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Research article

Investigating the effect of Iron ore wastes transportation and environmental pollution in Chadermalo

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Waste
Ore grade

Abstract

Mines have a considerable role in polluting the environment. Greenhouse gases and wastes mainly cause pollution. In this regard, trucks that carry ores in a mine are a primary source of these pollutants. Selecting trucks with low fuel consumption can help to reduce pollution. The present research seeks to evaluate the effects of the objectives (Cost objectives, Production objectives, and Environmental objectives) in mines on the type of trucks to select and the routes they take, as well as the effect of the duration of stone transportation on pollution. The study's data were obtained from the Chadormalu iron mine in Yazd Province. As the results showed, the objectives set in the mine affect the CO_2 level, and the goals followed with human health concerns induce lower CO_2 emissions. It found that the time ores are transported by trucks affects the CO_2 level. However, only the objective type affects the waste level resulting from tailings, not the speed of trucks. It is recommended that the duration of truck loading and unloading and the time the trucks waste waiting in lines be reduced to the extent possible to lower CO_2 emission.

1. INTRODUCTION

For thousands of years, ores have been extracted from mines in various ways. Depending on the distance of the ores from the surface and some other parameters, mining is performed in two significant ways: surface mining in open-pit mines and underground mining in deep mines. Open-pit mines require less investment and involve less risk than underground mines. However, the direct costs in an open-pit abundance are significant. The wastes in these mines are considerably large, and investment requires substantial funds due to the high expenses of large equipment. As a result, most of the decisions in this area are costly. Expensive equipment is used optimally to minimize costs. Therefore, planning in mining is of great importance.

Previous studies have shown that 50 to 60 percent of the costs in open pit mining are related to material transportation (Zhang and Xia, 2015). In this case, dump trucks in opencast mines consume about 32% of the total energy use (Sahoo et al., 2014). Planning for properly using machinery and optimizing the logistics and transportation system is, thus, necessary. The lack of planning in this respect causes less efficiency, more capital loss (due to the high machinery price), failure to achieve the production objectives (due to incorrect transportation or machinery interference), and non-optimal assignment of machinery to the loading sites. The routes (causing the congestion of machinery at one or more loading sites and lack of access to it at the other places), queues, and unnecessary increased working time. Trucks and shovels play an essential role in mining, especially in open-pit mines. In this regard, the proper planning of the trucks and shovels can significantly reduce the overall costs of the transportation system, such as fuel, maintenance, and downtime costs.

This research has the following contributions to the field:

- Proposing a binary integer programming model minimizes the total deviation from all the objectives through the proper allocation of trucks to different loading and unloading points.
- We are pursuing environmental objectives along with quantitative and qualitative goals.
- They are dividing the work cycle time of stone transport into different parts so that the trucks can be appropriately allocated to other places.
- It determines the type and number of trucks assigned to each loading point.

The rest of the paper is organized into several sections. Section 2 reviews the literature on open-pit mines to determine the research gap. Section 3 describes the problem along with the model formulation. The proposed model is validated in section 4, using the data taken from Bajany et al. (2017). In section 5, the proposed model is implemented in the case study (i.e., Chadormelo Mine), and the results are analyzed. The conclusion is presented in section 6, along with some future research directions.

2. LITERATURE REVIEW

Since the 1960s, a great bulk of research has been carried out on the operation and modeling of mining so as to make more effective decisions regarding mining issues. The studies are categorized into two groups as explained below.

2.1. Truck-Shovel Allocation Problem With Modeling

Given the critical role of the equipment in ore extraction, it is necessary to make better decisions regarding the type of equipment used and how it is used and allocated. For this purpose, scholars have created a wide use of operations research methods.

The role of trucks and shovels in extraction is so crucial that, if properly planned, they can bring about excellent results. A shovel plan is controlled by the number of trucks assigned; therefore, providing a proper truck schedule will lead to better use of the shovels. Since 2000, extensive studies have been conducted on this subject, some of which are presented in the following.

Merschmann (2002) developed an optimization system and a simulation model to analyze some production scenarios in open-pit mines. Coelho et al. (2009) presented an innovative method of solving a mixed-integer programming model to minimize the number of trucks and meet the required ore specifications. Hodkiewicz et al. (2010) assumed truck return times as constant, possible breakdowns, repair time, loading, and discharge of shovels and trucks in the form of probability distribution (i.e., Waybill or normal logarithm). Coelho et al. (2012) developed an algorithm based on metaheuristic Non-dominated Sorting Genetic Algorithm II (NSGA-II) to solve OPMOP, which provided better solutions with improved convergence. Lamghari and Dimitrakopoulos (2012) proposed a metaheuristic method based on a banned search method for open-pit mine scheduling. This method was used by Zhang and Xia (2015) to examine sand oil mines and determine the minimum number of trucks assigned to a shovel, subject to the capacity and grade constraints of the ore. Mena et al. (2013) proposed a nonlinear model to maximize the productivity of truck-shovel system performance with different loading and discharge sites. They achieved results by simulation. Sahoo et al. (2014) developed a model to examine the fuel consumption of trucks in mines. Zhang and Xia (2015) developed a linear model with several loading and discharge sites. The objective was to assign trucks to the routes to minimize operating costs. Chang et al. (2015) presented a scheduling model with different loading and discharge sites and developed an innovative method to solve it. Matamoros and Dimitrakopoulos (2016) presented a probabilistic-integer programming model with the objectives of minimizing mining costs, minimizing shovel displacement between mines, and maximizing truck and shovel productivity considering quality and production rates. Chaowasakoo et al. (2017) proposed an appropriate strategy for transportation by trucks using GPS technology and simulation. Patterson et al. (2017) proposed a mixed-integer linear programming model to minimize the amount of fuel consumed by shovels and trucks. Bajany et al. (2017) developed a nonlinear model to minimize the fuel requirements of trucks and shovels. Upadhyay and Askari-Nasab (2019) developed a model aimed at maximizing production rates, achieving the desired transportation capacity, the ore composition grade, and minimizing shovel displacements. Nakousi et al. (2018) presented a model for long-term transportation equipment scheduling to reduce equipment maintenance costs and reduce fuel consumption. Xu et al. (2018) presented a Dynamic Planning (DP) model to plan production in mines considering environmental costs. Afrapoli et al. (2019) proposed a multi-objective model for the dispatching of trucks. Bajany et al. (2019) presented a model to minimize fuel consumption in surface mining operations. Feng and Dong (2020) introduced a new method to generate an optimal energy management strategy, considering the total operation cost of a hybrid electric mining truck.

Noriega and Pourrahimian(2022) explained the use of Artificial Intelligence(AI) techniques in the strategic mine planning. They presented a systematic literature review to identify research trends in the field. Chung et al.(2022) proposed a mixed-integer programming model to obtain the optimal transition point and the transition period from open-pit to underground mining, maximizing the project's net present value.

Huo et al.(2023) proposed the algorithm trains the fleet to make better decisions based on payload, traffic, queueing, and maintenance conditions. Tabesh et al.(2023) presented a two-stage clustering- Multi-Integer Linear Programming(MILP) algorithm for long-term production planning in open-pit mines. The research integrates multi-range stockpiles in the decision-making process that leads to determining the optimum number of supplies required to maximize the discounted value of the mine.

The reviewed literature is categorized (Table 1) according to the following criteria:

- Number of points for stone loading and unloading: In some studies, there are multiple loading and unloading points, while others only consider one or no energy for loading and unloading.

- Transportation cycle time (Tt): It is considered as the sum of the loading time (tl), unloading time (tu), waiting time at loading and unloading points (tw), travel time of a loaded truck (tc), travel time of an empty truck (tr), and setup time of a loaded truck and an empty truck (tse).

- Objective function: Different objectives have been studied in the literature. In this study, they are categorized into three groups, including cost objectives (e.g., maintenance costs, oil changes and annual costs of trucks), production objectives (e.g., meeting the production rate, minimizing the deviation from the required ore grade, increasing the reliability of routes) and environmental objectives (i.e., the factors that affect the environment and manpower working in the mine).

- Research methods are divided into mathematical programming (solved by Exact or meta-heuristic models) and simulation.

Table 1. Literature review

Authors	Number of loading and unloading points	Hauling times	Objective functions			Research methods	
			Cost	Production	Environmental	Math	Simul.
Hodkiewicz et al. (2010)	---	tc , tl , tu		*			*
Coelho et al. (2009)	Different	Tt	*	*		*	
Lamghari and Dimitrakopoulos (2012)	---	---	*			*	
Rodrigo et al. (2013)	Different	---	*				*
Chung et al. (2013)	---	---	*			*	
Sahoo et al. (2014)	Different	tl , tc , tr , tw , tu	*		*	*	

Zhang and Xia (2015)	Different	tl , tu	*			*	
Chang et al. (2015)	Different	tl , tc , tr , tu	*				
Matamoros and Dimitrakopoulos (2016)	Loading points Different	Tt	*	*			
Bajany et al. (2017)	Different	tl , tc , tr , tu	*		*	*	
Chaowasakoo et al. (2017)	Loading points: Different	tl , tc , tr , tw , tu	*				*
Patterson et al. (2017)	Different	tl , tc , tr , tw , tu	*		*	*	
Upadhyay and Askari-Nasab (2017)	Different	Tt of shovels	*	*			*
Xu et al. (2018)	---	---	*			*	
Nakousi et al. (2018)	---	Tt	*			*	
Bakhtavar and Mahmoudi (2018)	Different	tl , tc , tr , tu	*			*	
Moradi Afrapoli et al. (2019)	Different	Idle time for shovel, tl , tc , tr , tu	*			*	
Bajany et al. (2019)	Different	tl , tc , tr , tu, idling time	*		*		*
Ozdemir and Kumral (2019)	Different	tl , tc , tr , tu	*				*
Feng and Dong (2020)	---	---	*			*	
Chung et al. (2022)	---	---	*			*	
Huo et al.(2023)	Loading points	Tt , Maintenance	*			*	
Tabesh et al. (2023)	---	---	*			*	
This research	Different	tl , tc , tr , tu , tw , tse	*	*	*	*	

Most reviewed studies dealt with single-objective problems and did not consider environmental objectives. Furthermore, they considered work cycle time in general and ignored its components, while each partial time has a vital role in allocating trucks. Moreover, the simulation results obtained in some of those studies are not accurate.

2.2. Cleaner Production In Mining

Since the late twentieth century, the emission of greenhouse gasses and their environmental effects has been the subject of some research. Luken and Navratil (2004), green products should be considered an efficient method of achieving stability in the environment and economic development. According to Severo et al. (2015), the concept of green production aims at the improvement of energy consumption efficiency, reduction of environmental effects resulting from the life cycle of products and development of optimum mechanisms to reduce greenhouse gases. Mining is considered high-consumption in terms of energy, imposing a variety of pollutions on the environment (through emission of greenhouse gases, destruction of perspectives, production of acid water, production of wastes, etc.). So, some studies have been performed in this respect to reduce the pollution level. As reported by Kaarsberg et al. (2007), the mean value of energy consumption in American mining is 115% higher than the minimum amount of the applied energy.

Using a simulation model, the energy efficiency of Autonomie equipment was evaluated by Lajunen (2015). Peralta et al. (2016) studied the relationship between the equipment reliability and the energy consumption level in mine-related transportation. Bharathan et al. (2017) examined the fuel consumption level and the amount of CO_2 emission in some Canadian mines. Bouchard et al. (2017) studied a control mechanism to determine the energy saving potential for grinding and jaw crushing. They did this by model optimization. The environmental effects of mines and mineral treatment operations in an underground copper mine in northern Norway were studied by Song et al. (2017) from the LCA (life cycle assessment) perspective. Similarly, through the LCA approach over several years, Martínez et al. (2019) evaluated the effect of a passive remediation system on the reduction of pollution resulting from effluent mine water.

Katta et al. (2020) developed a method to reduce the emission of greenhouse gases in iron, gold and potash mining in Canada. In another research, the CO_2 emission from the railway transportation of coal for power generators was studied by Sherwood et al. (2020). A new pattern was provided by Kinnunen et al. (2020) to retrieve waste water in mining sites so that they could have better environmental effects. Purhamadani et al. (2021) compared the truck transport system and IPC in terms of energy consumption. Bhuiyan et al.(2021) used multivariate statistical methods to study the dangers and harms caused by the presence of elements in coal mine water. They determined that the pollution indicators are very high and the water is unsuitable for drinking purposes. To reduce the risks caused by industrial dust in the mine, Wang and Jiang(2021) studied the performance of atomization by experiment and numerical simulation.

Sui et al.(2022) using a metal transfer and conversion module, simulated and studied the pollution level in the basins regarding mining activities. Feng et al.(2022) optimized several emerging clean powertrain solutions for a typical 240-tonnage MHT(Mining haul truck) using an integrated design and control optimization method and compares the energy efficiency and carbon dioxide (CO_2) emission to the benchmark MHT with a diesel engine and diesel-electric drive. Yu and Zahidi(2022) proposed a technique for monitoring mine dust pollution on a regional scale based on the Dense Dark Vegetation (DDV) algorithm.

Most of the above studies have ignored the effects of different objectives on management decisions, the allocation of trucks, and the consequences of factors such as the time duration between loading and unloading and the speed of trucks on the amount of pollution from stone transport.

The present research aims to develop a multi-objective planning model for allocating trucks to different loading sites. For this purpose, specific criteria are considered, such as loading time, transportation, load discharge and return of trucks, the distance between loading and discharge sites, and the capacity of shovels and trucks. The targeted domains are the average ratio of the cost of trucks to the transported ores, the balance of the fuel consumption to the transported ores, the reliability of routes, the reliability deviations across all the transportation routes, the variations of the ore grades, the production rate, and the impacts on the workforce involved in the production. This study's main objective is to investigate the effects of these goals and criteria on the mining hauling fleet's waste and greenhouse gas emissions.

3. PROBLEM STATEMENT

In open-pit mines, trucks are responsible for ore transportation. Each car has a working path from the loading to the unloading point, considered a completed cycle. Fig. 1 shows a truck's route between a source, loaded by a shovel, and a destination, where the material is unloaded.

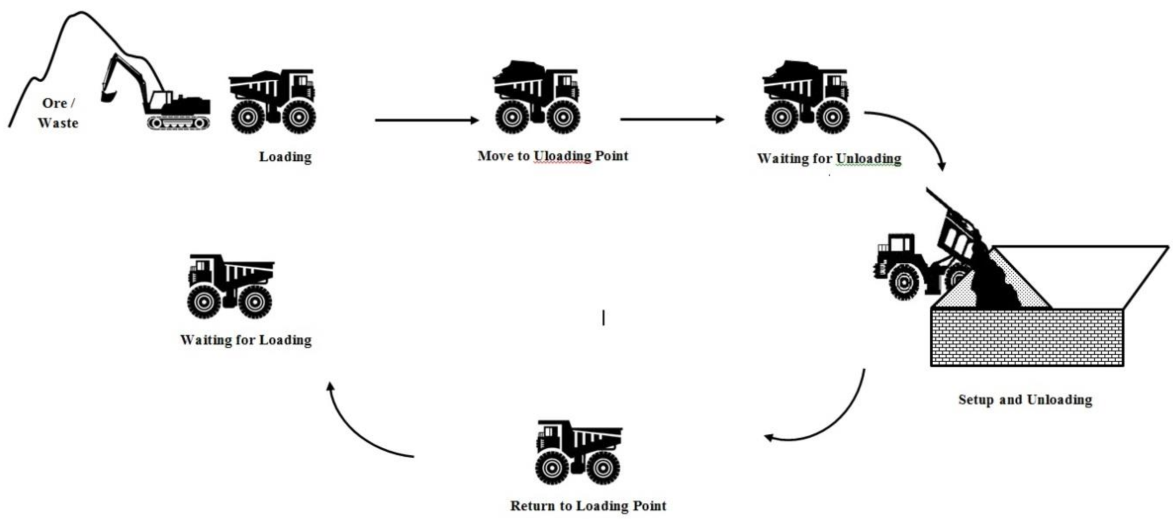

Fig. 1. The completed cycle of a truck from loading to unloading to return.

Considering the time details in the cycle time of stone transport is essential for its direct impact on the allocation of trucks for loading and unloading points. The work cycle time can be divided into two categories, inevitable time (travel time and setup time) and avoidable time (waiting time). All these times affect the costs and fuel consumption. Due to the impact of the adjusted times on the price and environmental objectives, it is necessary to reduce or eliminate the avoidable time as much as possible. As the avoidable time is eliminated, the productivity of shovels and trucks increases.

The model proposed in this study deals with transporting ores/wastes from the pit to the discharge sites involving several loading and discharge areas. In Fig. 2, the loading sites are marked with so_i, and the discharge sites with uo_i. Also, sw_i and uw_i represent the waste loading and discharge sites, respectively.

The objective functions of the study consist of a) reducing the average total cost, b) achieving quantitatively and qualitatively desirable production, and c) reducing the adverse environmental impacts of trucks and shovels. Each objective has its degree of importance. Moreover, the model has several production constraints to approach the actual working conditions. The technical limitations (e.g., equipment failure) and technological restrictions (e.g., slope) to avoid complexity are ignored. Some simplifying assumptions are made.

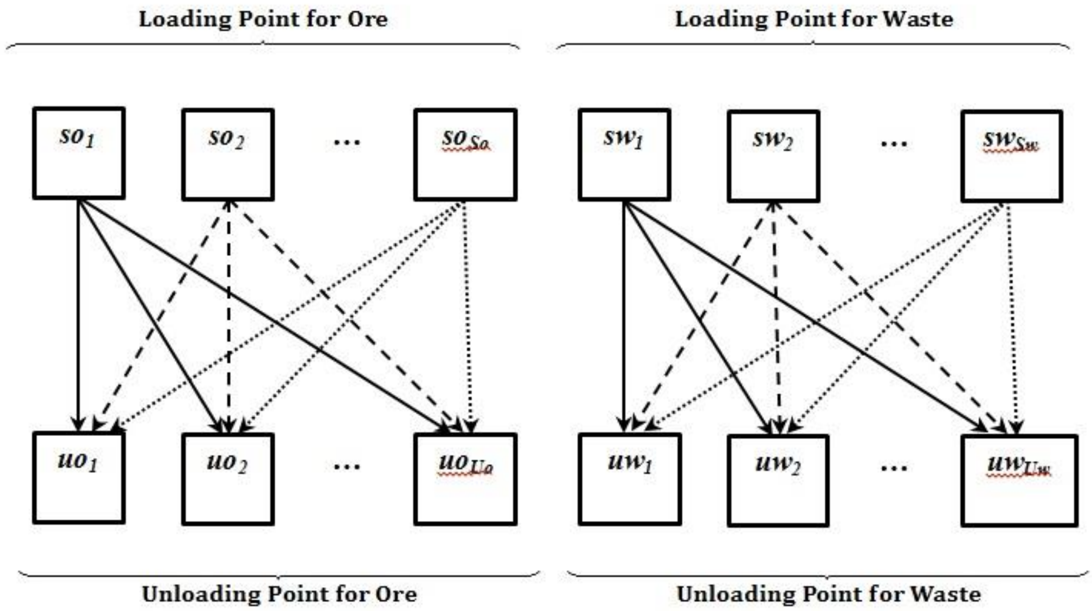

Fig. 2. The ore/waste transport routes in an open-pit mine.

Modeling the problem is based on certain assumptions, sets, parameters, and variables as follows:

3.1. Assumptions

The number of shovels is equal to the number of loading sites; however, due to some technical issues in the mine, every shovel may not be assigned to every loading site. This is determined at the beginning of each working shift.

- Departure routes (from loading to discharge) are the same as return routes (from discharge to loading).
- At each loading site, each shovel can only load one truck at a time.
- At each discharge site, only one truck can discharge the load.
- There are enough waiting places for trucks at each loading and discharge site.
- Operations are carried out based on the First in First out (FIFO) rule at each loading and discharge site.
- At a loading site, it is not possible to load ores and wastes at the same time. If both

happen at one loading site, it would be presumed as two sites.

- For any reason, if a loading or discharge site is not usable during a working shift, the site will be deleted.
- All the shovels are different in terms of capacity and characteristics, and the trucks have different capacities.
- The engine power, capacity, speed, and all the other characteristics of the trucks of a particular type are identical.
- The average cost of the trucks of a particular type is the same.
- Ores of varying grades are mixed at the discharge site and, through a crushing process, become a mass of an average-weighted grade.
- If a truck is assigned to a specific loading or discharge site, this is done continuously and changeably until the end of the shift.
- If a truck carries ores from a designated loading site to a designated discharge site, it will return to the same loading site.
- At the beginning of a working shift, the equipment that has to be stopped due to a maintenance task or a breakdown is identified and excluded from the shift list; however, there is a possibility that the equipment will be broken when in operation.

3.2. Sets And Indices

i	Truck number
j	Truck type
s	Loading point (Source) s = so ∪ sw
so	Ore loading point
sw	Waste loading point
u	Unloading point (destination) u = uo ∪ uw
uo	Ore unloading point
uw	Waste unloading point
k	Gross type
s'	Shovel index

3.3. Parameters

N_j	Number of trucks type j $N_j = \{1,2,\dots,n_j\}$
N_m	Number of truck types $N_m = \{1,2,\dots,M\}$
$N_{s'}$	Number of shovels $N_{s'} = \{1,2,\dots,S'\}$
N_s	Number of loading points $N_s = N_{so} + N_{sw} = \{1,2,\dots,S\}$, $S = S_o + S_w$
N_{so}	Number of ore loading points $N_{so} = \{1,2,\dots,S_o\}$
N_{sw}	Number of waste loading points $N_{sw} = \{1,2,\dots,S_w\}$
N_u	Number of unloading points $N_u = N_{uo} + N_{uw} = \{1,2,\dots,U\}$, $U = U_o + U_w$
N_{uo}	Number of ore unloading points
N_{uw}	Number of waste unloading points
N_k	Number of gross types $N_k = \{1,2,\dots,K\}$
N_{Tr}^{s}	Average number of trucks waiting for loading at point s
N_{Tr}^{u}	Average number of trucks waiting for unloading at point u
C_s	Average capacity of shovels at loading point s (ton)
C_j	Average capacity of truck type j (ton)

d^{su}	Distance from loading point s to unloading point u (km)
v_j	The driving speed of a loaded truck type j (km/h)
v'_j	The driving speed of an empty truck type j (km/h)
AC_j	Average costs of a truck type j during a working shift ($)
TAC	Total average costs of trucks during a working shift ($)
h_i	Priority goal i
t_s	Average loading and unloading time of a shovel at loading point s (min)
tl_j	Average loading time of a truck type j (min)
tc_j^{su}	Average travel time of a loaded truck from loading point s to unloading point u (min)
twa_j^u	Average waiting time of a loaded truck type j at unloading point u (min)
tse_j^u	Average setup time of a loaded truck type j at unloading point u (min)
tu_j^u	Average unloading time of a loaded truck type j at unloading point u (min)
tr_j^{su}	Average travel time of an empty truck from unloading point u to loading point s (min)
twa_j^s	Average waiting time of an empty truck type j at loading point s (min)
tse_j^s	Average setup time of an empty truck type j at loading point s (min)
Tt_j^{su}	Completed cycle time of a truck type j loaded at loading point s, moving to unloading point u, … and returning to loading point s for reloading (min)
Nlu_{ij}^{su}	Number of the journeys that truck i of type j has from loading point s to unloading point u during a working shift
Noc_{ij}^{su}	Number of the journeys that truck i of type j has to carry ore from loading point s to unloading point u during a working shift
Nwc_{ij}^{su}	Number of the journeys that truck i of type j has to carry waste from loading point s to unloading point u during a working shift
Nlu_s	Number of times that a shovel is loaded and unloaded at loading point s during a working shift
R_j	Time of rest for the driver of a truck type j during a working shift (min)
R_s	Time of rest for the driver of a shovel at loading point s during a working shift (min)
H	Shift duration (min)
Q_s	Quantity of ore/waste loaded by a shovel at loading point s during a working shift (ton)
LGo^u	Prescribed lower limit of the stripping ratio for ore at unloading point u
UGo^u	Prescribed upper limit of the stripping ratio for ore at unloading point u
$UGG^{u,k}$	Prescribed upper limit of the stripping ratio for gross type k at unloading point u
g_{ij}^{su}	Percentage or grade of ore at loading point s carried by truck i of type j to unloading point u
$gG_{ij}^{su,k}$	Percentage or grade of gross type k of ore at loading point s carried by truck i of type j to unloading point u
Lo	Required ore production during a working shift (ton)
Lw	Required waste production during a working shift (ton)
f_j	Average fuel consumption of a truck type j (lit/h)
Fco_j^s	Average fuel consumption of an empty truck type j at loading time (lit)

Fco_j^c	Average fuel consumption of a loaded truck type j at carrying time (lit)
Fco_j^{wau}	Average fuel consumption of a loaded truck type j at waiting time (lit)
Fco_j^{seu}	Average fuel consumption of a loaded truck type j at setup time (lit)
Fco_j^u	Average fuel consumption of a loaded truck type j at unloading time (lit)
Fco_j^r	Average fuel consumption of an empty truck type j that returns to loading point (lit)
Fco_j^{was}	Average fuel consumption of an empty truck type j at waiting time (lit)
Fco_j^{ses}	Average fuel consumption of an empty truck type j at the time setup for loading (lit)
$TFco_j^{su}$	Average fuel consumption of a truck type j in a completed cycle time from loading point s to unloading point u (lit)
F_t	The total fuel consumed by active trucks during a working shift (lit)
CO_2	The CO_2 emission from diesel fuels (ton/hr)
f_s	Average fuel consumption of a shovel at loading point s (lit/h)
F_s	The total fuel consumed by active shovels during a working shift (lit)
W_t	Total carried ore/waste during a working shift (ton)
No_{ij}	Dosimetry rate of truck i of type j during a working shift
Vi_{ij}	Vibration rate that truck i of type j imposes on the driver's body during a working shift
$SLNo_j$	Standard noise level created by a truck type j during a working shift
$SLVi_j$	Standard vibration rate created by a truck type j during a working shift
Re_{ij}	Reliability of truck i of type j during a working shift
$Re_{s'}$	Reliability of shovel s'during a working shift
Re^{su}	Reliability of the route for transportation from loading point s to unloading point u during a working shift
α_j^{su}	1 when a truck type j can carry ore/waste from loading point s to unloading point u during a working shift; otherwise, 0

3.4. Decision Variables

x_{ij}^{su}	1 when truck i of type j is allocated to a route that carries ore/waste from loading point s to unloading point u during a working shift; otherwise, 0
$y_{s'}^{s}$	1 when shovel $s'$is allocated to loading point s; otherwise, 0
do^-	Negative deviational variable for the ore quantity transported from a specified quantity during a working shift (ton)
do^+	Positive deviational variable for the ore quantity transported from a specified quantity during a working shift (ton)
dw^-	Negative deviational variable for the waste quantity transported from a specified quantity during a working shift (ton)
dw^+	Positive deviational variable for the waste quantity transported from a specified quantity during a working shift (ton)
dLq^{u-}	Negative deviational variable for the lower limit of ore quality (Percent)
dLq^{u+}	Positive deviational variable for the lower limit of ore quality (Percent)
dUq^{u-}	Negative deviational variable for the upper limit of ore quality (Percent)
dUq^{u+}	Positive deviational variable for the upper limit of ore quality (Percent)

dGq_k^{u-}	Negative deviational variable for the standard limit of gross type k (Percent)
dGq_k^{u+}	Positive deviational variable for the standard limit of gross type k (Percent)
$d\,Re^{su-}$	Negative deviational variable for the reliability of the route to transport materials from loading point s to unloading point u
$d\,Re^{su+}$	Positive deviational variable for the reliability of the to transport materials from loading point s to unloading point u
dNo_{ij}^{-}	Negative deviational variable for the standard noise of truck i of type j during a working shift
dNo_{ij}^{+}	Positive deviational variable for the standard noise of truck i of type j during a working shift
dVi_{ij}^{-}	Negative deviational variable for the standard vibration of truck i of type j during a working shift
dVi_{ij}^{+}	Positive deviational variable for the standard vibration of truck i of type j during a working shift
dNo_{ij}^{+}	Positive deviational variable for the standard noise of truck i of type j during a working shift
dVi_{ij}^{-}	Negative deviational variable for the standard vibration of truck i of type j during a working shift
dVi_{ij}^{+}	Positive deviational variable for the standard vibration of truck i of type j during a working shift

3.5. The Proposed Model

The general form of the proposed model including the objective functions and constraints is described here.

3.5.1. Objective Functions

The objective function consists of ten parts.

$$\underbrace{\mathrm{MinZ}_1=\frac{\mathrm{TAC}}{\mathrm{W_t}}}_{\text{1st}}\ ,\ \underbrace{\mathrm{MinZ}_2=\frac{\mathrm{F_t}+\mathrm{F_s}}{\mathrm{W_t}}}_{\text{2nd}}\ ,\ \underbrace{\mathrm{MaxZ}_3=\mathrm{W_{ore}}}_{\text{3rd}}\ ,\ \underbrace{\mathrm{MaxZ}_4=\mathrm{W_{Waste}}}_{\text{4th}}$$
$$,\ \underbrace{\mathrm{MinZ}_5=\sum_{u=1}^{U_o}\mathrm{dLq}^{u-}}_{\text{5th}}\ ,\ \underbrace{\mathrm{MinZ}_6=\sum_{u=1}^{U_o}\mathrm{dUq}^{u+}}_{\text{6th}}\ ,\ \underbrace{\mathrm{MinZ}_7=\sum_{u=1}^{U_o}\sum_{k=1}^{K}\mathrm{dGq}_k^{u+}}_{\text{7th}}\ , \tag{1}$$
$$\underbrace{\mathrm{MinZ}_8=\sum_{s=1}^{S}\sum_{u=1}^{U}\mathrm{d\,Re}^{su-}}_{\text{8th}}\ ,\ \underbrace{\mathrm{MinZ}_9=\sum_{j=1}^{M}\sum_{i=1}^{n_j}\mathrm{dNo}_{ij}^{+}}_{\text{9th}}\ ,\ \underbrace{\mathrm{MinZ}_{10}=\sum_{j=1}^{M}\sum_{i=1}^{n_j}\mathrm{dVi}_{ij}^{+}}_{\text{10th}}$$

The first part is the ratio of the total cost of trucks (excluding fuel and driver's costs) to the total transported ores during a working shift. The second part regards the ratio of the fuel consumption of trucks and shovels to the total transported ores. Objective functions (3) and (4) show the least amount of ores and wastes during a working shift. Functions (5) and (6) describe the amount of negative and positive deviations from the minimum grade required for the customers. Function (7) shows the positive deviation from the permitted impurities in the transported ores. The eighth objective function concerns the negative deviation from the required reliability. Finally, objectives (9) and (10) present a positive deviation from the noise pollution standard and the truck vibration. The objectives and Constraints are categorized into groups as follows:

3.5.1.1. First Objective: Cost Objectives

The objectives are related to truck costs per ton of ore (mining and tailings) and include maintenance and repair, operating, and shipping costs (driver, fuel, oil use, and tires). These objectives should be minimized.

$$MinZ_{Cost}=\frac{TAC}{W_t} \tag{2}$$

3.5.1.2. Second Objective: Production Objectives

The production objective function includes production challenges and problems. This function consists of 6 parts: the amount of ore transported per shift, the number of tailings removed per shift, the upper limit for ore grade, the lower limit for ore grade, ore allowable impurity limit, and the reliability in different roads.

The first two objectives mean transporting more ore and tailings, which should be maximized. Still, in the other objectives, given that the deviation (positive or negative) from the expected level is selected as the objectives, the deviation should be minimal.

$$MinZ_{Prod} = \begin{bmatrix} -W_{ore}, -W_{Waste}, \sum_{u=1}^{U_o} dLq^{u-}, \sum_{u=1}^{U_o} dUq^{u+} \\ , \sum_{u=1}^{U_o}\sum_{k=1}^{K} dGq_k^{u+}, \sum_{s=1}^{S}\sum_{u=1}^{U} d\,Re^{su-} \end{bmatrix} \quad (3)$$

3.5.1.3. Third Objective: Enviromental Objectives

The third group of objectives is dedicated to the pollution of the mining environment by trucks and the effect on the force working in the mine. It also includes three objectives, including the amount of fuel used per ton of ore transport, the amount of noise generated by the trucks, and the amount of vibration of the truck. All these objectives are minimized.

$$MinZ_{Envir} = \left[\frac{F_t}{W_t}, \sum_{j=1}^{M}\sum_{i=1}^{n_j} dNo_{ij}^{+}, \sum_{j=1}^{M}\sum_{i=1}^{n_j} dVi_{ij}^{+}\right] \quad (4)$$

3. 5. 2. Constraints

The constraints in the model are in the following groups.

3. 5. 2. 1. Constraints Related To Truck Allocation

Constraint 5 relates to the total number of j-type trucks allocated for ore transport on all roads, which should not exceed the total number of this type of truck.

$$\textstyle\sum_{s=1}^{S}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} \le n_j \quad , j = 1,2,,\dots, M \quad (5)$$

Constraint 6 ensures that each truck is allocated to only 1 road per shift.

$$\textstyle\sum_{s=1}^{S}\sum_{u=1}^{U} x_{ij}^{su} \le 1 \quad , \begin{matrix} i = 1,2,\dots,n_j \\ j = 1,2,\dots,M \end{matrix} \quad (6)$$

If a particular type of truck cannot be allocated according to the conditions of loading and unloading sites and the distance between the sites, Constraint 7 guarantees this.

$$x_{ij}^{su} \le \alpha_j^{su} \quad , \begin{matrix} i = 1,2,\dots,n_j \\ s = 1,2,\dots,S \\ u = 1,2,\dots,U \end{matrix} \quad (7)$$

3. 5. 2. 2. Constraints Related To The Amount Of Rock Transport

Constraints 8-10 relate to the amount of rock transport by the trucks per shift.

$$\textstyle\sum_{j=1}^{M}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} Nlu_{ij}^{su} C_j \le Q_s \quad s = 1,2,\dots,S \quad (8)$$

Constraint 8 guarantees that the amount of ore transported from a loading site cannot be more than the amount of ore loaded by shovels.

$$\textstyle\sum_{s=1}^{S_o}\sum_{j=1}^{M}\sum_{u=1}^{U_o}\sum_{i=1}^{n_j} x_{ij}^{su} Noc_{ij}^{su} C_j \ge Lo \quad (9)$$

$$\textstyle\sum_{s=1}^{S_w}\sum_{j=1}^{M}\sum_{u=1}^{U_w}\sum_{i=1}^{n_j} x_{ij}^{su} Nwc_{ij}^{su} C_j \ge Lw \quad (10)$$

The above two constraints state that the amount of ore and tailings transported to the unloading sites per shift should not be less than acceptable.

3. 5. 2. 3. Constraints Related To Ore Grade And Impurity

The guarantee of ore purity and impurity is expressed in three Constraints 11, 12, and 13.

Constraints 11 and 12 ensure that the grade of ore transported does not exceed the given range.

$$\textstyle\sum_{s=1}^{S_o}\sum_{j=1}^{M}\sum_{i=1}^{n_j} x_{ij}^{su} g_{ij}^{su} \ge LGo^u \sum_{s=1}^{S_o}\sum_{j=1}^{M}\sum_{i=1}^{n_j} x_{ij}^{su} \quad , \quad u = 1,2,\dots,U_o \quad (11)$$

$$\textstyle\sum_{s=1}^{S_o}\sum_{j=1}^{M}\sum_{i=1}^{n_j} x_{ij}^{su} g_{ij}^{su} \le UGo^u \sum_{s=1}^{S_o}\sum_{j=1}^{M}\sum_{i=1}^{n_j} x_{ij}^{su} \quad , \quad u = 1,2,\dots,U_o \quad (12)$$

Constraint 13 ensures that ore transported to the unloading sites has a lower percentage of impurity than the allowable limit.

$$\textstyle\sum_{s=1}^{S_o}\sum_{j=1}^{M}\sum_{i=1}^{n_j} x_{ij}^{su} gG_{ij}^{su,k} \le UGG^{u,k} \sum_{s=1}^{S_o}\sum_{j=1}^{M}\sum_{i=1}^{n_j} x_{ij}^{su} \quad , \begin{matrix} u = 1,2,\dots,U_o \\ k = 1,2,\dots,K \end{matrix} \quad (13)$$

3. 5. 2. 4. Constraints Related To Rock Transport Roads

Constraints 14 and 15 show that at least one truck will be allocated to each road per shift.

$$\sum_{j=1}^{M}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} \geq 1 \quad , \quad s = 1,2,\dots,S \qquad (14)$$

$$\sum_{j=1}^{M}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} \geq 1 \quad , \quad u = 1,2,\dots,U \qquad (15)$$

Constraint 16 can establish reliability in each road.

$$\left[\prod_{s'=1}^{S'}(Re_s)^{y_{s'}^{s}}\right]\left[1-\prod_{j=1}^{M}\prod_{i=1}^{n_j}(1-Re_{ij})^{x_{ij}^{su}}\right] + d\,Re^{su-} - d\,Re^{su+} = Re^{su} \;, \quad s = 1,2,\dots,S,\; u = 1,2,\dots,U \qquad (16)$$

3. 5. 2. 5. Constraints Related To Shovel Allocation

Constraint 17 indicates that no shovel is assigned to more than one location. Constraint 18 is presented to guarantee that only one shovel operates at each loading site.

$$\sum_{s=1}^{S} y_{s'}^{s} = 1 \quad , \quad s' = 1,2,\dots,S' \qquad (17)$$

$$\sum_{s'=1}^{S'} y_{s'}^{s} = 1 \quad , \quad s = 1,2,\dots,S \qquad (18)$$

3. 5. 2. 6. Constraints Related To Injury To The Driver

Constraints 19 and 20 express the deviation from noise, pollution and vibration standards for each truck.

$$No_{ij}\sum_{s=1}^{S}\sum_{u=1}^{U} x_{ij}^{su} + dNo_{ij}^{-} - dNo_{ij}^{+} = SLNo_j \quad , \quad i = 1,2,\dots,n_j,\; j = 1,2,\dots,M \qquad (19)$$

$$Vi_{ij}\sum_{s=1}^{S}\sum_{u=1}^{U} x_{ij}^{su} + dVi_{ij}^{-} - dVi_{ij}^{+} = SLVi_j \quad , \quad i = 1,2,\dots,n_j,\; j = 1,2,\dots,M \qquad (20)$$

3. 5. 2. 7. Constraints Of Decision Variables

Constraint 21 emphasizes that the decision variables in the model are zero and one.

$$x_{ij}^{su} = 0 \text{ or } 1 \quad , \quad i = 1,2,\dots,n_j,\; j = 1,2,\dots,M,\; s = 1,2,\dots,S,\; u = 1,2,\dots,U \qquad (21)$$

Furthermore, the model involves some parameters to calculate, which are defined as follows:

The time of a complete cycle is equal to the sum of the eight-stage times (loading, loading, waiting to unload, preparing to unload, unloading, returning, waiting to load, and training to load), which is a time from the start of loading until the return of the truck to the loading site (Fig. 1).

$$Tt_j^{su} = \left(\frac{C_j}{C_s}\times t_s\right) + \frac{d^{su}}{v_j} + [N_{Tr}^{u}\times(tu^u + ts^u)] + tse_j^u + tu_j^u + \frac{d^{su}}{v'_j} + [N_{Tr}^{s}\times(tu^s + ts^s)] + tse_j^s \qquad (22)$$

Relation (23) specifies the number of working cycles during a shift.

$$Nlu_{ij}^{su} = \frac{H - R_j}{Tt_j^{su}} \qquad (23)$$

Relation (24) shows the capacity of loading trucks with shovels during a working shift.

$$Q_s = Nlu_s \times t_s \qquad (24)$$

The calculation of the total cost of trucks is provided in relation (25).

$$TAC = \sum_{j=1}^{M} AC_j \sum_{s=1}^{S}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} \qquad (25)$$

The fuel consumption of trucks and shovels is dealt with in relations (26) and (27).

$$F_t = \sum_{s=1}^{S}\sum_{j=1}^{M}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} Nlu_{ij}^{su}\, TFco_j^{su} \qquad (26)$$

$$F_s = \sum_{s=1}^{S}\left[(H-R_s)Kf_s + \left(\sum_{j=1}^{M}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} Nlu_{ij}^{su}\frac{tl_j}{60}\right)(1-K)f_s\right] \qquad (27)$$

Relation (28) shows the total amount of ores and wastes transported by trucks during a working shift.

$$W_t = \sum_{s=1}^{S}\sum_{j=1}^{M}\sum_{u=1}^{U}\sum_{i=1}^{n_j} x_{ij}^{su} Nlu_{ij}^{su}\, C_j \qquad (28)$$

The amount of fuel consumed by each truck and the CO_2 emission from diesel fuel is measured with relations (29) and (30) (Kecojevic and Komljenovic, 2010).

$$f_j = 0.3 \times P_j \times LF \qquad (29)$$

$$CO_2 = 0.00268 \times F_t \qquad (30)$$

4. THE VALIDATION AND VERIFICATION OF THE PROPOSED MODEL

It used the data taken from Bajany et al. (2017) to validate the proposed model. They regarded three loading points, two unloading points, and three types of trucks. The objective functions and the constraints of the proposed model were similar to those used in Bajany et al. (2017). After simplifying the model implemented, and compared the results to those obtained by Bajany's team. According to Table (2), the results of the two studies were very similar. It thus validated the proposed model.

Of course, there were specific differences between the two studies. It may have been due to the decision variables defined in the present study being 0 and 1 and as integers in the other. Bajany's team divided the work cycle's time into transport, loading, and unloading. Still, the present research involved those three times and accounted for the waiting and preparation times. To evaluate the validity, after the GAMS software coded the primary model, selected the data related to a small problem, and checked the authenticity of the obtained results to show the validity of the model.

Table 2. Results of the proposed model with simplified assumptions versus Bajany's model

Assign trucks to each route				
Loading points		s_1	s_2	s_3
Unloading points	u_1	OK	OK	---
	u_2	---	OK	OK
Results	Bajany et al.		This Research	
Objective Function(lit/ton)	Z=0.137		Z=0.14	
Fuel Consumption(lit)	5154.15		5397.83	

5. CASE STUDY

In this section, data of case study and the necessary parameters are presented, then the problem is solved through Weighted LP-Metric.

5.1. Description Of Case Study And Input Data

As a case study, the proposed model was implemented in Chadormalu Mine (located in the heart of the central desert of Iran, on the northern hillside of the Chah Mohammad Gray Mountains in the south of Saghand Salt Lake, 180 km to the northeast of Yazd City and 300 km to the south of Tabas). In this mine, five main types of trucks were used to carry ores. Table 3 gives the truck specifications.

Table 3. Truck specifications

Trucks	A	**B**		C	
Type	A	B_1	B_2	C_1	C_2
Number of Trucks	44	29	3	20	1
Capacity(ton)	130	90	51	91	36
Speed of loaded truck (km/h)	19	21	23	19	24
Speed of empty truck (km/h)	36	36	42	32	42

In the mine, collected ores and wastes are in different blocks. It was almost impossible to determine the exact distance of each block from the discharge sites because the number and location of each block changed with the change of working shifts. Therefore, the loading areas were divided into three major groups, including upper, middle, and lower zones. Also, the discharge sites were of two major and closely related groups. It depends on the magnetite or hematite type of ores and the percentage of iron and phosphorus contents in them. Thus, one site was considered the discharge site to determine the approximate distance between the loading and the discharge sites. It is to be noted that, due to the variability of the ore purity and impurity rates at each loading site, the data were gathered randomly (Table 4).

Table 4. Distance between the loading and discharge sites (km)

Ore unloading point / Ore loading points		uo
Upper zones (so_1)	ore quality(Percent): 44	2.5
	gross (Percent): 0.3	
Middle zones (so_2)	ore quality(Percent): 30	3
	gross (Percent): 2	
Lower zones (so_3)	ore quality(Percent): 60	3.5
	gross (Percent): 0.8	

Similarly, the waste loading and unloading sites were divided into three main zones. The distances between the zones are presented in Table 5.

Table 5. Distance between the loading and discharge sites for wastes (km)

Waste unloading points / Waste loading points	South (uw_1)	West (uw_2)	East (uw_3)
Upper zones (so_1)	1.5	2.6	---
Middle zones (so_2)	1.9	3.6	3
Lower zones (so_3)	---	4	5

5. 2. Solving The Model Based On The Data Of Chadormalu Mine

The global criterion method was employed to deal with the proposed multi-objective model. It coded the proposed model in the GAMS software based on the data available in Chadormalu Mine.

The proposed model was analyzed in two parts as follows:

1) Investigating the effect of each selected objective and the speed of trucks on the amount of Co_2 and waste extraction.

2) Investigating the effect of the change in the idle time durations of the model (waiting and preparation times) on the amount of Co_2.

5. 2. 1. Investigating The Impact Of Each Objective Function And The Speed Of Trucks

Generally, CO_2 emission and waste production due to tailings lead to environmental pollution. In this study, the effects of selecting each objective. It evaluated the speed of trucks on CO_2 emission and waste production. ANOVA at the 5% error level was used for the analyses. The statistical hypotheses were as follows:

$$\begin{cases} H_0: \textit{The speed of the trucks has impact on the Criterion} \\ H_1: \textit{The speed of the trucks has no impact on the Criterion} \end{cases}$$

$$\begin{cases} H'_0: \textit{Obejctive functions have an impact on the Criterion} \\ H'_1: \textit{Obejctive functions have no impact on the Criterion} \end{cases}$$

The results are presented in Tables 6 and 7.

Table 6 shows the effects of the selected objective functions and the speed of trucks on the level of CO_2 production.

Table 6. Impact of the objective functions and the speed of trucks on the amount of Co_2

Source of Variation	SS	df	MS	F	P-value
Speed of trucks	22.159	2	11.079	18.808	0.00
Objective functions	1603.877	9	178.209	302.518	0.00
Error	10.604	18	0.589		
Total	1636.639	29			

As Fig. 3 shows, the objectives of Z_9 (i.e., minimum positive deviation from noise pollution) and Z_{10} (i.e., minimum positive deviation from truck vibration) would lead to minimum CO_2 emission. Meanwhile, Z_3 (i.e., maximum iron ore harvesting) and Z_4 (i.e., maximum tailings) objectives were accompanied by CO_2 pollution. It also emerged that the lowest amount of CO_2 would be produced if the trucks drove at the possible top speed; in other words, lower truck speeds would lead to more CO_2 emission.

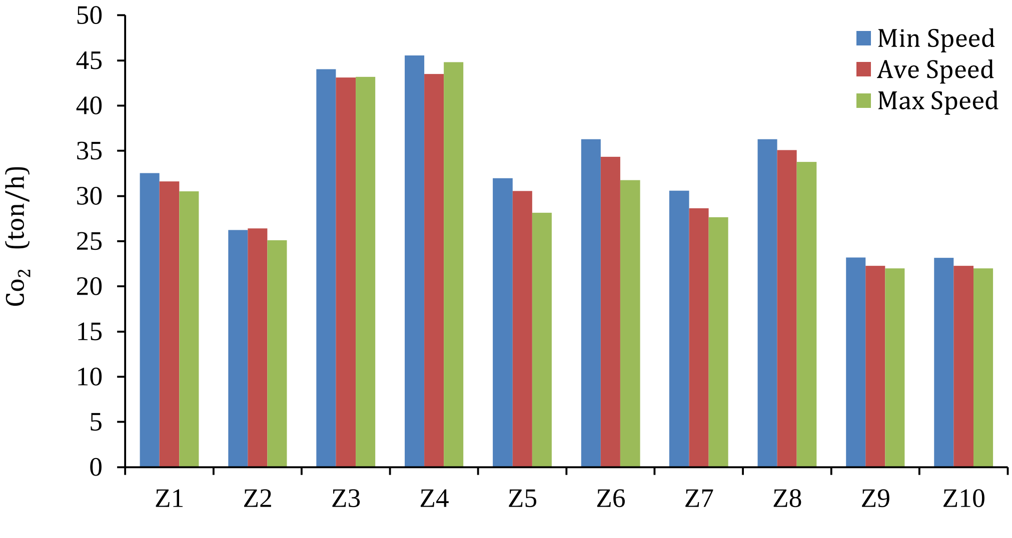

Fig. 3. Impact of each objective functions and speed of Trucks on the amount of Co_2.

As Table 7 shows, only selecting a specific objective function would affect the waste resulting from tailings. The speed of trucks was not effective in this regard.

Table 7. Impacts of objective functions and speed of trucks on the amount of waste

Source of Variation	SS	df	MS	F	P-value
Speed of trucks	1578534	2	789266.9	1.048	0.371
Objective functions	1.63 E+09	9	1.81 E+08	240.903	0.00
Error	13560411	18	753356.2		
Total	1.65 E+09	29			

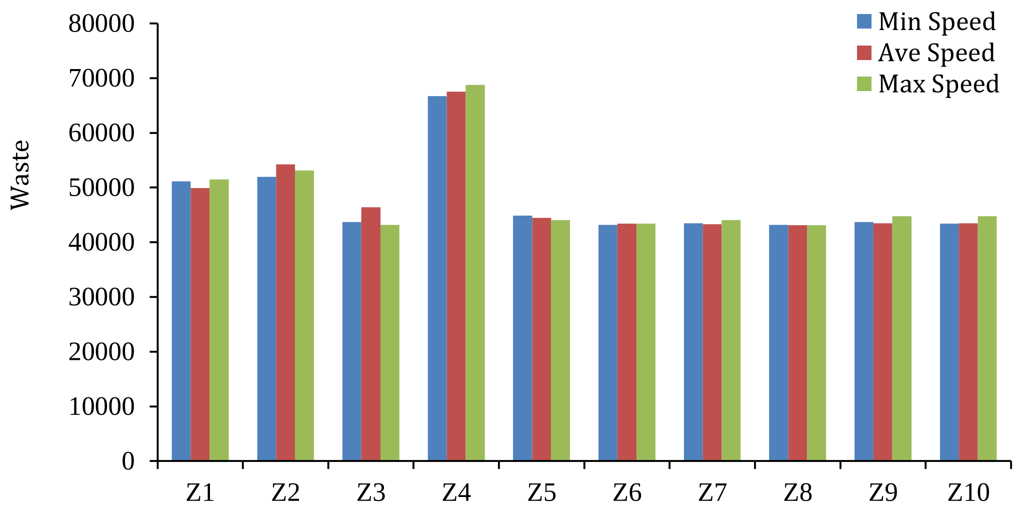

Fig. 4. The impact of each objective functions and speed of Trucks on the amount of Waste.

5. 2. 2. Investigating The Effect Of Change In The Idle Times Of The Model On The Amount Of Co₂

The effect of the idle lengths (i.e., preparation and waiting times of loading and unloading) on the level of CO_2 production be studied. It is primarily a general objective function (including all objectives). Then, using this objective function, determined the effect of idle times on CO_2 emission.

a) Determination Of The Weight Of Each Group Of Objectives

The objective function of the global criterion method is formulated as $\left(\frac{f_i - f_i^{Min}}{f_i^{Max} - f_i^{Min}}\right)$, where f_i^{Max} and f_i^{Min} are the maximum and minimum values for each objective function, respectively.

$$MinZ_t = h_1\left(\frac{Z_{Cost} - Z^*_{Cost}}{Z^{Max}_{Cost} - Z^{Min}_{Cost}}\right) + h_2\left(\frac{Z_{Prod} - Z^*_{Prod}}{Z^{Max}_{Prod} - Z^{Min}_{Prod}}\right) + h_3\left(\frac{Z_{Envir} - Z^*_{Envir}}{Z^{Max}_{Envir} - Z^{Min}_{Envir}}\right), h_1, h_2, h_3 \geq 0 \quad (31)$$

In this respect, the objective function of the global criterion method was examined, and its effect on the value Z_t was evaluated by the changing of the weight of each set of objectives $(\circ < h_i < 1)$.

Table 8. The value of Z_t according to h_1, h_2 and h_3

h_1	h_2	h_3	Z_t
0.7	0.15	0.15	0.08
0.7	0.1	0.2	0.075
0.6	0.2	0.2	0.1
0.6	0.1	0.3	0.074
0.5	0.25	0.25	0.125
0.5	0.1	0.4	0.075
0.4	0.3	0.3	0.159
0.4	0.1	0.5	0.077

The general objective function is as follows:

$$MinZ_t = 0.6\left(\frac{Z_{Cost} - Z^*_{Cost}}{Z^{Max}_{Cost} - Z^{Min}_{Cost}}\right) + 0.1\left(\frac{Z_{Prod} - Z^*_{Prod}}{Z^{Max}_{Prod} - Z^{Min}_{Prod}}\right) + 0.3\left(\frac{Z_{Envir} - Z^*_{Envir}}{Z^{Max}_{Envir} - Z^{Min}_{Envir}}\right) \quad (32)$$

b) Investigating the effect of the change in the idle times

Considering various values for the preparation and waiting times could calculate the amount of the produced CO_2. Indeed, the relationship between determined idle lengths of time and the rate of CO_2 emission through regression analyses.

Table 9. Regression coefficients

Source of Variation	Coef.	St. Error	t Stat.	P-value
Constant	19.657	1.023	19.217	0.00
Setup Time	3.441	0.527	6.529	0.00
Waiting Time	2.298	0.575	3.999	0.001

According to Table 10, the equation is:

$$Co_2 = 19.657 + 3.441(\text{Setup Time}) + 2.298(\text{Waiting Time}) \quad , \quad R^2=83.7\% \tag{33}$$

6. CONCLUSION

Although stone transportation in open-pit mines has been the subject of many studies, this research undertook the modeling of stone transport in open-pit mines with cost, production, and environmental objectives. Each objective function affected the choice of the type and number of trucks differently from the others. The vital concern of the model proposed in this study was achieving a solution to meet all the objectives. For this purpose, trucks were allocated to different loading areas and transportation routes according to their importance coefficients. A critical point distinguishing this study from others is investigating assigning trucks' preparation, transportation, shopping, and unloading time durations. The model was implemented in Chadormalu Mine as a case study.

Examining the data of the Chadormello mine shows: Objective functions affect the wastes resulting from tailings, but the speed of trucks was not effective.

The selection of the objective function affects the amount of CO_2. Environmental Objectives (minimum positive deviation from noise pollution and minimum positive deviation from truck vibration) would lead to minimum CO_2 emission. Meanwhile, production objectives (maximum amount of ore transported and maximum waste) were accompanied by the highest amount of CO_2 pollution.

It analyzed the rate of CO_2 production by the trucks and the amount of waste resulting from the tailings activities as it emerged in the first part of the study. It became clear that the selection of objectives affected the production of CO_2 and wastes. But truck speed was effective only in CO_2 emission; if stone transport trucks could run at a maximum speed, the lowest amount of CO_2 would be emitted. The second part of the study dealt with the effect of the preparation and waiting times of stone transport trucks on the amount of CO_2 emitted. As the results showed, both idle times were effective in that regard. Every minute added to the preparation time increased CO_2 production by 3.441 tons. Also, an increase of one minute in the waiting time would lead to 2.298 tons more CO_2. The conclusion can be generally seen that the shorter the waiting time for loading and unloading, the larger the scope of action for the trucks; the more the idle time is reduced will emit the less CO_2. The mine managers must plan truck loading and unloading in such a way that the idle time is minimized.

Some of the parameters considered in this study were, indeed, uncertain. Therefore, it is recommended for future studies to evaluate the carrying capacity of trucks and the loading, unloading, and waiting times as uncertain parameters. To this end, it is necessary to do uncertain programming to deal with uncertainties. It will also be of insight and value to research the grade of ores and the percentage of impurities in them.

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