Simulation-Based Optimization of Truck Allocation in Material Handling Systems

Matin Ghasempour Anaraki[1], Masoud Rabbani[1], Moein Ghaffari[2] and Ali Moradi Afrapoli[3]

[1] University of Tehran, Tehran, Iran
[2] Ferdowsi University of Mashhad, Mashhad, Iran
[3] IntelMine Lab, Laval University, Quebec, Canada

ABSTRACT

In this article, a bi-objective mathematical model is developed that aims to minimize the transportation costs and carbon released to the environment concurrently. Mining investment is about hundreds of millions up to billions of dollars in some mines because of the large equipment used in different aspects. So, utilization of equipment can save millions of dollars. This article also considers different aspects related to material handling systems like the speed of trucks, different age bins, etc. The results show that a short improvement can significantly improve the efficiency of the mine and decrease its operational costs and carbon emission.

1. Introduction

Mining is an industry that needs costly equipment like excavators, loaders, etc. it costs several million dollars. A business must control its expenses. Transportation and also maintenance costs are two main costs. They form about 60 percent of operational costs, and a short improvement can save significantly. The hauling system must do its job at the scheduled time because any delay causes to increase in operational expenses.

Two approaches are suggested to reduce operational costs. Using trucks with more capacity to transport material to the dumpsite is the first option that brings some risks because we need to keep the utilization rate up. The second option is operation research techniques (Moradi Afrapoli & Askari-Nasab, 2019). The researchers were attracted by operations research techniques recently. The main goal of the articles was to improve productivity and efficiency and to determine the destination for trucks in the period (Ozdemir & Kumral, 2019).

This article seeks to explore a bi-objective mathematical model that aims to minimize the transportation costs and carbon produced simultaneously. Although this methodology is illustrated for surface mining operations, it also can be used for every kind of business that incorporates trucks and faces maintenance costs.

The contribution of this work is presenting a mathematical model that minimizes the transportation costs and carbon produced concurrently. The paper considers a limitation in the working hours for shovels and dumpsites. Also, different types of trucks with two age bins are considered in the developed mathematical model. The difference between the costs of using loaded and empty trucks is mentioned. It is the first study considering the impact of speed on transportation costs and carbon released to the environment.

ISBN: 978-1-55195-486-8

2. Literature Review

Afrapoli, Tabesh, and Askari-Nasab (2019) developed a multi-objective model related to the distribution of trucks based on dispatching time. It minimizes the idle time of active shovels, trucks waiting time for operations, and the summation of deviations from flow rates of the paths simultaneously. Ta, Ingolfsson, and Doucette (2013) proposed a mathematical model to minimize the number of trucks assigned to open mines. One type of truck is considered in this article. Zhang and Xia (2015) used integer programming to minimize the total operating costs of trucks in mines. The expenses depend on the distance between the shovel and a dump site, and the number of trips is the second factor. Various kinds of trucks are considered for this issue and each of them has its specific capacity. Afrapoli, Upadhyay, and Askari-Nasab (2018) presented a MILP model to solve the dispatching problem of trucks in open-pit mines. The input parameters are considered stochastic, and a fuzzy approach is implemented to solve the mathematical model. A case study on the surface mine illustrates the smaller fleets of trucks to meet production requirements. Dimitrakopoulos (2020) developed a novel stochastic optimization model. It considers the uncertainties were related to equipment performance, geological, and truck cycle time. A metaheuristic solution method is corporate to solve the large-scale problem. Topal and Ramazan (2010) proposed a mathematical model to minimize the maintenance costs for trucks used in the mining industry. The planning horizon for scheduling trucks is considered multi-year. The trucks separate into different bins according to their working hours, and each of them has its specific maintenance cost. Ahangaran, Yasrebi, Wetherelt, and Foster (2012) presented integer programming to minimize the transportation cost in open-pit mines. This model considers the difference between the expenses of transporting unloaded and loaded trucks. A limited number of trucks are ready to work at each period. Ta, Kresta, Forbes, and Marquez (2005) illustrated a model using chance constraint and a stochastic optimization approach formulated for truck allocation. This model decreases the operation costs and deals with uncertain process parameters. Alexandre, Campelo, and Vasconcelos (2019) presented multi-objective strategies aiming to minimize costs of transportation and maximize the production level simultaneously. Two multi-objective genetic algorithms are illustrated the first specialized crossover and mutation operators, while the second employs Path-Relinking as its main variation engine.

Moradi Afrapoli, Tabesh, and Askari-Nasab (2019) illustrated the deficiencies of traditional methods. It presented an integrated optimization simulation frame to determine the needed trucks fleet size in mining operations. Samavati, Essam, Nehring, and Sarker (2018) explained a new extraction method for exploiting material from mines. This method is presented in a way that is intelligible for the operation research community to understand. Souza, Coelho, Ribas, Santos, and Merschmann (2010) presented a MIP to minimize the deviations from the production and quality goals. It also tries to decrease the truck numbers used in the production planning throw dynamic truck allocation. Saliba and Dimitrakopoulos (2019) explained a paper that optimizes mining, processing decisions, and destination at the same time. The case study shows that market uncertainty impacts all components of a production schedule. Gurgur, Dagdelen, and Artittong (2011) developed two Mixed Integer Programming and Linear Programming aims to maximize the NPV of the material movement in periods and minimize the deviation of the mine progress from the production targets simultaneously. Some parameters consider uncertainties because of the conditions. Afum, Ben-Awuah, and Askari-Nasab (2020) proposed a MILP model that determines the best strategy that uses different types of mining methods. The illustrated model confronts several kinds of constraints that limit the extraction. The case study for a gold open pit mine presented at the end of the paper confirms that the model can increase the generated NPV. Levinson and Dimitrakopoulos (2020) represent a simultaneous stochastic optimization in a gold open-pit mine. The illustrated mathematical model aims to maximize net present value and minimize the risk of falling to meet production targets and environmental issues, costs of mining and processing, deviations from waste, and stockpile facility capacities. A metaheuristic solution method is applied in this paper.

Ataeepour and Baafi (1999) implemented an ARENA simulation model for truck dispatching in surface mines for the first time. Smith, Linderoth, and Luedtke (2021) presented a nonlinear optimization model that considers queueing effects and also a time-discretized model is presented as the first and second approaches. Zeng, Baafi, and Walker (2019) illustrated a discrete-event simulation model to determine the impacts of bunching on the efficiency and productivity of a material handling system. Mena, Zio, Kristjanpoller, and Arata (2013) presented an optimization and simulation model that aims to maximize the total expected productivity. Mohtasham, Mirzaei-Nasirabad, Askari-Nasab, and Alizadeh (2021) presented a mathematical model that aims to minimize the deviations of the match factor from its target value. It proposes two strategies for solving the equipment sizing problem. A simulation method contains three steps used in this article. Meng, Nageshwaraniyer, Maghsoudi, Son, and Dessureault (2013) presented a data driven modeling and a discrete-event simulation model for the material handling system of coal mines based on their structural and operational data.

Mane, Djordjevic, and Ghosh (2021) presented a methodology to identify fuel-efficient drivers by data envelopment analysis. It aims to determine the critical driving behavior factors related to fuel consumption in heavy-duty vehicles. The results show that average speed, braking, and idling are vital factors. Walnum and Simonsen (2015) presented an article to understand what can affect fuel consumption. It shows that variables associated with infrastructure and vehicle properties have a more significant influence than driver-influenced variables while driving on narrow mountainous roads. It can help transport companies to determine the right vehicle for a specific transportation task to reduce fuel consumption. Winebrake and Green (2017) discuss the key factors that influence firm-level decision making concerning fuel efficiency. Montiel and Dimitrakopoulos (2015) presented a risk-based method for mining complexes and also transportation systems. It aims to reduce the deviations from blending targets and capacities. Peralta, Sasmito, and Kumral (2021) assessed the effect of truck maintenance on energy consumption and greenhouse gas emissions in mining trucks. It shows that there is a trade-off between energy and maintenance costs. They implemented a Regression analysis to estimate the reliability contribution of the specific fuel consumption variations.

3. Modeling of the Truck Location Problem

This article presents a bi-objective mathematical model that aims to minimize transportation costs as the first objective. The second objective is to minimize the carbon released into the environment. The model deals with making the best decision to allocate the best available trucks to each destination, whether it is loaded or empty. It happened by looking at the production requirements of each dumpsite and the available trucks at that time. This model considers different kinds of trucks according to their capacity for handling materials, Costs of allotting of different age bins, etc.

3.1. Assumptions

- Trucks are allocated at the beginning of the period.
- Each truck can do many travels in one period.
- Duration of maintenance activities for trucks are negligible.
- The proficient of the driver and changes in the weather condition is not considered.

3.2. Mathematical Model

Sets	Description
p	Period
a	Age
t	Truck
s	Shovel
d	Dumpsite

Parameters	Description
C_t	Capacity of truck type t
CL_t	Cost of trucks type t when loaded per kilometer
CUL_t	Cost of trucks type t when unloaded per kilometer
AW_{sp}	Available waste at shovel s in period p
PR_{dp}	Production requirement of the dumpsite d in period p
SP_t	Speed of truck type t
AT_p	Available working time in period p
DC_{tap}	Discounted cost value for truck type t age bin a in period p
LSS_{ts}	Loading speed for truck type t in shovel s
LSD_{td}	Loading speed for truck type t in dumpsite d
F_{sd}	Distance from shovel s to dumpsite d
CP_{ta}	Amount of carbon produced by truck type t age bin a per hour

Variables	description
X_{tasdp}	Total trip numbers of trucks type t age a from shovel s to dumpsite d in period p
Y_{tasdp}	Total trip numbers of trucks type t age a from dumpsite d to shovel s in period p

The first presented objective function aims to minimize transportation costs. The difference between loaded and unloaded trucks is considered. Different kinds of trucks have their own maintenance cost. The second objective function aims to minimize the carbon released into the environment. There are three age bins according to driven kilometers, and as they become older, they produce more carbon.

$$z = Minimize \sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{d=1}^{D} CL_t \times X_{tasdp} \times F_{sd}$$
$$+\sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{d=1}^{D} CUL_t \times Y_{tasdp} \times F_{sd}$$
$$+\sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{d=1}^{D} DC_{tap} \times (X_{tasdp} + Y_{tasdp}) \times F_{sd} \tag{1}$$

$$z = Minimize \sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{d=1}^{D} CP_{ta} \times (X_{tasdp} + Y_{tasdp}) \times \frac{F_{sd}}{SP_t} \tag{2}$$

Subject to:

$$\sum_{t=1}^{T}\sum_{a=1}^{A}\sum_{d=1}^{D} C_t \times X_{tadsp} \le AW_{sp} \forall s \in \{1,...,S\}, \forall p \in \{1,...,P\} \tag{3}$$

$$\sum_{t=1}^{T}\sum_{a=1}^{A}\sum_{s=1}^{S} C_t \times X_{tadsp} \ge PR_{dp} \forall d \in \{1,...,D\}, \forall p \in \{1,...,P\} \tag{4}$$

$$\sum_{d=1}^{D} X_{tasdp} = \sum_{d=1}^{D} Y_{tasdp} \forall s = \{1,...,S\}, \forall p = \{1,...,P\}, \forall a = \{1,...,A\}, \forall t = \{1,...,T\} \tag{5}$$

$$\sum_{s=1}^{S} X_{tasdp} = \sum_{s=1}^{S} Y_{tasdp} \forall d = \{1,...,D\}, \forall p = \{1,...,P\}, \forall a = \{1,...,A\}, \forall t = \{1,...,T\} \tag{6}$$

$$\sum_{t=1}^{T}\sum_{a=1}^{A}\sum_{s=1}^{S}\sum_{d=1}^{D} X_{tasdp} \times \frac{C_t}{LSS_{ts}} \le AT_p \forall p \in \{1,...,P\} \tag{7}$$

$$\sum_{t=1}^{T}\sum_{a=1}^{A}\sum_{s=1}^{S}\sum_{d=1}^{D} Y_{tasdp} \times \frac{C_t}{LSD_{ts}} \le AT_p \forall p \in \{1,...,P\} \tag{8}$$

$$X_{tasdp}, Y_{tasdp} \ge 0 \tag{9}$$

There are different types of trucks used in mining operations, and they are many kinds of trucks at the beginning of the planning horizon and these trucks can be used for many periods. This model shows that the cost of using loaded and unloaded trucks is different for every kind of truck. According to Constraints (3) and (4), the number of trips should satisfy the demand of dumpsites and not exceed the capacity of shovels. Constraints (5) and (6) ensure that the number of trucks entering and leaving must be equal in shovels and dumpsites. Constraints (7) and (8) consider the available working time in each period that limits the number of travels between shovels and dumpsites.

4. Integrated Model

Production system simulation uses software to create computer models of a production system and their analysis to obtain necessary information. It has become one of the most popular business science among production managers. This technique is a valuable tool used by engineers to evaluate the effectiveness of investments in physical equipment and supplies such as warehouses, factories, and distribution stations.

Generally, there is 4 step to making a simulations model:

Step 1 - Explain the problem

The key to any successful simulation project is clearly stating what the problem needs to be solved, and what success looks like.

Step 2 - Process modeling

The simulation scheme modeling method is easy and intuitive to model any process without requiring unique code or programming.

Step 3 - Change items

The simulation program gives confidence and peace of mind that the changes suit the business.

Step 4 - Repeat

Improving the workflow is not a one-time task. This is an ongoing process that successful organizations take to ensure that they are ahead of the competition.

A simulation model is presented to evaluate the surface mining operation system through ARENA software. The presented deals with the shovel and dumps operations, truck travel, and the carbon released into nature. The simulation model assumes that the quality of the material is not changed during the runtime, and also, every kind of equipment is available. Specific schedules like maintenance are considered. The expertise of truck and shovel operators and conditions of the weather are negligible. The best-fitted probability distribution is allocated to each required parameter in ARENA software.

5. Simulation Model

The simulation model of the truck dispatching system is implemented to determine actions in real mines. Various kinds of uncertainties that happen in ore and wastes are implemented in the model. It also considers the possibility of unexpected actions like failures and maintenance activities at the time of random events. The Rockwell Arena 12 is used for the proposed model because it can implement existing systems' gestures that logically make decisions.

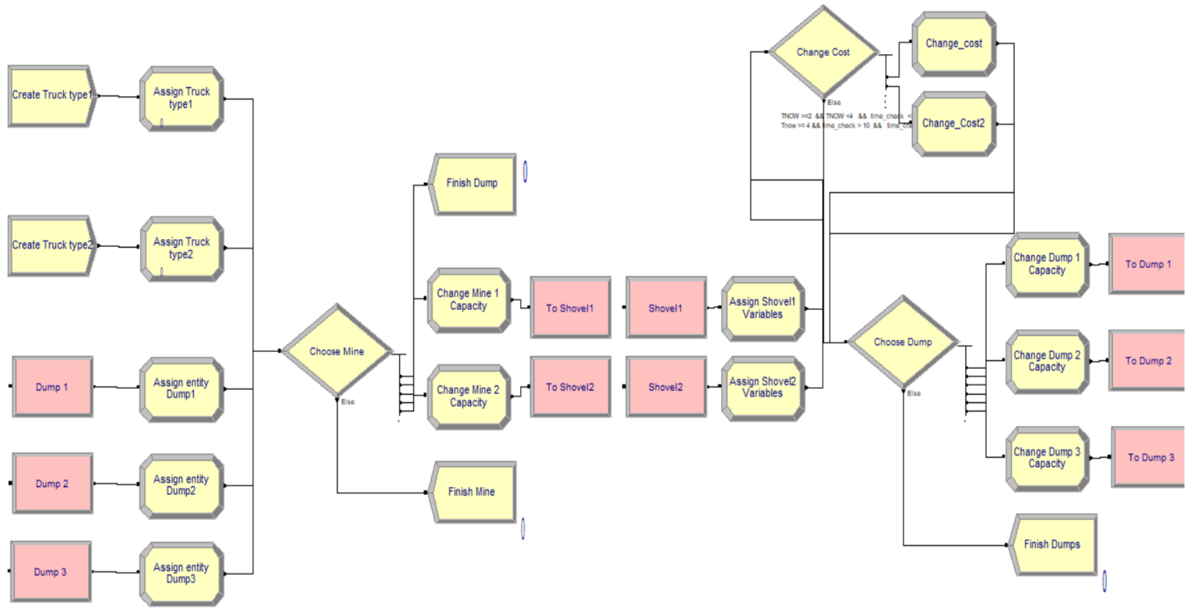

Figure 1. Arena® Model.

6. Results

Table 1 demonstrates that two different types of trucks in three age bins are corporated in the material handling system. The difference in truck types is related to their capacity and other specifications.

Table 1. Unit maintenance cost per kilometer for different types of trucks.

City or Town	Age Bin 1	Age Bin 2	Age Bin 3
Truck Type 1	4	7.2	12
Truck Type 2	3.5	6.3	10.5

The method corporated in the simulated model prioritizes the newer trucks to reduce costs. The implemented model also satisfies the requirement of shovels. The simulated model considers different aspects related to the trucks in order to reach the best schedule.

The illustrated model aims to minimize transportation costs. It consists of predictable and unpredictable costs—the costs of transporting related to the capacity of trucks and age bins.

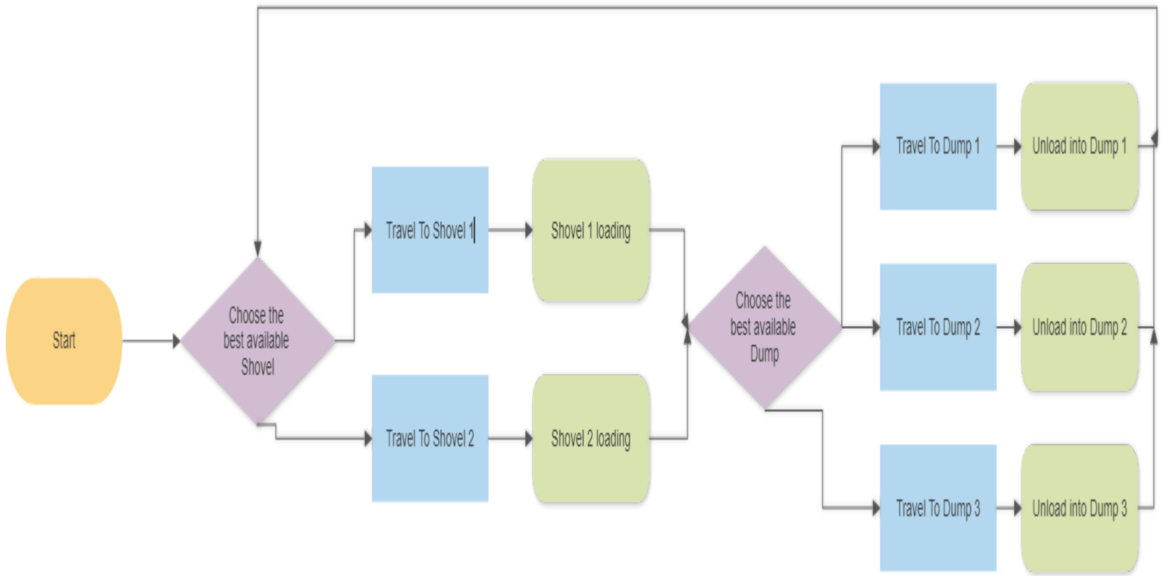

Figure 2. Flow Chart.

The studied mine consists of two shovels and three dumpsites. The distance between each shovel and dumpsite is presented in Table 2.

Table 2. Distance between shovels and dumpsites (km).

City or Town	Dumpsite 1	Dumpsite 2	Dumpsite 3
Shovel 1	2	3	5
Shovel 2	1	2	4

As can be seen in table 3, the shovels have different capacities. The larger shovels have more volume. The dumpsites also have distinct demands that production requirements should be met.

Table 3. Production requirements of dumpsites and available material in shovels in periods (Kg).

Shovel 1	Shovel 2	Dumpsite 1	Dumpsite 2	Dumpsite 3
12500	10500	7000	7000	7000

First of all, according to the simulated model. Trucks have different capacities. Truck type one can transport 180 tons and truck type two 120 tons per trip. The average speed of trucks is 28km/h and there is no difference between the trips for shovels to dumpsites and vice versa. Shovels' loading rates are considered 1.848kt/h and also Trucks' dumping rates are 3.078kt/h on average for both kinds of trucks. The trucks are in the second age bin produce One and seven-tenths carbon of the new trucks. The trucks are in the last age bin produce triple carbon of new trucks.

6.1 Average Capacity of Trucks

Figure 3 shows that using trucks with more capacities can make a reduction in costs and the carbon produced in the period. It can also be concluded from figure 3 that this reduction is more while implementing the simulated model.

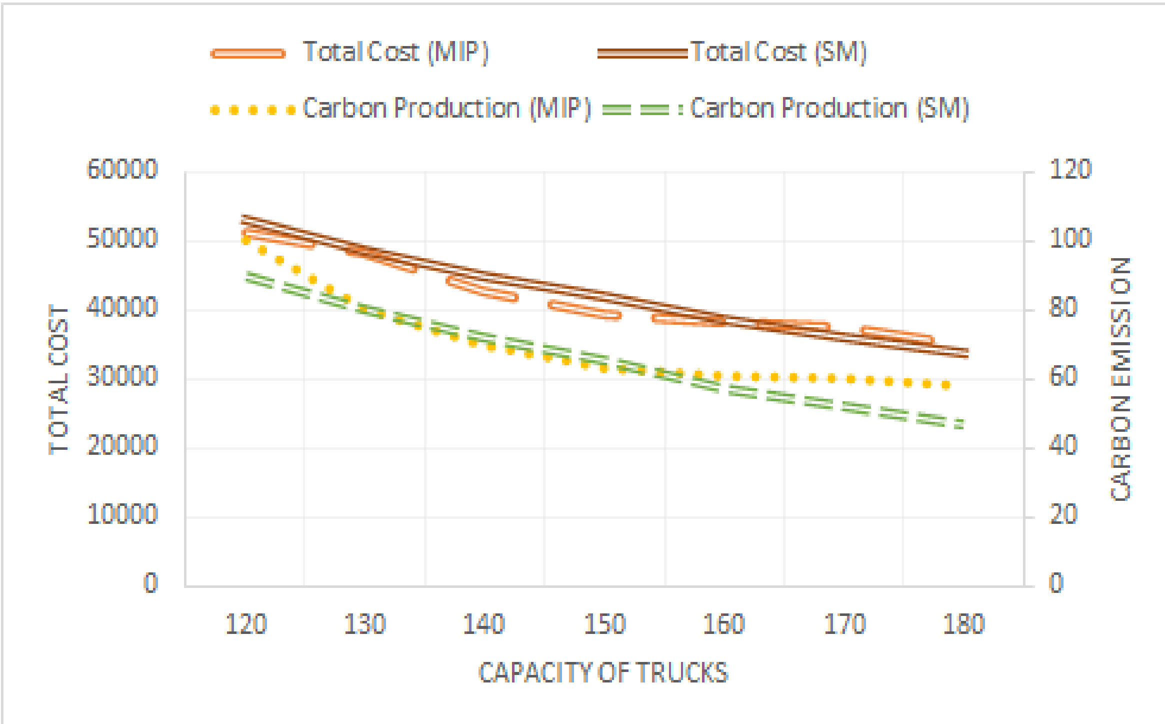

Figure 3. Comparison between the total carbon produced and total cost using the simulated truck dispatching model (SM) and the proposed mixed linear programming (MIP) truck dispatching model while changing the average capacity of trucks.

6.2 Average Speed of Trucks

Figure 4 shows that using trucks that can drive faster can reduce the carbon released to the environment. It can also be concluded from figure 4 that this reduction is more while implementing the simulated model.

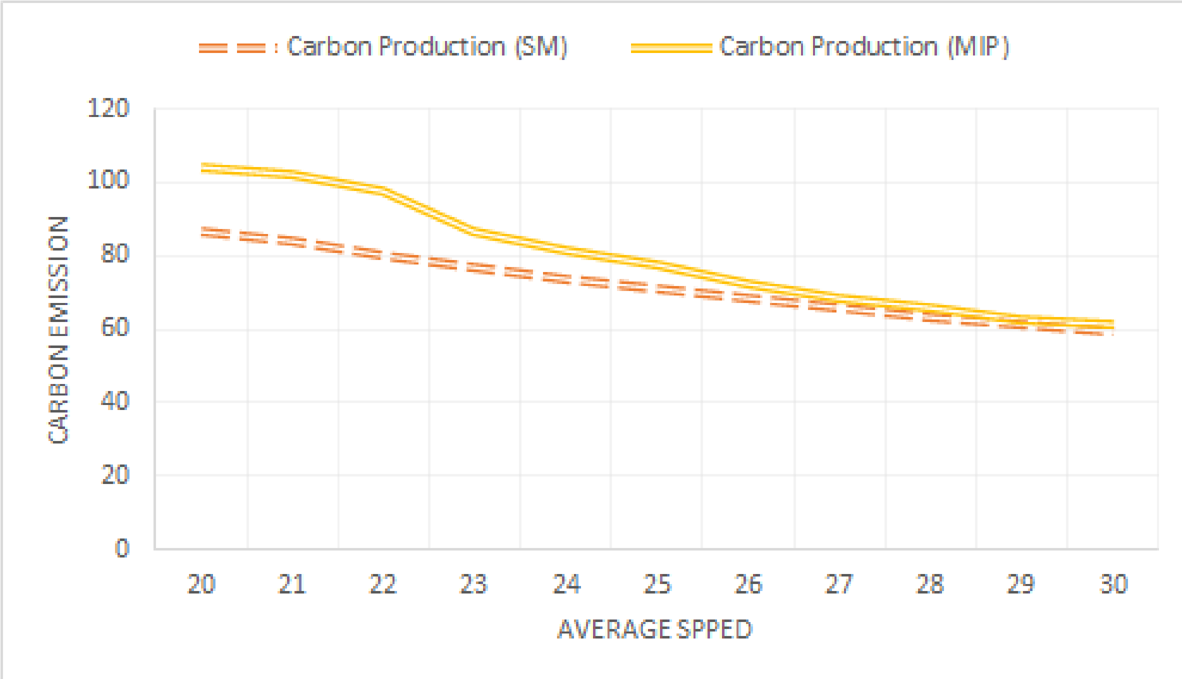

Figure 4. Comparison between the simulated truck dispatching model (SM) and the proposed mixed linear programming truck dispatching model (MIP) while changing the average speed of trucks and its impact on carbon production.

6.3 Capacity of Trucks

Figure 5 shows that an increase in the number of trucks used in transportation systems can make a reduction in costs and the carbon produced in the period. It can also be concluded from figure 5 that this reduction is more while implementing the simulated model.

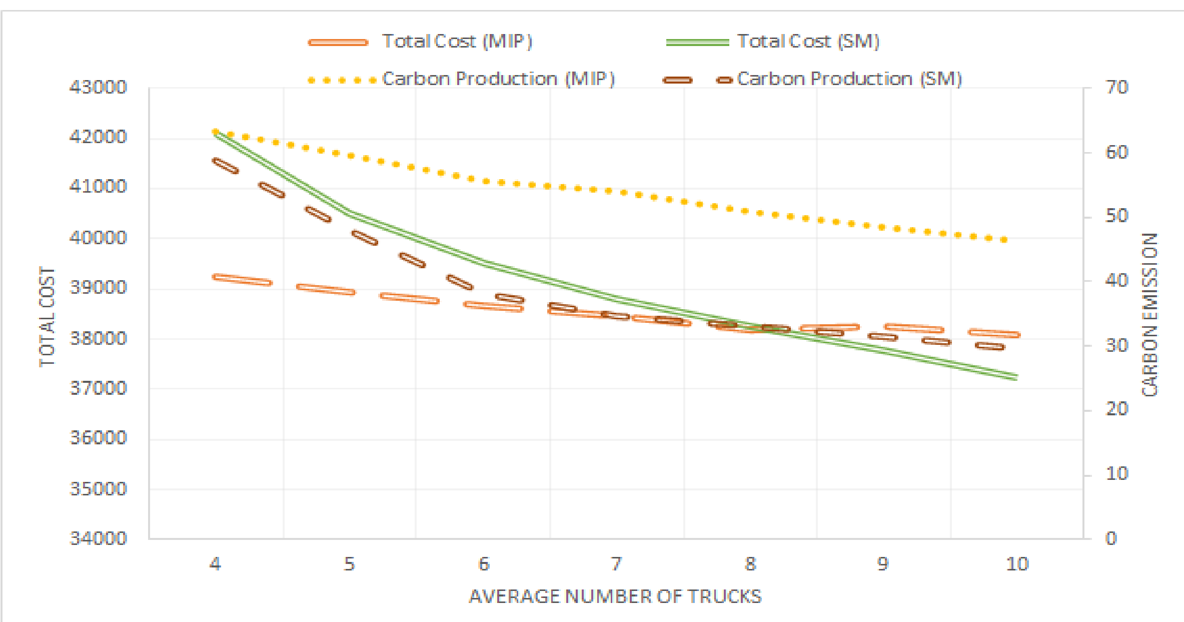

Figure 5. Comparison between the total carbon produced and total using the simulated truck dispatching model (SM) and the proposed mixed linear programming (MIP) truck dispatching model while changing the average number of trucks.

7. Conclusions

The equipment of material handling systems costs millions of dollars, so utilization at them can increase profitability. It can be gained by optimizing the schedule for equipment. Most articles related to mining operations are related to efficient production. Only a few were about the dispatching system. However, it is not an easy task according to conditions that confront different uncertainties. These variables impact unpredictable costs like unexpected equipment failures and operator effects.

This paper presented a mathematical bi-objective model that aims to minimize truck transportation and maintenance costs. It also tries to minimize the carbon released to the environment because there are different types of trucks. They are of different ages, which makes a difference in the maintenance costs and pollution they cause. The presented model can save system costs by increasing equipment utilization and productivity especially in large-scale mines that include heavy equipment.

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