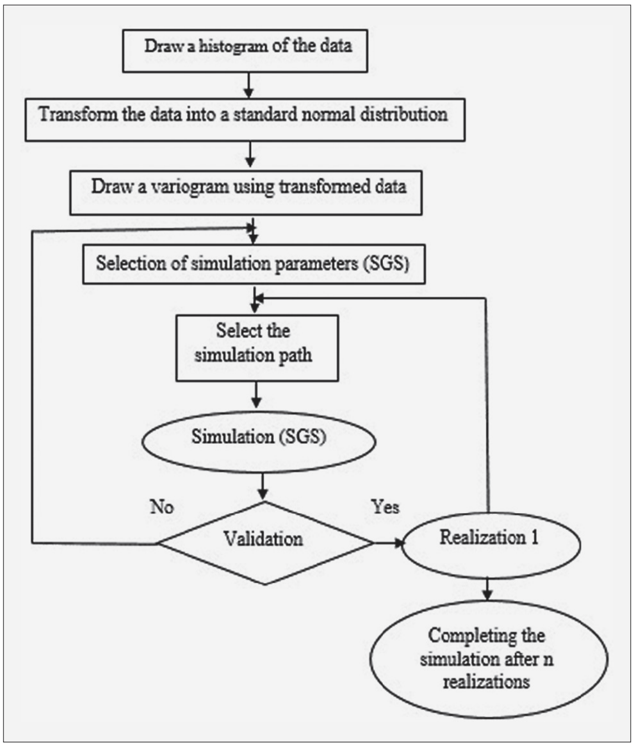

Figure 5: Sequential Gaussian simulation flowchart

steps are simulated. To perform the sequential Gaussian simulation algorithm, standard normal data is required. The sequential steps of Gaussian simulation are shown in **Figure 5**.

For any realization produced to be recognized as a valid realization from the simulation, it must have at least one of the following two basic conditions:

- The frequency distribution of the simulated variable should be consistent with the frequency distribution of the grade variable in the original sample. It almost has the same statistical parameters as the original sample.
- The variogram obtained from the simulated model should have a certain similarity with the variogram of the original samples. This issue indicates the similarity of geostatistical parameters in them.

After checking the uncertainty of iron ore grade using the Gaussian simulation method in SGeMS software, 100 realizations have been simulated. Finally, to validate the simulation results, the histogram of the initial data and the histogram of the realizations have been compared. For example, the statistical parameters of ten realizations, numbers 10, 20, 30, 40, 50, 60, 70, 80 and 90, and the initial data are compared in **Table 3**.

It is observed that the frequency distribution of the simulated variable is similar to the frequency distribution of the grade variable in the original sample, and the statistical parameters are almost the same as in the original sample. These realizations are known as valid realizations resulting from simulation. **Figure 6** shows the grade uncertainty graph in western and central mines. In A mine, the minimum average iron ore grade is 33.31%, and the maximum average grade is 43.12% in the simulations. In B mine, the minimum average iron ore grade is 36.10%, and the maximum average grade is 60.66% in the simulations. In the Northern C (CN) mine, the minimum average iron ore grade is 42.27%, and the maximum average grade is 52.20% in the simulations. In the Dardav (DV) mine, the minimum average iron ore grade is 38.24%, and the maximum average grade is 39.33% in the simulations. The minimum average iron ore grade in the Baghak (BK) mine is 32.53%, and the maximum average grade is 40.79% in the simulations. The grade of iron ore, iron oxide, and sulfur are three important qualitative parameters in the allocation of plant feed. The type of iron ore is important in allocating feed for plants. Iron ore minerals are divided into 5 categories in this article: magnetite, hematite with iron oxide 0 to 5%, hematite with iron oxide 5 to 10%, siderite magnetite with 25 to 30% iron oxide, and siderite.

The possibility of realizing the amount of iron ore required by the plants in the western and central mines by iron ore mineral type is shown in **Table 4**. The total reserves that can be mined and fed to plants in central and western mines are 642,541,056 tons of magnetite iron ore with a grade of 44.38%, iron oxide 20.60%, and sulfur 0.81%.

By maintaining the extraction of the mineral magnetite (siderite-magnetite, hematite, and siderite reserves

Table 3: Validation of realizations

Statistical parameters	Mean	Variance	Max	Upper quartile	Median	Lower quartile	Min
initial data	37.01	340.86	68.82	52.56	41.76	21.92	0.22
Realizations 10	38.63	319.20	68.80	53.28	43.36	25.43	0.22
Realizations 20	36.48	343.44	68.80	52.11	41.27	21.19	0.22
Realizations 30	37.15	319.80	68.80	52.05	41.67	23.13	0.22
Realizations 40	40.31	303.26	68.80	54.28	45.33	28.99	0.22
Realizations 50	40.77	301.16	68.80	54.53	45.97	29.72	0.22
Realizations 60	37.14	328.80	68.80	52.25	41.68	22.72	0.22
Realizations 70	37.74	322.29	68.80	52.65	42.43	24.01	0.22
Realizations 80	40.51	300.96	68.80	54.40	45.57	29.40	0.22
Realizations 90	36.84	325.50	68.08	51.90	41.55	22.47	0.22

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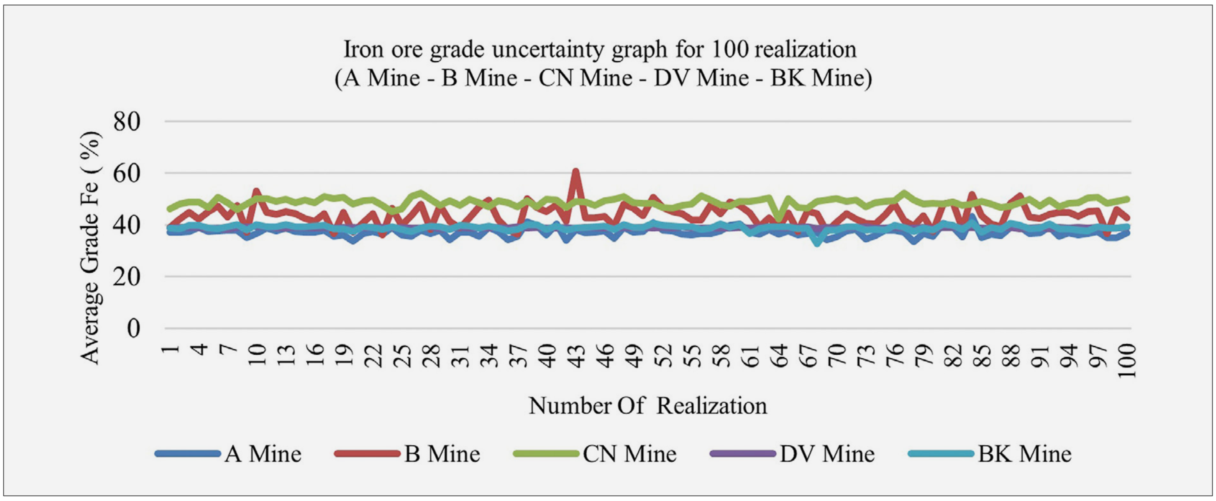

Figure 6: Graph of the results realizations in western mine and central mines

Table 4: Total mineable reserves of central and western mines by type of iron ore mineral

Category	Tons	Fe(%)	FeO(%)	S(%)
Waste	2,506,388,562	*	*	*
Iron Ore (Magnetite)	642,541,056	44.38	20.60	0.81
Magnetite Siderite	76,734,231	51.14	26.22	0.82
Siderite	6,555,053	48.29	30.49	0.53
Hematite 5-10	4,843,528	45.61	7.73	0.25
Hematite 0-5	3,788,247	50.31	3.06	0.09
Inferred	81,798,377	42.79	20.12	0.62
Total	3,322,649,054	44.89	20.97	0.52

Table 5: Amounts of iron ore and waste that can be mined in central mines

Category	Tons	Fe (%)	FeO (%)	S (%)
Waste	881,865,136	*	*	*
Iron Ore (Magnetite)	265,347,407	45.98	21.15	1.94
Magnetite Siderite	27,790,052	51.54	26.28	3.4
Siderite	4,422,798	51.78	31.23	6.96
Hematite 5-10	41,393	30.88	9.38	0.57
Hematite 0-5	0	*	*	*
Total	1,179,466,786	46.56	21.75	2.15

are not considered as plant feed), the amounts of iron ore required by plants in central mines and western mines are shown in **Tables 5** and **6** according to the type of iron ore mineral.

265 million tons of magnetite reserves are in central mines, and 377 million tons are in western mines. There are about 32 million tons of iron ore as magnetite-siderite, siderite, and hematite in the mineable reserves of central mines, and there are also about 59.5 million tons of iron ore as magnetite-siderite, siderite, and hematite in the mineable reserves of western mines. In this article, it is not considered as feed for plants. Therefore, the iron ore required by the plants in 5-year periods in western and central mines is shown in **Tables 7** and **8** based on the announcement of the maximum requirement of plant feed in the amount of 37 million tons per year. Based on this, the share of central mines in the supply of plant feed is 15 million tons, and western mines are 22 million tons.

Table 6: Amounts of iron ore and waste that can be mined in western mines

Category	Tons	Fe (%)	FeO (%)	S (%)
Waste	1,624,523,426	*	*	*
Iron Ore (Magnetite)	377,193,649	44.38	20.60	0.81
Magnetite Siderite	48,944,179	51.14	26.22	0.82
Siderite	2,132,256	48.29	30.49	0.53
Hematite 5-10	4,802,135	45.61	7.73	0.25
Hematite 0-5	3,788,247	50.31	3.06	0.09
Inferred	81,798,377	42.79	20.12	0.62
Total	2,143,182,269	45.18	20.96	0.77

Table 7: Mining capacity of central mines in 5-year periods

Period	Ore (Tons)			
Years	Magnetite	Fe(%)	FeO(%)	S(%)
Period 1 (5 years)	77,127,733	46.68	21.4	2.64
Period 2 (5 years)	77,006,576	46.70	21.5	1.59
Period 3 (5 years)	77,137,979	45.18	21.0	2.02
Period 4 (2.4 years)	34,075,119	44.59	20.0	0.95
Total Period (17.4 years)	265,347,407	45.98	21.15	1.94

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Table 8: Mining capacity of western mines in 5-year periods

Period	Ore (Tons)			
Years	Magnetite	Fe(%)	FeO(%)	S(%)
Period 1 (5 years)	109,289,685	44.25	20.00	0.39
Period 2 (5 years)	109,297,901	46.74	21.28	1.22
Period 3 (5 years)	109,323,259	42.24	20.92	0.68
Period 4 (2.4 years)	49,282,804	44.19	19.71	1.20
Total Period (17.4 years)	377,193,649	44.38	20.60	0.81

5. Allocation modeling

When dealing with a complex decision-making problem, it is seldom possible to fully specify all the existing complexities, so a model should be used. A model is a summarized reality that is often more straightforward and less complex than the original reality. Primarily, the model replaces the real phenomena for economic reasons, including cost and time-saving.

5.1. Two methods for modeling the problem of supplying feedstock to plants had been examined in this paper:

- Feed supply method without using iron ore dump
- Feed supply method using iron ore dump

Figure 7 shows the schematic design of feed supply of multiple plants from multiple mines without using iron ore dump, and **Figure 8** shows the schematic design of feed supply of multiple plants from multiple mines using iron ore dump. The model has no iron ore distribution terminal in the allocation method without an iron ore dump. This method sends the input feed directly from the mine to the plant (direct feed). In the allocation method with iron ore dump, iron ore extracted from mines, based on qualitative characteristics such as the type of iron ore (hematite or magnetite), iron grade, iron oxide, and sulfur content, fractionation is done in the dump. Then, considering proportional distribution and ore blending, the feed of the plants is provided.

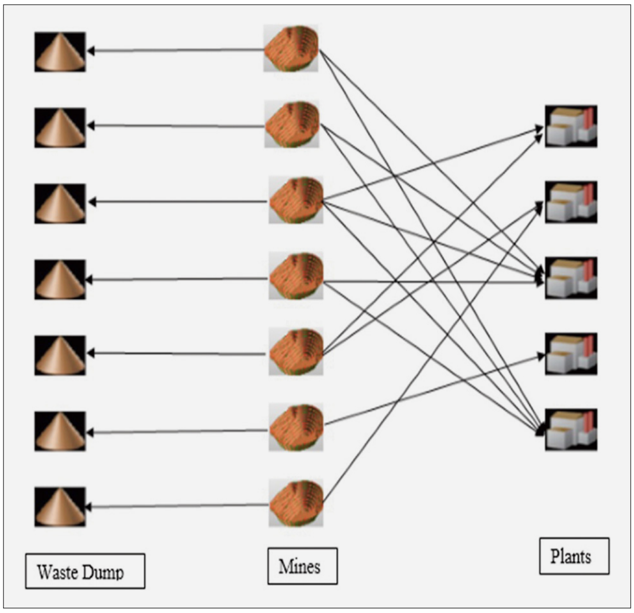

Figure 7: Schematic model of feed supply without iron ore dump

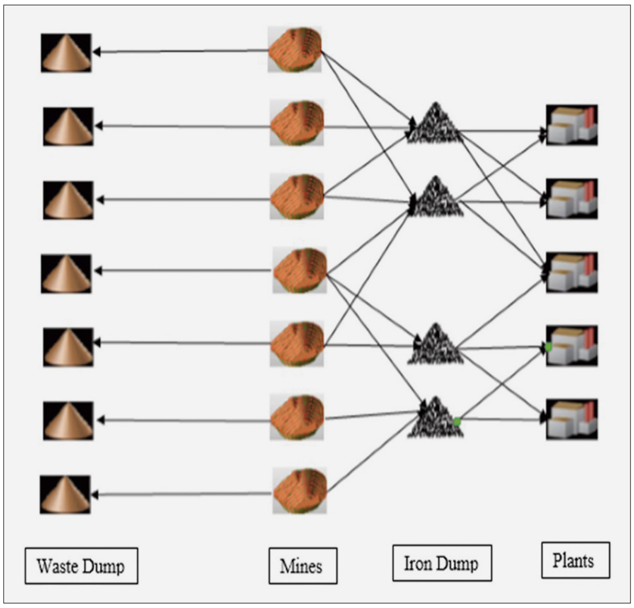

Figure 8: Schematic model of feed supply with iron ore dump

5.2. Magnetite and hematite iron ore grade category

According to the intermediate dumps, fractionation of iron ore grade and other quality characteristics should be considered. Based on the classification, each dump has a specific identity card regarding mineral matter quantity and quality. To achieve this goal, the grade of iron ore in the dumps has been coded into three categories: low grade, medium grade, and high grade, and other quality specifications are also coded in the dumps. The characteristics of magnetite and hematite iron ore are shown in **Tables 9** and **10.**

Table 9: Specifications of magnetite iron ore grade

1	Magnetite High Grade	($Fe \geq 50\%$)	MH
2	Magnetite Medium Grade	($40\% \leq Fe < 50\%$)	MM
3	Magnetite Low Grade	($20\% \leq Fe < 40\%$)	ML

Table 10: Specifications of hematite iron ore grade

1	Hematite High Grade	($Fe \geq 50\%$)	HH
2	Hematite Medium Grade	($40\% \leq Fe < 50\%$)	HM
3	Hematite Low Grade	($20\% \leq Fe < 40\%$)	HL

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5.3. Objective function, decision variables and model constraint

The objective function of the problem is defined in **Equation 1**. The cost of sending iron ore from each mine to each plant is shown in **Table 11**.

Table 11: Cost of sending iron ore from each mine to each plant ($/ton)

Location	Plant NO.1	Plant NO.2	Plant NO.3	Plant NO.4	Plant NO.5
Mine NO.1	2.3	4.3	2.7	2.1	4.3
Mine NO.2	1.9	3.9	2.2	1.9	3.9
Mine NO.3	2.0	2.1	1.7	2.3	2.1
Mine NO.4	1.9	2.2	1.6	2.1	2.2
Mine NO.5	2.9	2.6	3.1	3.3	2.6
Mine NO.6	2.8	2.4	2.6	3.0	2.8

The objective function:

$$Minimize\ z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij}.x_{ij} \quad (1)$$

Where:

Z: Total cost of iron ore sent from origin i to destination j (*$*)

x_{ij}: The amount of iron ore sent from origin i to destination j (ton)

c_{ij}: Cost of iron ore sent from origin i to destination j (*$/ton*)

Decision variable:

x_{ij}: Amount of iron ore shipped from origin i to destination j (*ton*)

Parameters:

M_i: Iron ore extraction tonnage per mine per year, supply (*ton/year*)

S_j: Tonnage of iron ore required by each plant per year, demand (*ton/year*)

a: Binary variable (If iron ore is sent from any source (i) to any destination (j), a = 1 otherwise a = 0)

g_i^{fe}: Average grade of iron ore in a mine per year (*%*)

g_j^{fe}: Average grade of iron ore required by each plant per year (*%*)

g_i^{feo}: Average grade of iron oxide in a mine per year (*%*)

g_j^{feo}: Average grade of iron oxide required by each plant per year (*%*)

g_i^{S}: Average grade of sulfur in a mine per year (*%*)

g_j^{S}: Average grade of sulfur required by each plant per year (*%*)

Constraint:

Mining capacity constraint (supply constraint): The Constraint related to the mining capacity per year is in the form of **Equation 2**. Demand constraint required by plants (demand constraint): Therefore, the demand constraint of plants is according to **Equation 3**:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \le M_i \quad (2)$$

$$\sum_{j=1}^{n} \sum_{i=1}^{m} X_{ij} \ge S_j \quad (3)$$

Binary variable Constraint:

If iron ore is sent from any mine to any dump, a=1, otherwise a=0. **Equations 4** and **5**.

If iron ore is sent from any dump to any plant, b=1, otherwise b=0. **Equations 6** and **7**.

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a.X_{ij} > 0 \quad (4)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a.X_{ij} = 0 \quad (5)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} b.X_{ij} > 0 \quad (6)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} b.X_{ij} = 0 \quad (7)$$

The Constraints of iron ore, iron oxide, and sulfur are presented in **Equations 8**, **9**, **10** and **11**, respectively.

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \left(g_i^{fe} - g_j^{fe} \right) \ge 0, i \in I \ and\ j \in J \quad (8)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij}.g_i^{fe} / \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \ge g_j^{fe}, i \in I \ and\ j \in J \quad (9)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij}.g_i^{feo} / \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \ge g_j^{feo}, i \in I \ and\ j \in J \quad (10)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij}.g_i^{s} / \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \le g_j^{s}, i \in I \ and\ j \in J \quad (11)$$

5.4. Solve the model, iron ore sent from any origin to any destination over a period of 5 years

Using a linear programming model and problem-solving in Lindo-lingo software, model outputs in the first to fifth year **Tables 12** to **16** are provided for sending iron ore from any origin to any destination to supply feed to plants.

Table 12: Iron ore sent in the first year (ton)

Location	Plant NO.1	Plant NO.2	Plant NO.3	Plant NO.4	Plant NO.5
Mine NO.1	0	0	0	3200000	0
Mine NO.2	5200000	0	3000000	1800000	0
Mine NO.3	0	0	2000000	0	0
Mine NO.4	0	0	5000000	0	0
Mine NO.5	0	0	0	0	5000000
Mine NO.6	0	5000000	0	0	0

Table 13: Iron ore sent in the second year (ton)

Location	Plant NO.1	Plant NO.2	Plant NO.3	Plant NO.4	Plant NO.5
Mine NO.1	0	0	0	5000000	0
Mine NO.2	8850000	0	1150000	0	0
Mine NO.3	0	0	2000000	0	0
Mine NO.4	0	0	5000000	0	0
Mine NO.5	0	0	0	0	5000000
Mine NO.6	0	5000000	2850000	0	0

Table 14: Iron ore sent in the third year (ton)

Location	Plant NO.1	Plant NO.2	Plant NO.3	Plant NO.4	Plant NO.5
Mine NO.1	0	0	0	5000000	0
Mine NO.2	10000000	0	0	0	0
Mine NO.3	0	0	2000000	0	0
Mine NO.4	0	0	5000000	0	0
Mine NO.5	0	0	0	0	5000000
Mine NO.6	1000000	5000000	4000000	0	0

Table 15: Iron ore sent in the fourth year (ton)

Location	Plant NO.1	Plant NO.2	Plant NO.3	Plant NO.4	Plant NO.5
Mine NO.1	0	0	0	5000000	0
Mine NO.2	10000000	0	0	0	0
Mine NO.3	0	0	2000000	0	0
Mine NO.4	0	0	5000000	0	0
Mine NO.5	0	0	0	0	5000000
Mine NO.6	1000000	5000000	4000000	0	0

Table 16: Iron ore sent in the fifth year (ton)

Location	Plant NO.1	Plant NO.2	Plant NO.3	Plant NO.4	Plant NO.5
Mine NO.1	0	0	0	5000000	0
Mine NO.2	10000000	0	0	0	0
Mine NO.3	0	0	2000000	0	0
Mine NO.4	0	0	5000000	0	0
Mine NO.5	0	0	0	0	5000000
Mine NO.6	1000000	5000000	4000000	0	0

6. Discussion

Since 2002, according to the multitude of research conducted by researchers, many research studies have been conducted in the field of open pit mining with the topics of optimal final pit limit design, optimal production planning, and maximizing the net present value (NPV). In the studies conducted using integer programming and transportation model, single destination is considered for sending materials.

This model is a special case of the transportation model called the allocation problem. Solving the model using one source and one destination is easy. In this article, sending materials from multiple sources to multiple destinations using a combination of a transportation model and material allocation is considered. In some of the conducted studies, the uncertainty of grade conditions has not been investigated. While here, the uncertainty of iron ore grade in mines has been studied using Sequential Gaussian simulation. By using the transportation model and integer programming in operation research and considering quantitative and qualitative limitations in the defined objective function, the most appropriate model is presented.

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Table 17: Efficiency of iron ore concentrate plants (%)

Plant	Efficiency of concentrate plants without using iron ore dump (%)	Efficiency of concentrate plants using iron ore dump (%)	Percentage increase in efficiency of iron ore concentrate plant (%)
Plant NO.1	63	69	6
Plant NO.2	61	70	9
Plant NO.3	57	68	11
Plant NO.4	59	67	8
Plant NO.5	60	68	8

The quantity and quality of minerals (iron ore) based on the type of rock (waste, magnetite iron ore and hematite iron ore) in central mines and western mines are shown in **Tables 5** and **6**. It is very important to use the combination of transportation model and simulation in this article, which has not been observed in other research. In this paper, the cost of sending materials from any source to any destination is the least possible. The efficiency of iron ore concentrate plants has increased according to **Table 17**. The results of the presentation of the model have shown an increase in efficiency of at least 6%, and at most 11% of iron ore concentrate plans.

7. Conclusions

In this paper, the amount of minerals from multiple sources to multiple destinations has been done by using research modeling in operations and linear programming. The model's objective function is considered by minimizing the cost of sending materials from multiple sources to multiple destinations (transportation and allocation model). The iron ore sent from different mines to the concentrate plants is classified according to the constraint in supply, the type of rock, and the needs of the destinations. By maintaining the extraction of magnetite minerals, siderite-magnetite, hematite, and siderite resources are not considered plant feed. There are 91.7 million tons of minerals in mines that are not considered as feed for plants, and compared to 642.5 million tons of minerals used in concentrate plants, 14.2% of unusable minerals in factories. The requirement of the plants during the 5 years is a maximum of 37 million tons with an average grade of iron (Fe) of 42%. Regarding iron oxide (FeO), the constraint is greater than or equal to 12%. Regarding sulfur (S), the constraint is less than or equal to 4%. The allocation of plants from central mines (first 5-year period) is 77,127,733 tons of magnetite with a grade of 44.68%, iron oxide 21.4%, and sulfur 2.64%. Allocation of plants from western mines (first 5-year period) is 109,289,685 tons of magnetite with 44.25% iron grade, 20% iron oxide, and 0.39% sulfur. Therefore, the share of central mines in supplying feed to plants is approximately 15 million tons, and western mines 22 million tons per year. In the same way, the allocation for the supply of concentrate plants from different mines will be made for the second 5-year period and until the end of the life of the mining operations.

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SAŽETAK

Model raspodjele željezne rude u postrojenju za proizvodnju koncentrata iz višestrukih izvora do višestrukih odredišta uzimajući u obzir nesigurnost sadržaja rude: studija slučaja u rudniku Sangan u Iranu

Operacijska istraživanja dio su znanosti koja se koriste u raznim područjima. Ona su skup kvantitativnih tehnika koje pomažu stručnim voditeljima i organizatorima u donošenju odluka korištenjem znanstvenih metoda i povezana su s mnogim procesima donošenja odluka u upravljanju. Zbog toga se još nazivaju i znanost o upravljanju. Imaju široku primjenu u industriji i rudarstvu. Jedna od najprikladnijih metoda za rješavanje operacijskih problema jest korištenje linearnoga programiranja u rudarskim projektima. Ova studija provedena je u rudniku željezne rude Sangan u Iranu. U ovoj studiji proučavana je raspodjela željezne rude u oplemenjivačkome postrojenju za proizvodnju koncentrata korištenjem modeliranja linearnoga programiranja i rješavanja problema transporta uzimajući u obzir nesigurnost sadržaja rude. Ona se bavi proučavanjem i kvantitativnim i kvalitativnim utvrđivanjem količine rezervi željezne rude u rudnicima i potrebom postrojenja za oplemenjivanje s ciljem opskrbe sirovinama uzimajući u obzir nesigurnost sadržaja željezne rude u rudnicima i odlučivanja o pravilnoj raspodjeli. Modeliranje i procjena količine minerala koji se mogu izdvojiti izvršeni su pomoću blok-modela. Nesigurnost sadržaja željezne rude u blok-modelu istražuje se metodom sekvencijske Gaussove simulacije. Veličina rudarskoga kapaciteta i njegov redoslijed planira se s obzirom na vrstu željezne rude koja se koristi tijekom petogodišnjih razdoblja. U ovome je članku napravljeno modeliranje koje uzima u obzir postojeća ograničenja u rudnicima kao što su količina rezervi, sadržaj željezne rude, željezni oksid i sumpor. S druge strane, u modeliranju se razmatraju ograničenja u postrojenjima, kao što su potražnja, vrsta i sadržaj željezne rude, željeznoga oksida i sumpora. Rješavanjem istraživačkoga zadatka prikazana je i količina željezne rude koja je transportirana iz svakoga rudnika u svako postrojenje tijekom pet godina.

Ključne riječi:
površinski kop, rudnici željezne rude, postrojenje za oplemenjivanje, operacijska istraživanja, raspodjela

Author's contribution

Iman Eskandari Nezhad (PhD Candidate): Compiler of all articles, author of the complete manuscript, and implementer of the research concept. **Mohammad Ataei** (Professor): Idea generator and supervisor on the review section related to preparation parameters for modeling. **Farhang Sereshki** (Professor): Idea generator and supervisor on the review section related to preparation parameters for modeling.

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