Alignment of Short-Term and Operational Plans using Discrete Event Simulation

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Abstract

Optimal resource allocation is an important aspect in many industries. In the mining industry, resource allocation usually refers to the truck-and-shovel allocation. Since truck-and-shovel technology has been widely used in open-pit mining operations, the efficiency of trucks-and-shovel mining systems is an essential issue in mining operations. Truck and shovel operations are main contributors to mine operating costs. Therefore, determining the optimum number of trucks and shovels is an important and complex process, which can result in reducing the overall mining cost. This paper analyzes the operations of trucks and shovels in an open pit mine using ARENA simulation software.

1. Introduction

Open pit mining is widely used for large deposits. Because of the size of open pit mines, the revenue and the costs of such large projects are enormous. Most of the time, revenue cannot be controlled due to unpredictable behavior of the final price of the product, which in metal mining is usually a metal concentrate. On the other hand, one of the major costs for an open pit mine is the number of trucks and shovels and the reallocation strategy of the mining fleet. A small percentage reduction in costs involved with trucks and shovels would have a significant impact on the profit of a project.

Yuriy and Vayenas (2008) developed a reliability assessment model based on a genetic algorithm to evaluate and generate the time between trucks' failures. The output of the model is used as an input to a discrete event simulation model to analyze the impact of the failures on the production. Two different simulation software packages are used to compare the merits of them. Fioroni et al. (2008) presented a two stage method in which the first step is a mathematical programming model applied to allocate the shovels and the trucks. In the second stage, simulation is used to assess the results in real time operations.

In this paper, a discrete event simulation methodology is proposed and Arena Software is used for modeling (Rockwell Automation Technologies, 2009). In the first stage, various scenarios with different number of trucks and shovels are examined to determine the appropriate number of each resource. Then, the uncertainty in velocity of empty and full trucks, movement speed of shovel, loading time, and dumping time are taken into account. The results show the effect of such uncertainties on the extracted tonnage of different material types and grades of elements of interest.

2. Problem definition

In the first stage, this paper presents the problem of determining the number of shovels and trucks to be employed at the beginning of the mine plan. The only constraint considered in this part is meeting the extraction schedule in each period. The decision on the number of trucks and shovels is made based on criteria such as shovel utilization and truck utilization in different scenarios.

Using the results from the previous stage, the effect of uncertainties on trucks and shovels operations are evaluated in the second stage. These uncertainties consist of full truck movement speed, empty truck movement speed, shovel movement speed, loading time, dump time, and load tonnage. Variables of interest which are assessed for multiple realizations includes: total ore tonnage dumped at the mill, total ore tonnage dumped at the stockpile, total waste tonnage, P grade, S grade, MWT grade at the mill and stockpile, and resource utilizations.

The extraction plan considered consists of 12 time periods. The extraction schedule provides information about the number of blocks to be extracted and their sequence of extraction, block type, tonnage, coordinates, extraction fraction, and grade of different materials. The type of each block specifies its destination either as process area or waste dump. Distances between blocks and different destinations are also provided. Based on the information of each period, a shovel travels to the first block which is at the top of the sequence. It takes some time for the shovel to travel from its current location to the block's location. Simultaneously, a truck travels from its current location to the block's location where the shovel is going. The shovel starts its work to extract a portion of the block and load it into the truck. The tonnage which the shovel can extract at each time is not constant and is determined based on a random distribution. The truck stays by the working shovel until it is fully loaded. Knowing the type the block which is extracted, the truck travels to either the process area or the waste dump. At the same time, another truck travels to the shovel to be loaded. The shovel moves to the next block right after the current block is completely depleted.

On the other side of the mine, trucks unload their material at the waste dump or the processing plant. At the processing plant, based on the MWT grade, trucks go to the mill or the stockpile. There is no limit on the number of trucks which can unload at one destination, either at the mill or the waste dump, but there is a limitation on the number of trucks that can dump their material into the crusher simultaneously. There is space for only one truck at the crusher to dump at a time. Fig. 1 shows a schematic view of the problem. The next section introduces the logic of the simulation model which is modeled in ARENA.

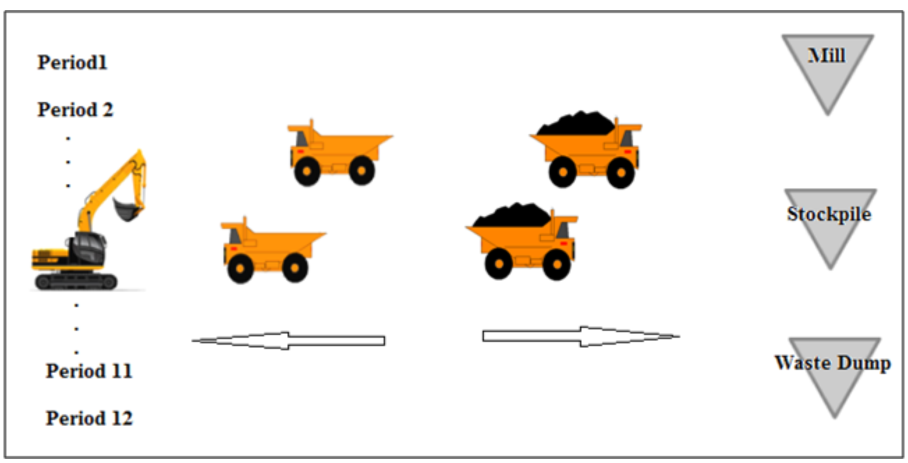

Fig. 1. Schematic view of the problem

3. Methodology

For modeling a problem in ARENA simulation software, the first step is to define appropriate entities. In the model built in this study, entities are block portions for each period. For simplification, each block portion is considered as an entity. At the beginning of the model, entities are introduced to the system at small time intervals. As an entity arrives to the system its attributes are assigned, consisting of the entity's number, coordinates of x, y and z, block tonnage, fraction, destination, distance to destination, and grades. Each entity's tonnage is calculated using Eq. (1).

$$entity\,tonnage = origin\,block\,tonnage \cdot fraction \tag{1}$$

At this stage, variables such as total waste tonnage and ore tonnage entering the system and the initial coordinates of the shovels' locations are calculated and assigned. Also, coordinates of the mill, stockpile, and waste dump are defined. Blocks entering the system wait in a queue to seize a shovel and a truck as resources. Once they seize a shovel and a truck, the shovel and the truck travel from their current locations to the block's location. Speeds of the shovel and the truck follow a Normal distribution with a small deviation (Eq. (2) and Eq. (3)). The time that it takes for the shovel and the truck to reach the block is the maximum of Eq. (4) and Eq. (5).

$$speed_{shovel} \approx Normal\left(100,50\right)\ \left(m/min\right) \tag{2}$$

$$speed_{empty\,truck} \approx Normal\left(500,20\right)\ \left(m/min\right) \tag{3}$$

$$time_{shovel\,travels\,to\,the\,block} = \frac{distance_{shovel-block}}{speed_{shovel}} \quad \left(min\right) \tag{4}$$

$$time_{truck\,travels\,to\,the\,block} = \frac{distance_{truck-block}}{speed_{empty\,truck}} \quad \left(min\right) \tag{5}$$

Once both truck and shovel reach the block, the extraction begins and it takes a time of Eq. (6) to load the truck each time. The truck's nominal capacity is 200 tonnes and is fully loaded by 2 loads.

$$time_{loading} \approx Triangular\left(0.67,0.80,0.91\right)\ \left(min\right) \tag{6}$$

The tonnage that the shovel can load follows Triangular distribution (80, 90, 100) tonnes. If the remaining tonnage of the entity is less than 80 tonnes, the remaining amount will be loaded to the truck. After each load, three variables are updated: (1) the remaining entity tonnage, (2) the number of loads on the current truck, and (3) the tonnage loaded to the truck. In this part of the model a decision must be made according to three situations as follows:

- If the block is completely extracted, the shovel working at this block is released and the truck working with the shovel travels to its destination. When a shovel is released it moves from its current location, which is the extracted block's location, to the next block's location and new coordinates are assigned to the shovel.
- If the entity is not completely extracted but the truck is fully loaded, the model duplicates the entity to 2 entities: block and load. The block entity which is the original entity seizes a new truck and the load entity representing the full truck will go to its destination.
- If the entity is not completely extracted and the truck is not fully loaded, the shovel and the truck remain at their current locations and continue the extraction and loading process.

When a truck decides to leave the block, a decision must be made about its destination. If a truck's load is ore, it goes to the processing plant and if it is waste, it goes to the waste dump. Trucks going to the processing plant can dump at either the mill or the stockpile. If the average MWT grade of the coming truck is less than 70%, it dumps at the low grade stockpile, otherwise it dumps at the mill. There is no limit on the number of trucks that can dump at the waste dump or the stockpile at the same time. The traveling time of the truck is based on its speed when it is loaded (Eq. (7)) and the distance between the block and its destination. Distance between each block and all possible destinations (mill or stockpile or waste dump) are provided as inputs to the model. Eq. (8), Eq. (9) and Eq. (10) indicate the traveling time of the full truck based on its destination.

$$speed_{full\,truck} \approx Normal(300,100)\ (m/min) \tag{7}$$

$$time_{truck\,travels\,to\,the\,destination} = \frac{distance_{block-destination}}{speed_{full\,truck}}\quad (min) \tag{8}$$

$$time_{truck\,travels\,to\,the\,stockpile} = \frac{distance_{block-stockpile}}{speed_{full\,truck}}\quad (min) \tag{9}$$

$$time_{truck\,travels\,to\,the\,waste\,dump} = \frac{distance_{block-waste\,dump}}{speed_{full\,truck}}\quad (min) \tag{10}$$

After dumping, the truck returns to the shovel and they wait to be seized by the next entity. The returning time is calculated using Eq. (8) to Eq. (10), with the only difference that the truck is empty, so Eq. (3) is used as the denominator. After returning, the truck is released and is ready to be seized by the next coming block.

The model keeps track of some variables of interest during the run. These variables consist of ore tonnage at the mill, ore tonnage at the stockpile, waste tonnage at the waste dump, average P grade at the mill, average P grade at the stockpile, average S grade at the mill, average S grade at the stockpile, average MWT grade at the mill, average MWT grade at the stockpile, average shovel utilization, and average truck utilization.

At the end of the simulation time the model creates a dummy entity to record these variables and write them to an output EXCEL file. Fig. 2 shows the flowchart of the model.

4. Implementation and results

As explained in the previous sections, each fraction of a block is an entity. We used the output of WITTLE software as an input data for our model. The model reads the production schedule data of an iron ore mine. The input data include block tonnage, block fraction extracted, destination, coordinates, P grade, S grade, MWT grade, distance to the mill, distance to the waste dump, and random distributions from the excel file for each period. The entire time horizon consists of 13 years. The yearly production schedule of the 13 periods is shown in Fig. 3.

As mentioned before, in the first stage the problem is to determine the optimal number of trucks and shovels. In the model proposed in this paper, shovels and trucks are modeled as resources. Different scenarios are produced with different number of trucks and shovels, with year 7 selected to examine different scenarios. ARENA Process Analyzer is used to run the scenarios and the results are demonstrated in Table 1.

Starting with 1 shovel and 3 trucks, in some periods there are some blocks which are not extracted completely. By increasing the number of trucks, the remaining tonnage in each period decreases but then stabilizes (at that level). After this point, further increasing the number of trucks reduces utilization of resources and does not affect the extracted tonnage.

It is inferred that the number of shovels must increase. Scenario number 12 with 4 shovels and 10 trucks seems to be the best scenario. In this scenario all waste and ore are completely extracted and utilization of resources is reasonable. After this point, increasing the number of trucks or shovels is not going to change the level of production (see Fig. 4).

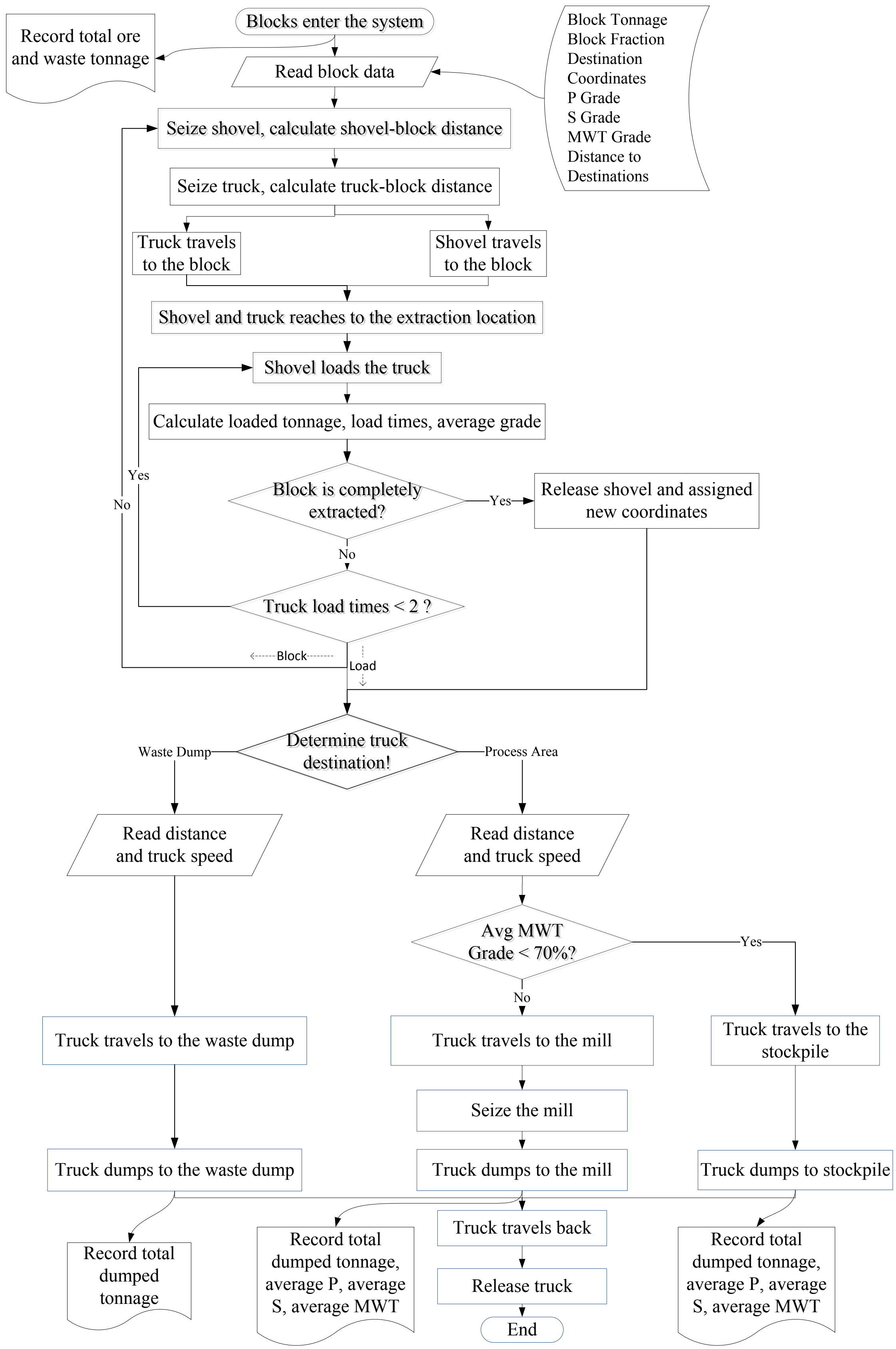

Fig. 2. Flowchart of the model

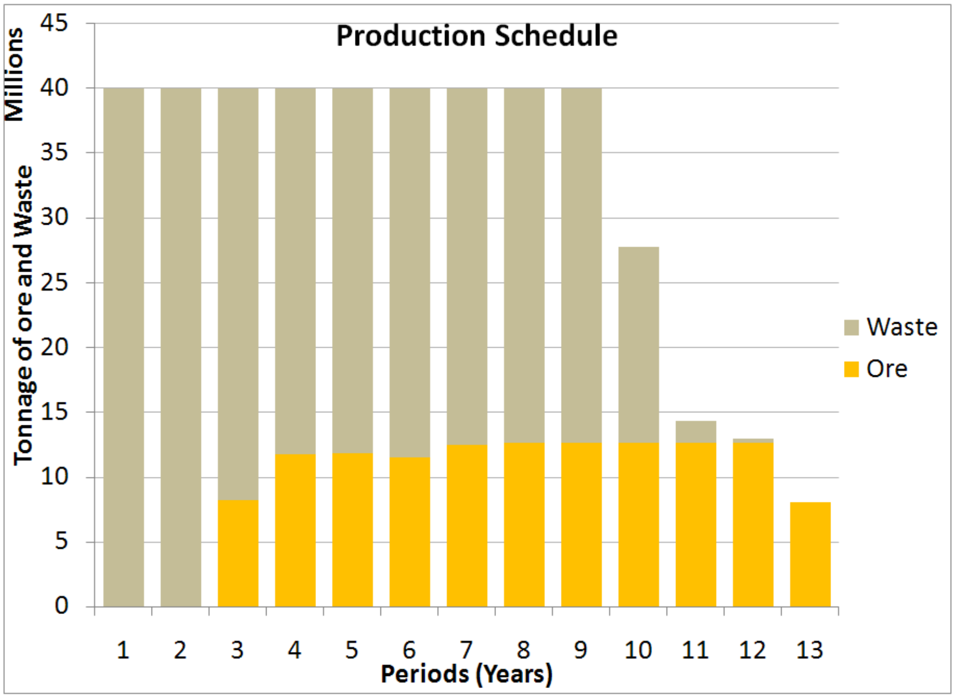

Fig. 3. Production schedule as input data

Table 1. Results of different scenarios for year 7

Scenario ID	Shovel #	Trucks #	Extracted ore (tonnes)	Extracted Waste (tonnes)	Shovel Utl.	Truck Utl.
1	1	3	10147861	2656537	0.903	0.7431
2	1	6	10460710	3753151	0.9997	0.4123
3	2	4	12487312	6656762	0.7721	0.9049
4	2	6	12487312	6584494	0.9311	0.7752
5	3	3	12483208	4897333	0.4455	1
6	3	6	12487312	18068258	0.8486	0.8953
7	3	9	12487312	23475918	0.9753	0.7017
8	3	11	12487312	24642616	0.9952	0.5955
9	3	13	12487312	25637419	0.9974	0.5771
10	4	6	12445212	15059571	0.7872	0.9567
11	4	8	12487312	23715803	0.8119	0.9446
12	4	10	12487312	27512677	0.8616	0.7306
13	4	16	12487312	27497624	0.9161	0.5318
14	4	19	12453528	24971572	1	0.4102
15	5	8	12452663	25489468	0.8024	0.9613
16	5	10	12460822	27512677	0.8808	0.8235
17	5	13	12483268	27512677	0.9019	0.6362
18	5	16	12487312	27512677	0.7252	0.4709

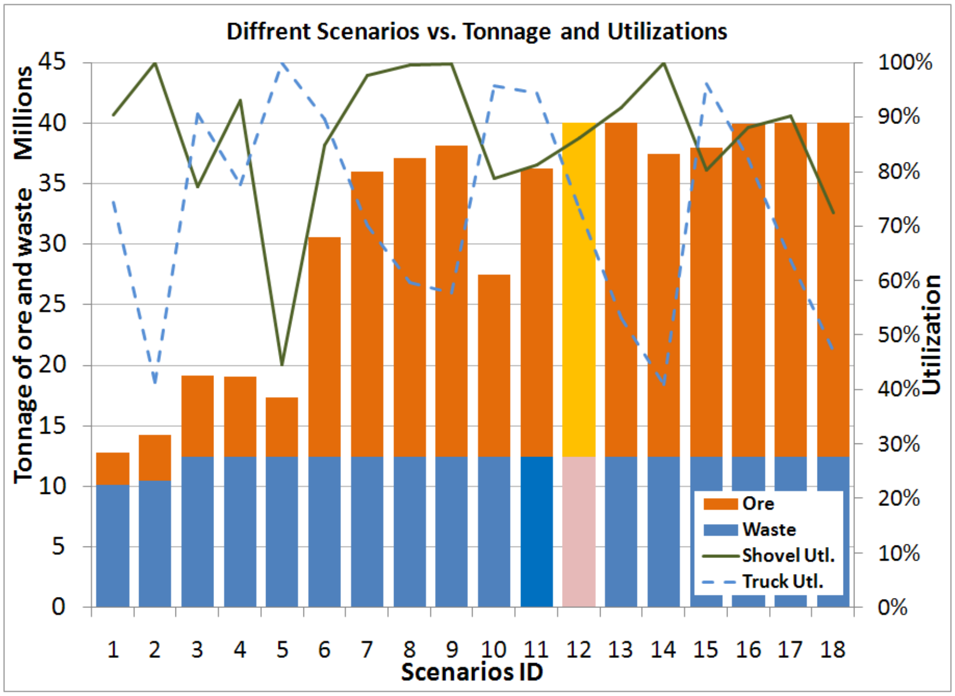

Fig. 4. Illustrative results of different scenarios

Using the fixed number of resources determined in the previous stage, the effect of uncertainties is studied during the second stage. These uncertainties include the variations in speed of loaded truck, speed of unloaded truck, speed of shovel, loading time, dump time, and extraction tonnage. These uncertain parameters result in variations in outputs. The model is run for 100 328-day replications.

Fig. 5 shows extracted ore tonnage going to the mill or to the stockpile, and extracted waste tonnage. For each period, box plots are used to show the variations in the waste tonnage going to the waste dump (Fig. 5), average shovel utilization (Fig. 6), and average truck utilization (Fig. 7) over 100 replications. The top and the bottom of the box represent the upper quartile (75^{th} percentile) and the lower quartile (25^{th} percentile) respectively. The line in the middle of the box shows the median (50^{th} percentile). Ends of the upper and lower whiskers indicate the maximum and minimum values respectively. Summary of the related statistics are given in Table 2, Table 3 and Table 4. As an instance, the histogram of average truck utilization for 100 realizations is sketched in period 7 (Fig. 8).

Fig. 9 through Fig. 14, respectively, show the following results: average P grade at the mill, average S grade at the mill, average MWT grade at the mill, average P grade at the stockpile, average S grade at the stockpile, and average MWT grade at the stockpile.

5. Conclusions and future work

This paper presented a simulation model to assess the operational plans in the mine by taking into account the uncertainties associated with the operation of trucks and shovels. In further research the failure of trucks, shovels, mill, and their regular service times should be considered in long term planning. In order to achieve a more precise model, different number of stockpiles with various grade limitations should be used. To extend the model much further, some complex processes after extraction can be added to the model. Results from mathematical programming models for allocating the trucks and shovels can be used as an input to the simulation model. Consequently, an interactive approach between the simulation model and the mathematical programming model can be studied.

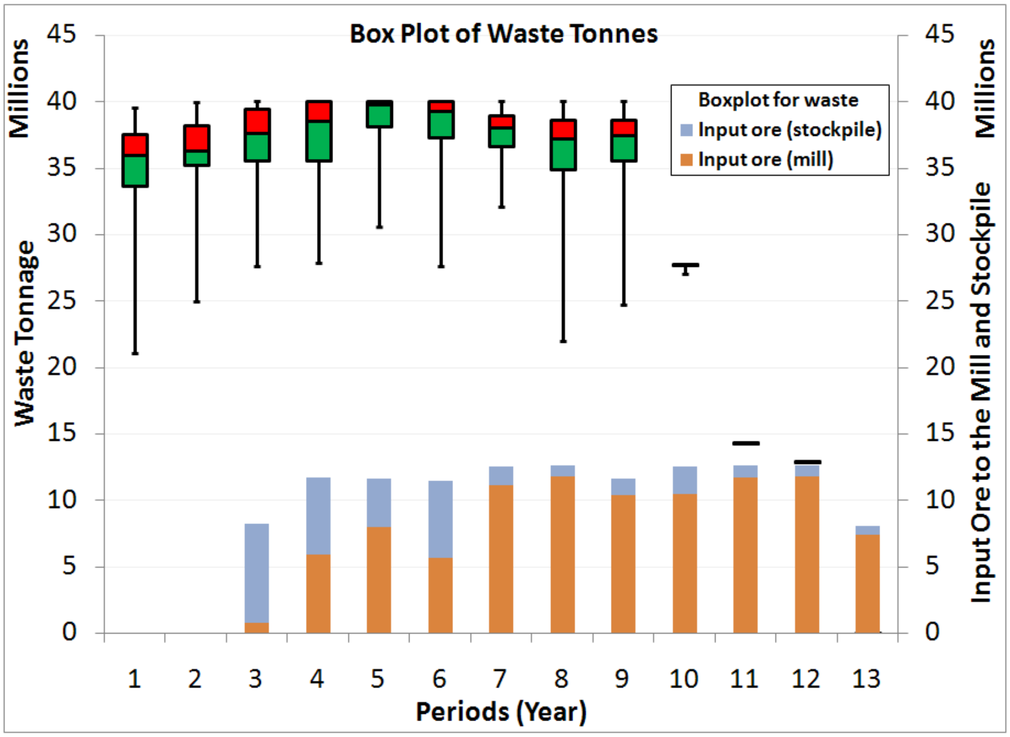

Fig. 5. Material tonnage going to the mill, stockpile and waste dump

[1]Table 2. Summary statistics of waste tonnage going to the waste dump (over 100 realizations)

Period	1	2	3	4	5	6	7	8	9	10	11	12	13
Minimum	21.1	25.0	19.4	16.2	18.7	16.1	19.6	9.4	12.1	14.4	1.7	0.3	0.0
Quartile 1	33.7	35.2	27.4	23.9	26.3	25.8	24.1	22.3	23.0	15.2	1.7	0.3	0.0
Meadian	35.9	36.3	29.4	26.9	27.9	27.8	25.6	24.6	24.8	15.2	1.7	0.3	0.0
Quartile 2	37.5	38.2	31.2	28.3	28.2	28.5	26.5	26.0	26.0	15.2	1.7	0.3	0.0
Maximum	39.6	39.9	31.8	28.3	28.2	28.5	27.5	27.4	27.4	15.2	1.7	0.3	0.0
Average	35.4	36.1	28.8	25.8	26.9	26.6	25.1	23.8	24.3	15.1	1.7	0.3	0.0
Standard deviation	2.8	2.6	3.0	2.9	2.0	2.6	2.0	3.1	2.5	0.1	0.0	0.0	0.0

[1] Values in Table 2 are in millions.

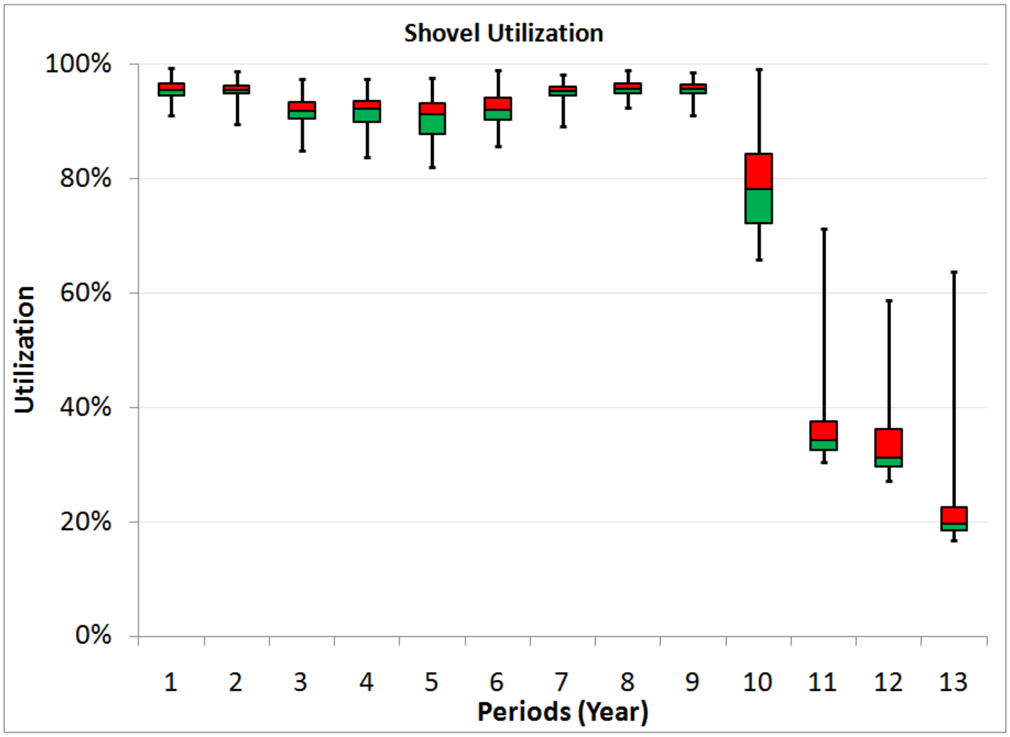

Fig. 6. Shovel utilization

Table 3. Summary statistics of average shovel utilization (over 100 realizations)

Period	1	2	3	4	5	6	7	8	9	10	11	12	13
Minimum	0.91	0.90	0.85	0.84	0.82	0.86	0.89	0.92	0.91	0.66	0.30	0.27	0.17
Quartile 1	0.94	0.95	0.90	0.90	0.88	0.90	0.95	0.95	0.95	0.72	0.33	0.30	0.19
Meadian	0.96	0.95	0.92	0.92	0.91	0.92	0.95	0.96	0.96	0.78	0.34	0.31	0.20
Quartile 2	0.97	0.96	0.93	0.94	0.93	0.94	0.96	0.97	0.96	0.84	0.37	0.36	0.23
Maximum	0.99	0.99	0.97	0.97	0.98	0.99	0.98	0.99	0.99	0.99	0.71	0.59	0.64
Average	0.95	0.95	0.92	0.92	0.90	0.92	0.95	0.96	0.96	0.79	0.36	0.34	0.22
Standard deviation	0.02	0.02	0.03	0.03	0.04	0.03	0.01	0.01	0.01	0.09	0.07	0.07	0.07

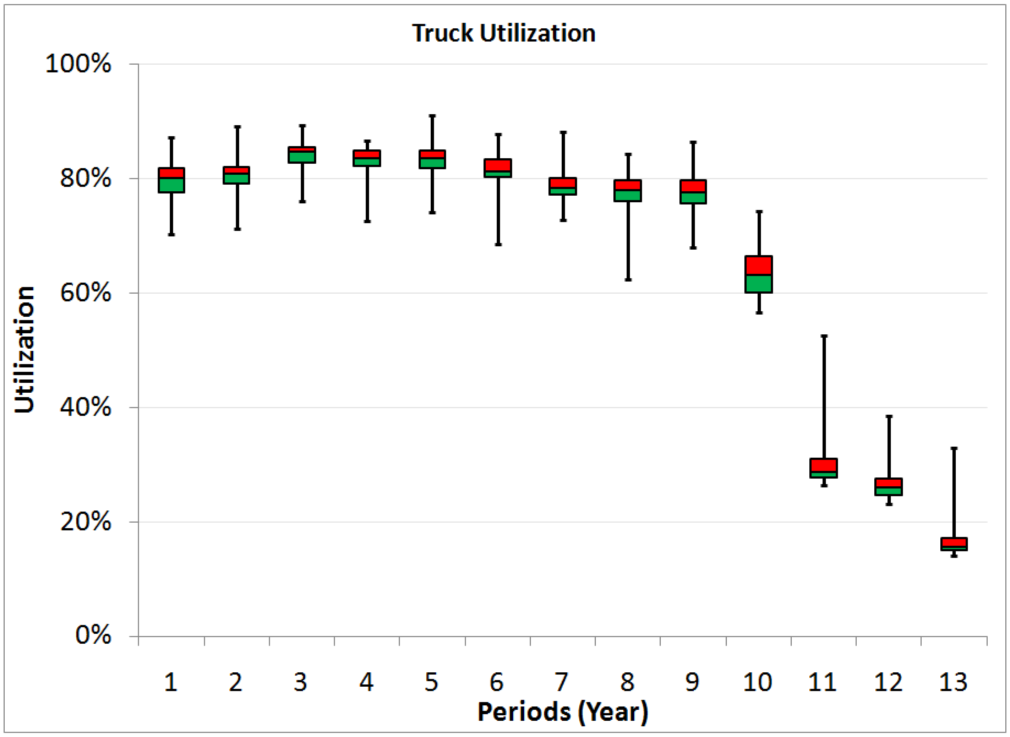

Fig. 7. Truck utilization

Table 4. Summary statistics of average truck utilization (over 100 realizations)

Period	1	2	3	4	5	6	7	8	9	10	11	12	13
Minimum	0.70	0.71	0.76	0.73	0.74	0.69	0.73	0.62	0.68	0.57	0.26	0.23	0.14
Quartile 1	0.78	0.79	0.83	0.82	0.82	0.80	0.77	0.76	0.76	0.60	0.28	0.25	0.15
Meadian	0.80	0.81	0.85	0.84	0.84	0.81	0.78	0.78	0.78	0.63	0.29	0.26	0.16
Quartile 2	0.82	0.82	0.86	0.85	0.85	0.83	0.80	0.80	0.80	0.66	0.31	0.28	0.17
Maximum	0.87	0.89	0.89	0.87	0.91	0.88	0.88	0.84	0.86	0.74	0.53	0.39	0.33
Average	0.80	0.81	0.84	0.83	0.83	0.81	0.79	0.78	0.78	0.64	0.30	0.27	0.17
Standard deviation	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.03	0.03

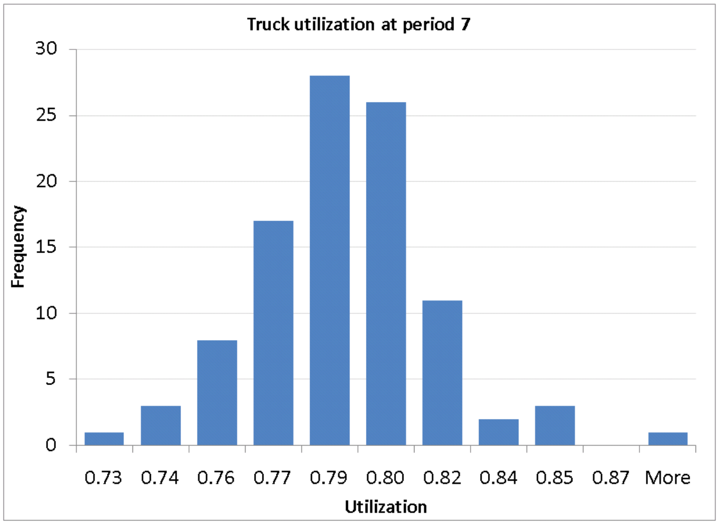

Fig. 8. Histogram of average truck utilization at period 7 over 100 replications

Fig. 9. Average P grade of material going to the mill

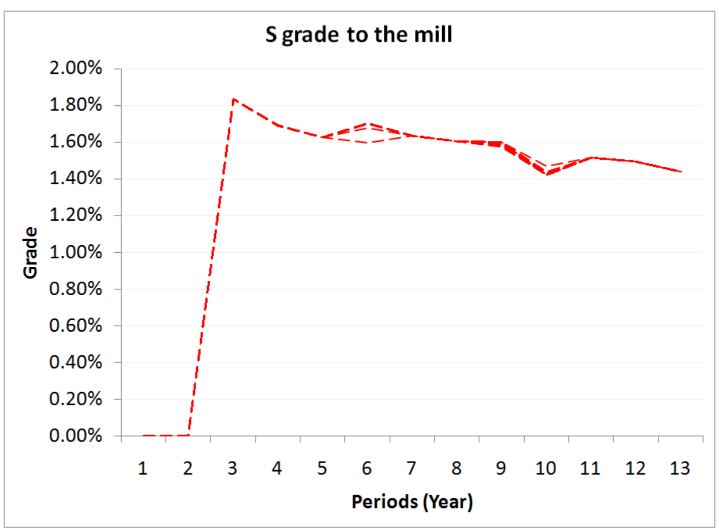

Fig. 10. Average S grade of material going to the mill

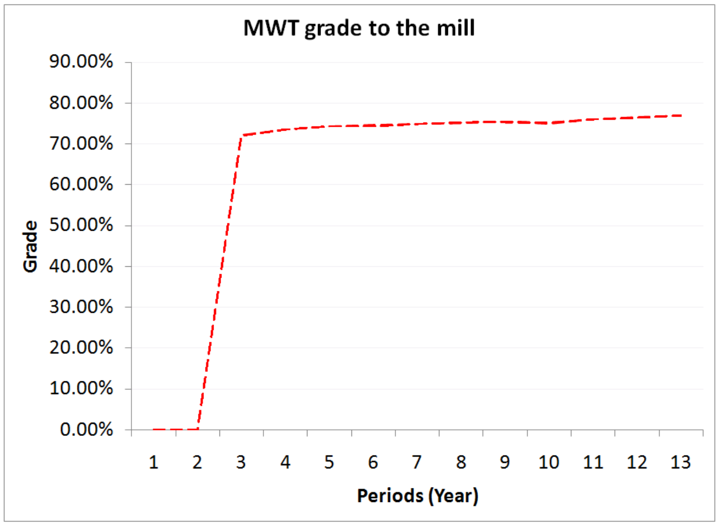

Fig. 11. Average MWT grade of material going to the mill

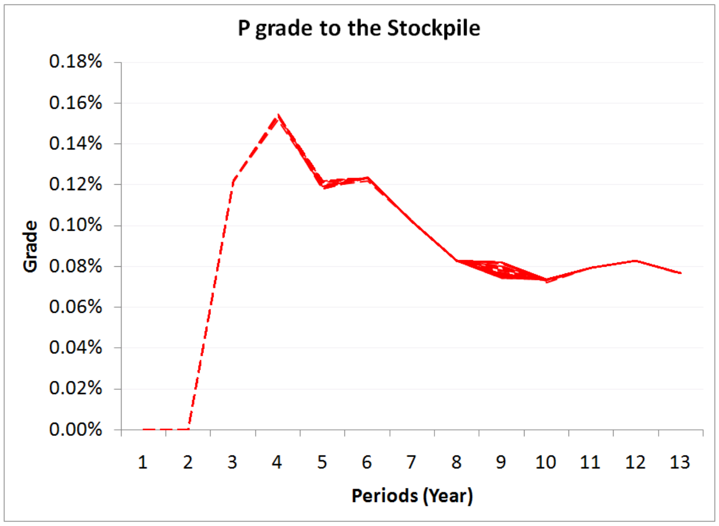

Fig. 12. Average P grade of material going to the stockpile

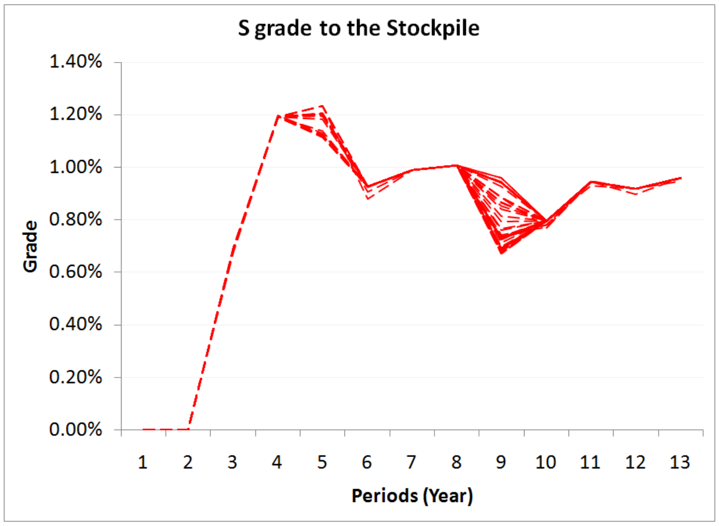

Fig. 13. Average S grade of material going to the stockpile

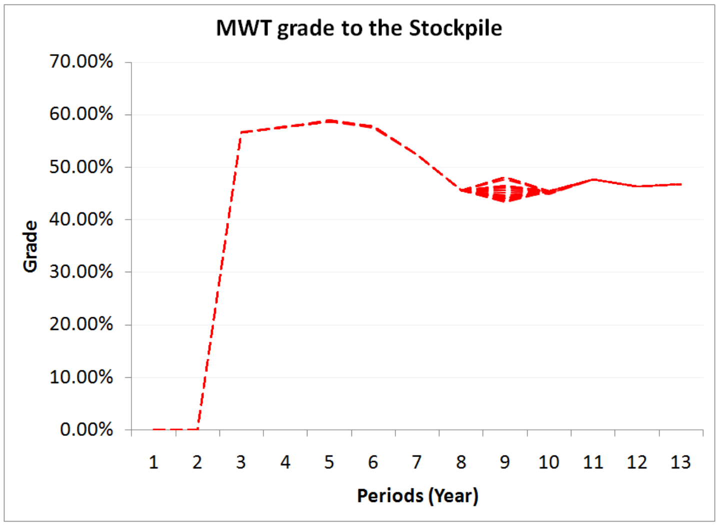

Fig. 14. Average MWT grade of material going to the stockpile

6. References

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