

Discrete Event Simulation of Truck-Shovel Operations in Open Pit Mines

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Abstract

Discrete event simulation is a powerful tool that has been used by many researchers to study complex systems and analyze the performance indicators for the current system versus proposed modifications and expansion scenarios. In the paper, we take a holistic approach at an open pit mining operation by incorporating the truck-shovel operations, road networks, processing plants, stockpiles, equipment failures, maintenance and capacity changes into a simulation model. The model is developed in Arena simulation software and is complemented by Matlab, Excel, Word and VBA modules to offer a complete flexible package that can be rebuilt and reused overtime by operation managers. Our framework takes production and maintenance schedules, haul road network, truck list and allocation strategy, shovel list, operation control parameters, and other probability distribution functions as inputs through spreadsheets and produces the reports required for analyzing the system performance and comparing expansion and modification scenarios. This paper explains all the steps required to develop and implement a simulation model by automating the procedure through programming and flexible model building and concludes by presenting normalized operation versus simulation statistics and plots to show the accuracy and reliability of our simulation model.

Keywords

Discrete Event Simulation, Open Pit Mining, Truck-Shovel Operation, Dispatching

1. Introduction

Accurate prediction based timely decisions result in improved outcomes for organizations. Simulation techniques have evolved over the years to accurately model the systems and predict on outcomes for user desired scenarios. Accurate modeling of such simulation models is essential for reliable and confident decision making involving huge capital investments. This paper presents the development, implementation, and validation of an industrial strength simulation model of a large scale open pit mine with truck-shovel operations.

The application of simulation in mining can be traced back to around 1940. With the evolution and familiarization, simulation techniques have been widely accepted as the powerful tool for modeling

the processes and analyzing the system responses with changing parameters of the system; and in-turn optimizing the system performance. Sturgul (2001) describes the importance of simulation in mining and describes GPSS/H and SIMAN based ARENA as the two most commonly used discrete event simulation languages in this field. Researchers have used simulation for a wide number of mining applications. Ataeepour and Baafi (1999), Forsman et al. (1993), Kolonja and Mutmanský (1994) and many others have used simulation to analyze the impact of dispatching strategies on the mining operations. Awuah-Offei et al. (2003) used simulation to determine the optimal truck and shovel requirements in a mine. Upadhyay et al. (2013) used simulation to determine optimum truck requirements in continuous surface mining systems. Simulation models developed by Sturgul and Eharrison (1987), Peng et al. (1988), and Forsman et al. (1993) among others are all developed for specific mining systems due to the nature of mining operations.

Simulation model have also been used in conjunction with external engines for decision making purposes. Fioroni et al. (2008) uses simulation in conjunction with a mixed integer linear programming model to reduce mining costs by optimal production planning. Yuriy and Vayenas (2008) use discrete event simulation in conjunction with a reliability assessment model based on genetic algorithms to analyze the impact of equipment failures on production, mechanical availability and equipment utilizations. In another paper Hodkiewicz (2010) provide a broad review of simulation modeling in mining and describe the applicability of the simulation modeling in understanding the impact of preventive and corrective maintenance on the production. Raj et al. (2009) provides a critical review of the application of simulation techniques for production optimization in mining.

The researchers, through various simulation models, have proved the power of simulation and in-turn proved the opportunity to improve the mining operations through simulation. Most literature on the application of simulation modeling in mining focuses on the aspect of robustness of simulation and do not detail the development of the models as such. The literature reviewed does not talk about the ease of application and re-usability of the models over time.

The development of a simulation model involves four major stages: 1) data analysis and distribution fitting, 2) simulation modeling, 3) verification and validation and 4) experimental design of scenarios and analysis. One of the major objectives set for this project was to develop a validated simulation model which is flexible and reusable over time within the given mining system. To achieve the objectives set for this project all the four major stages discussed above have been completed by designing user friendly interfaces which enable the user to recreate the model for the same mining system over time.

The objective of this project is to create a reliable simulation tool of the truck-shovel operation based mining system in conjunction with the downstream processing plant assets to be used in large scale open pit mining operations as a planning tool in the presence of uncertainty. The key features desired in the model are:

- A logic within the simulation model for truck dispatching to replicate the fleet management system's dispatch algorithm (Leica Geosystems Mining; Modular Mining Systems Inc.; Wenco International Mining Systems Ltd.),
- Assign truck speeds on the haul road network based on the rimpull curve (Bonates, 1996) configuration of trucks; and haul road gradients and rolling resistances of the road segments,
- Truck movements on the haul roads maintaining a safe following distance leading to platoon formations and traffic congestions,
- Incorporate a short-term production schedule as the input into the simulation model,
- Model the effect of shift change and coffee breaks on the production,
- Model the effect of seasons and weather events on the production,

- Incorporate various types of failures and preventative maintenance of equipment,
- Model the material flow in and out of the processing plants,
- Model uptime and downtime of crusher and downstream assets,
- Model stockpiles as a buffer balancing the discrete mine operation with the continuous processing plant operation.

Including the mine haul road network and moving the trucks based on haul road characteristics, safety distances, and yielding the right of way at the intersections on the haul roads brings this simulation model closer to reality, where the model provides further insights on the traffic congestions and its impact on production. This is one of the key features missing from the simulation models found in the literature, which fail to account for the platoon formations on the haul roads hampering production operations significantly.

A truck dispatching logic is another key addition in this model which helps reproduce dispatching decisions similar to those made in the real time mining operations by Fleet Management Systems (Leica Geosystems Mining; Modular Mining Systems Inc.; Wenco International Mining Systems Ltd.).

A simulation model on such a large scale has to be flexible and user friendly to run different scenarios and analyze results easily. The simulation model is therefore created in Arena (Rockwell Automation) taking all model inputs from an external configuration file. A VBA interface in Arena has been created to rebuild the model completely in case the haul road network, type and number of trucks and shovels, the production schedule, or any other input parameter of the mine changes.

Apart from modeling the mine and processing plant systems, it is essential to analyze the outputs easily and quickly. The simulation model generates large amount of data, which is stored in a database in the same format as the mine fleet management database (Leica Geosystems Mining; Modular Mining Systems Inc.; Wenco International Mining Systems Ltd.). To generate and analyze the results quickly a Matlab GUI is created which sends queries to the database, generates and plots the descriptive statistics, histograms, and quantile-quantile plots of data versus simulation results and creates a word file report of the results. The whole simulation tool is created by keeping its implementation as simple as possible, keeping in mind the needs of the user with no prior knowledge of simulation modeling to analyze the impact of desired scenarios on the overall system operations over time.

The rest of the paper is structured as follows: the next section describes the problem definition, scope and limitations of the model developed in this paper, followed by the methodology section which presents a broad overview of the approach adopted to achieve the objectives of the project. The section on “simulation” then presents the logic adopted in developing the simulation model. The model implementation, validation, and results are then presented followed by conclusions and future work directions.

2. Problem Definition

2.1. System

The system being modeled is a large scale open pit mine operation consisting of shovels, trucks, processing plants, stockpiles, and waste dumps along with the haul road network of the mine.

2.2. Objective

The objective of the project presented in this paper is to develop a simulation model of the system, validate it against the historical data and use it as a planning tool to run new scenarios to analyze the impact of new mine layout, haul road network, equipment type and size on the major key performance indicator of the open pit mine and processing plant system.

2.3. Scope and limitations

Although the flexibility included within the model makes it reusable over time within the same mining system; due to the nature of the simulation models and the input probability density functions based on historical data, the model is not a general tool. Modifications are required to the model to be tailored to other mining operations. Model, although, is capable to handle changes for the same mining system through the external input file, without changing the model. Major changes that can be made using the external input file include:

- Haul road network
- Probability density functions,
- Maintenance schedules,
- Number and characteristics of trucks and shovels,
- Plant characteristics and downstream flow rates,
- Truck allocation strategy to be used for truck dispatching by fleet management system.

3. Methodology

3.1. Framework

We needed to develop a framework to handle the historical dispatch, failure, and preventive maintenance data analysis outcome and probability distributions, and to set and modify model parameters and generate the reports. Moreover, the level of reporting required was beyond the built-in capabilities of Arena. Therefore, various codes and databases were developed to perform each task. A brief explanation of the framework pieces is presented here.

- Database: the historical dispatching and failure required a database in order to hold the information and provide fast and flexible access to perform analysis on different subsets of data. On the other hand, since the project required complex and customized reports, we decided to create a database import every cycle of the truck-shovel operation, failures and maintenance records and plant production from the simulation model into a database. Therefore, Microsoft SQL database engine was used with four pairs of tables for original and simulation data. The tables hold the dispatch records, failure and maintenance, and processing plants hourly production.
- Matlab®: Matlab R2015b (The MathWorks) is used for performing statistical analysis on historical and simulation data. Various functions and GUIs are developed to retrieve subsets of data from the historical and simulation databases and perform statistical analysis.
- Excel: we needed a GUI to input parameters for creating and controlling the simulation model which is easy to manipulate. Therefore, we used Excel workbooks with macros to create a GUI for setting model input parameters that are read into Arena and used for generating the model and setting operation parameters.
- Word: we have automated the report generation process by developing macros in Microsoft Word to import graphs including histograms, quantile-quantile plots, and descriptive statistics to generate desired reports for historical data and simulation outcome analysis.

3.2. Data Analysis

Statistical analysis of the historical and simulation data is a very important part of any simulation project. The analysis has to be performed on the historical dispatch and failure data in order to obtain probability distributions and determine valid boundaries for control and output parameters. On the other hand, the simulation results have to be statistically analyzed to be able to validate the

model; and afterwards, perform meaningful and reliable comparisons of different expansion and modification scenarios. Therefore, we developed Matlab codes to retrieve data from historical and simulation databases with various groupings on the shovels, trucks, material groups and destinations, time intervals and operations crews. We have used these functions to plot histograms and create statistical summaries of more than 200 combinations of data fields and groups. The historical dispatch data analysis is summarized in Table 1.

Table 1. Statistical Analysis for Historical Dispatching Data

	Groups			Histogram	Probability Distribution
	Truck Type	Shovel Type	Destination		
Load Tonnage	×	×		×	×
Empty Distance			×	×	
Full Distance	×		×	×	
Empty Velocity	×			×	×
Full Velocity	×			×	×
Empty Haul Time	×		×	×	
Full Haul Time	×		×	×	
Spot Time	×	×		×	×
Loading Time	×	×		×	×
Hang Time		×		×	
Queue Time				×	
Dump Time	×		×	×	×

In order to model the truck, shovel and plant facility failures we grouped multiple failure codes to have enough records of historical data for distribution fitting and also to decrease the number of failures defined in the model. However, we kept the groups within failure categories to be able to model and report different categories of downtime independently. On the other hand, multiple maintenance schedules are modeled with fixed uptime and downtime for trucks, shovels and plant facilities independent from the failures and report under their designated category. The time categories for the equipment are presented in Table 2.

Table 2. Equipment Time Categories

ID	Category	Trucks	Shovels	Plant Facilities
1	Work	×	×	×
2	Operations Delay	×	×	
3	Operations Standby	×	×	
4	Short Down	×	×	
5	Down Service	×	×	×
6	Down Technical	×	×	×
7	Down Waiting	×	×	
8	Out of System	×	×	

3.3. Fitting distributions

As mentioned earlier, we developed multiple Matlab functions to retrieve subsets of data and fit probability distributions. However, since the distributions are going to be used in Arena we developed another function to retrieve the values and write them to a text file. Arena Input Analyzer is then used to import the text file and determine fitting probability distributions for each

set of values. The two methods work in parallel and provide an ability to have multiple distributions for one parameter and choose the one that fits data better theoretically and statistically. Moreover, we created a function to create Empirical probability distributions wherever finding a theoretical distribution is not possible. More than 1300 probability distributions were modeled as input parameters into the simulation model.

3.4. Building the model

The simulation model consists of two parts: the fixed and the dynamic parts. The fixed part of the model is built in Arena and controls the logic of the model and all the modules required for simulation. On the other hand, we developed a VBA procedure in order to dynamically build the rest of the simulation model from a configuration file. Our code reads the list of shovels, trucks, mining polygons, road network and all the required distributions and settings from an Excel configuration file and updates the corresponding resources, transporters, variables, expressions and module settings in Arena. Therefore, we have the flexibility to change the model without touching the main logic. Moreover, this provides the option to change the model without having the modeling knowledge necessary to build a model in Arena. The details of fixed and dynamic parts of the model are presented in the fourth section of the paper.

3.5. Validation and scenario evaluation

As mentioned earlier, we decided to use the database for generating validation and scenario evaluation process. To do so, we need to save every cycle of the truck-shovel operation, equipment failures and plant productions into the database. Arena provides an option to directly write into SQL databases using ADO method; however, the procedure is time consuming as it has to open and close a connection to the database for every record. Therefore, we write all the simulation records into a text file and import them into SQL after the simulation is over. The Microsoft SQL bulk import and export command prompt tool is called from a VBA function to automatically import the results into the database. The bulk import is the fastest way of importing large text files into SQL database.

After importing simulation data into SQL database, post-processing stored procedures are called to clean up the simulation results and make them ready for reporting. Three sets of Matlab functions are developed to validate the results and evaluate various scenarios. The first set compares one replication of simulation results to the historical data by creating field by field comparison reports and graphs as shown in section 5. The reports include summaries of production and operation KPIs as well as field by field comparisons. The second set compares multiple replications of simulation results to the historical data through comparing the historical recorded values to replication means and half widths calculated from multiple replications. Report and graph examples are presented in sections 5.1 and 5.2. The third set is developed to compare multiple replications from two simulation scenarios. The codes are developed to compare the means and half widths from two different sets of simulation replications.

4. Simulation

The most important step in building a simulation model is the conceptual modeling. This step of the procedure helps us understand the model without getting into the details of modeling and is independent from the software and modeling environment we are planning to use. We have broken down the system into various sub-models and built conceptual models in different resolutions in different stages of modeling. Most of these conceptual models cannot be presented here due to confidentiality of the project. However, high level models, which are related to processes shared by all truck-shovel operations, are presented in this section. The high level conceptual model of the whole operation is presented in Fig. 1. Details of modeling and some of the sub-models will follow in the upcoming sections.

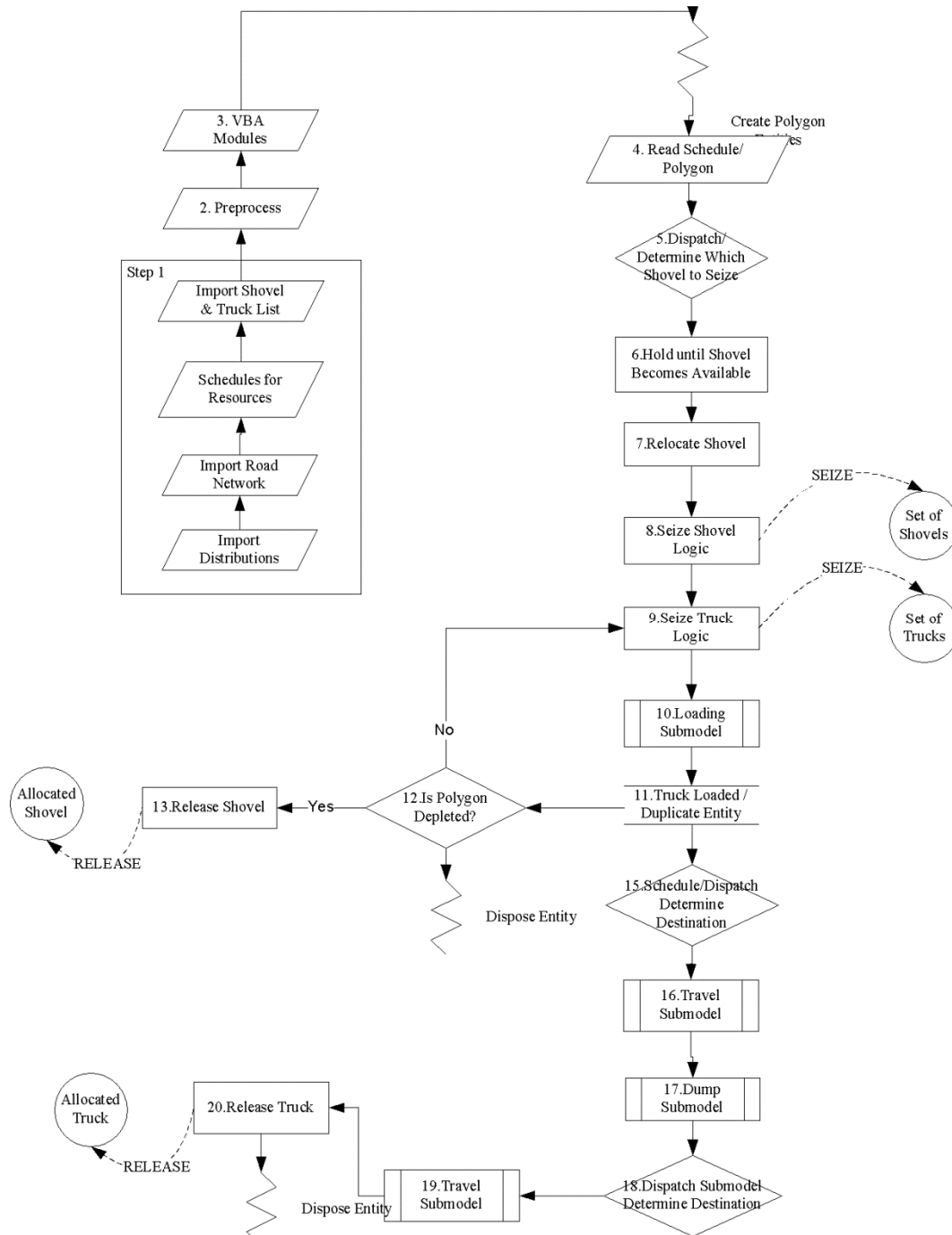


Fig. 1. Conceptual Model

4.1. Production schedule

One of the most important parts of a truck-shovel operation simulation is the production schedule. The production schedule is an input into the simulation model and can be used to validate the model against the historical data and to evaluate various scenarios of moving shovels from ore to waste and vice versa, and of changing mining directions and lead and lag in bench mining. The production schedule in our model is a sorted list of mining polygons with polygon center coordinates, destinations, material types and tonnages, grade and contaminant values, and assigned shovel IDs. However, the model is capable of importing polygon precedence and assigning shovels to mining polygons when they are available. Although the destination of material extracted from

each polygon is determined in the production schedule, the dump location (e.g. hopper) is decided in the simulation model by an embedded dispatching logic.

4.2. Travel

Truck haulage is a critical part of the mining system which proves to be a bottleneck in most production operations. The major problem is posed by the platoon formations on the haul road segments which significantly affects the truck travel times and thus hampers production. Thus it is necessary to capture such truck interactions in the simulation. The major reason of such truck interactions is the difference in speed of trucks of different types and also intersections at various points of the haul road network. Such interactions are very common in mixed fleet systems where speed of different truck types differ significantly on different haul road conditions. To account for these truck interactions and to capture the realistic truck travel times, the simulation must incorporate the haulage road network of the mine and impart truck speeds based on the haul road conditions.

To build the haul road network of the mine, the road network poly-lines of the mine are exported from any design software and written as segments in the configuration input file using a GUI interface built in Matlab. The GUI provides the capability to merge the segments, based on the gradient and length tolerance, to reduce the total number of segments created in Arena if the road network of the mine is very large. The VBA interface in Arena is then used to create the haul road network as connected road segments. The configuration file also contains the haul road gradients and rolling resistances of the road segments to assign appropriate speeds to trucks.

The truck travel is modeled as presented in Fig. 2. Trucks are moved on the network through the segments by imparting speeds based on the rimpull curve characteristics of the truck; and gradient and rolling resistance of the road segment. When a truck reaches to the start of a segment, its sampled flat haul speed is multiplied with a speed factor based on the total resistance of the next segment and the rimpull characteristic of the truck as the speed of the truck on the next segment.

To model the safe following distance between trucks and restricting overtaking, the trucks are modeled as guided path transporters and haul road network is built as network in Arena. The network in Arena is made by using the segments as network links consisting of zones. The truck movements on these links occur by seizing the next zone and releasing the occupied zones. By setting the zone control rule as "Start", Arena allows any trailing truck to seize the next zone only when it has been released by the leading truck. This enables the model to restrict overtaking of trucks. To model a safe following distance, the zone lengths are set as the summation of average truck length and the safety distance. Thus a trailing truck will have to stop at the safety distance if the leading truck stops.

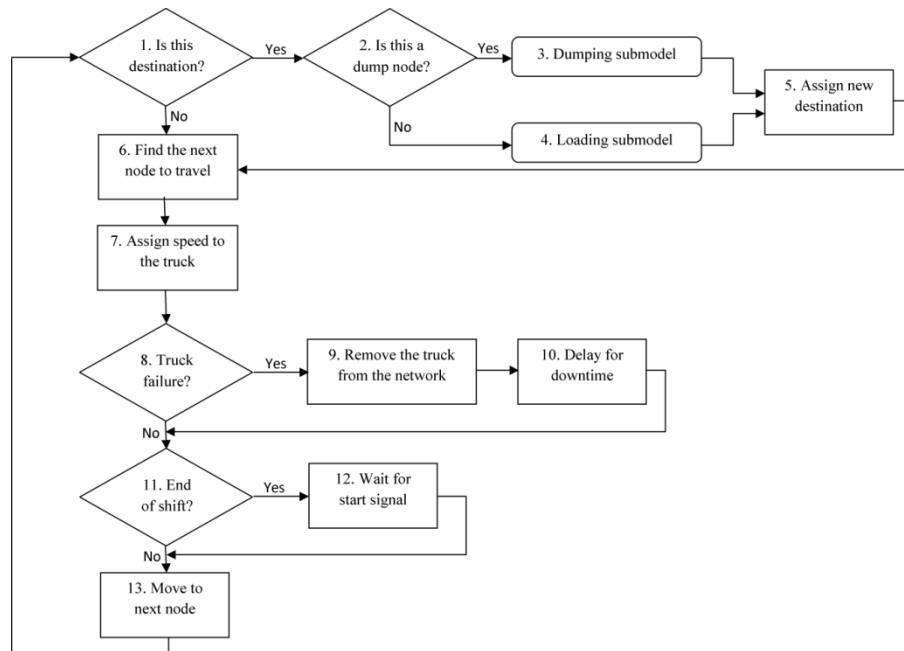


Fig. 2. Haulage system logical flow diagram

Modeling haulage system using guided path transporters and network links brings the travel model very close to reality. This type of modeling can be considered to be closer to micro-simulation approaches. One of the major drawbacks posed by this approach is the longer run times of the simulation model. Another parallel approach is therefore created in Arena which although restricts overtaking of trucks, does not guaranty safety distance between trucks. Replacing guided path transporters and network links with free path transporters and distances in Arena, reduces the run time of the model significantly. The major problem with free path transporters is that it does not move the trucks zone by zone and thus allows any overtaking based on speed of trucks. This is controlled by adjusting the speed of trucks on the segments so that a trailing truck does not reach the end of the segment before its leading truck and thus restricting overtaking. A comparison between the two approaches shows that run time with the free path approach is significantly lower than the guided path approach and the production results are marginally higher with the free path approach.

4.3. Season

The effects of season changes have to be considered in the simulation model. Therefore, we divided the historical data into two seasons while performing statistical analysis and determined which parameters require separate distributions for the summer and winter. On the other hand, a variable in simulation model changes based on simulation time and makes simulation modules choose the proper distribution based on the current season.

4.4. Truck and shovel downtimes

As mentioned in the previous sections, we grouped various failures for trucks and shovels within the defined categories and fitted distributions on the TBF (time between failure) and TTR (time to repair). The shovels are defined as the resources in the Arena model. Therefore, we can use the resource schedules and failures modules in Arena. However, using the built-in modules removes the ability to collect independent statistics based on failure categories. Therefore, we created a separate logic to sample TBF and TTR values for each shovel and control the maintenance schedules. The logic is presented in Fig. 3. A 1-dimensional variable is used to hold the state of each shovel to allow failure and maintenance downtime overlaps. We are holding the failure entity in a queue if the shovel is already inactive due to other failures or maintenance. Therefore, the

sampled total downtime would be preserved by postponing the failure until the shovel becomes available. A similar logic is implemented for the trucks with another 1-dimensional state variable. However, since the trucks are modeled as transporter modules in Arena, they cannot be set to inactive through a module. Therefore, we check the truck state variable in every intersection of the road network and take it out of the network if failed. The logic for truck failure modeling is presented in Fig. 4.

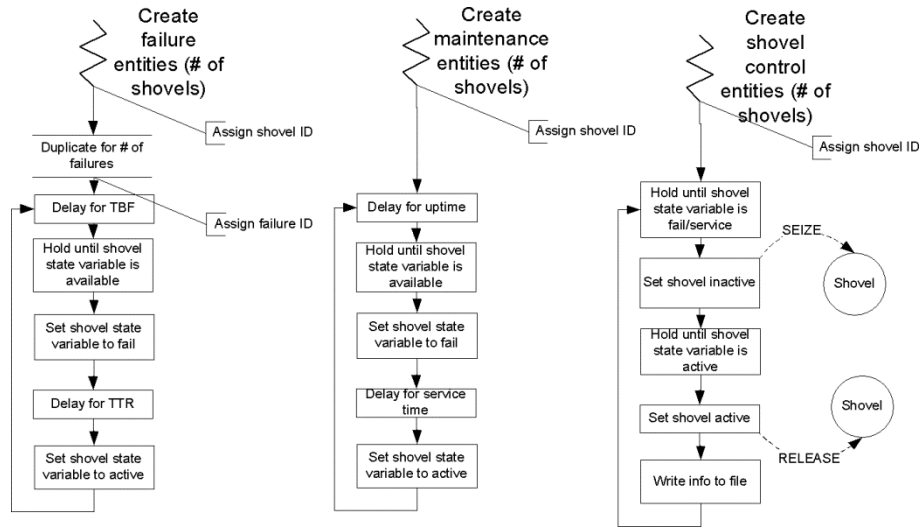


Fig. 3. Shovel Failure Logic

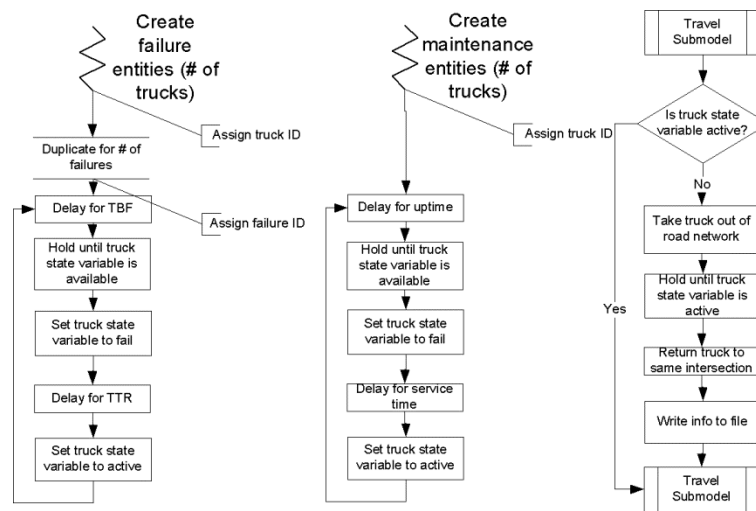


Fig. 4. Truck Failure Logic

4.5. Shift change, coffee break and weather events

Shift changes and coffee breaks are events that happen on a regular basis compared to failures and affect all the trucks and shovels simultaneously. However, how long they take can be determined by a probability distribution. On the other hand, weather events happen randomly but affect all the trucks and shovels. We modeled these three independently by changing state variables for all trucks and shovels when they happen. The same module explained for truck and shovel failures will set the equipment to inactive for the duration of these events.

4.6. Processing plant

Adding the processing plant to the simulation model can significantly improve the reliability of the truck-shovel simulation due to queuing for dumping at the hoppers. On the other hand, processing plants can be unavailable or be working with less than nominal capacities when failures occur on downstream assets. Therefore, we added the upstream processes of the processing plant to the simulation model to mimic the hopper capacity constraints and changes in the throughput rate. Two separate plants with seven hoppers are simulated with the initial crushers and conveyer belts. A combination of continuous and discrete modules is used to model the plants in Arena. Eleven facilities are modeled as resources to simulate failures and maintenance schedules for the plants, seven hoppers and two surge bins are modeled as tank modules with limited capacities, and eleven conveyer belts are modeled to account for variations in the throughput rates with distributions fitted on historical data. The load dumping sub-model logic is presented in Fig. 5. The processing plant details cannot be presented due to confidentiality. However, an example of how the relationships between the surge bins and conveyer belts are modeled is presented in Fig. 6.

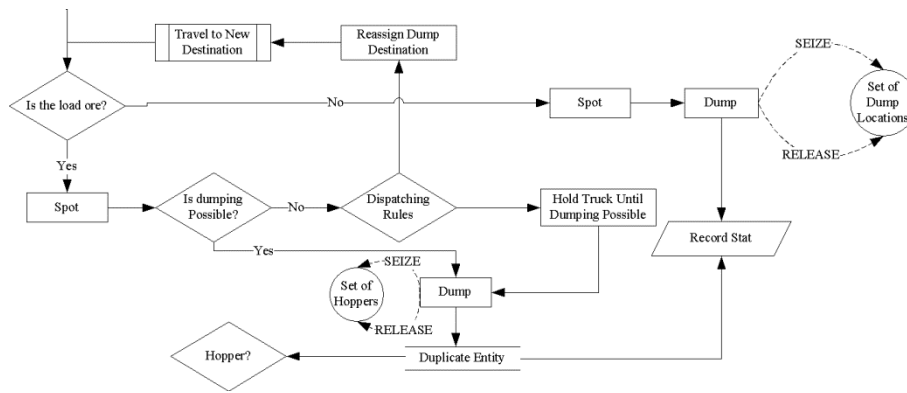


Fig. 5. Dump Submodel

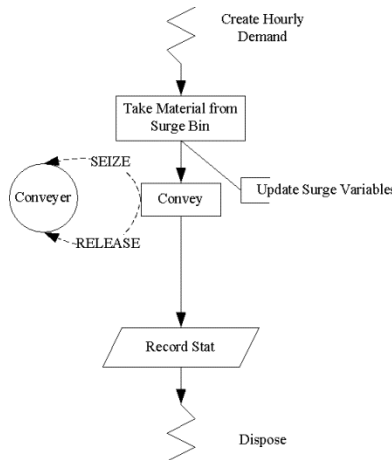


Fig. 6. Surge Bin to Conveyer Belt Logic

4.7. Dispatching

We have developed two dispatching modules in our simulation model. The first module is responsible for assigning empty trucks to shovels and the second module is responsible for determining and updating the dump location of loaded trucks. The latter works simply based on assigning trucks to the dump location currently available and with the least number of trucks on route. Therefore, in this section, we explain the procedure used to assign the empty trucks to shovels in more details.

First, we calculate the cycle time for each shovel based on the current polygon destination and average values for loading and spot times, velocities and dump times. Next, we calculate the number of trucks required for each shovel to be fully utilized. Afterwards, we assign a dispatch value to each shovel and assign the truck to the shovel with the lowest value. The dispatch value is calculated based on the following parameters:

1. Number of trucks currently assigned to the shovel divided by the number of trucks required,
2. The distance from the current location of the truck to the shovel,
3. Over-delivery of ore to the processing plants,
4. Truck to shovel type assignment probability,
5. Truck to material type assignment probability,
6. Truck to material type lock status,
7. Truck to pit lock status,
8. Current state of the shovel (i.e. active, fail and idle),
9. Maximum number of trucks allowed to be allocated to one shovel.

The first five parameters work as weighted decision making factors while the rest work as hard constraints that should not be violated by the assignment. Therefore, there are weights defined and calibrated for the first five factors to adjust the dispatching module to the reality of the operation. The first factor represents shovels' need for trucks to be fully utilized. The second factor is considered to avoid long distance assignments. Next, the past hour delivery of ore to the processing plants is compared to an adjustable threshold and will penalize ore shovels if the plant is overfed to avoid long queues at hoppers. The shovel type and material type probabilities are calculated from the historical data and can be adjusted for every truck in the system. On the other hand, the sixth and seventh factors provide the option to lock a number of trucks to a specific material type and/or pit, or to allow floating based on the current state of the operation. Moreover, we have to avoid allocating trucks to shovels that have failed or are not working due to not having any mining face available. Finally, we added an external control parameter to control the maximum number of trucks assigned to each shovel at any time during the simulation.

4.8. Warm-up time

Another important part of the simulation model is the warm-up time. We have considered ten days for the warm-up with specifically marked dummy polygons for the truck-shovel operation to get to a stable point before we start collecting statistics. The load records, failures and plant production records from the warm-up period are flagged and deleted during post-processing.

5. Results

In this section, we present the results of validating the simulation model against the historical data. We break down this section into two main parts for validating the model for three months: a) validating the model using one replication, and b) validating the model using multiple replications. The results and graphs are automatically generated by the developed Matlab codes and Excel spreadsheets.

5.1. Three-month single replication

We have setup the model based on distributions obtained from the historical data and fine-tuned the model parameters to achieve results similar to the last three months of the available data. Moreover, we created the production schedule from the historical data recorded for the same shovel in the same order of extraction. The production schedule consists of mining polygons including the warm-up polygons. The percentage difference between the simulated results and the historical data

for all statistics is presented in Table 3. The actual values are omitted for confidentiality purposes. Two examples of normalized histograms of recorded and simulated parameters along with the quantile-quantile (QQ) plots are presented in Fig. 7 to Fig. 12.

Table 3. Single Replication Results

	Count	Min	Max	Range	Mean	Median	ST.Dev.	Summation
Measureton	10%	0%	0%	0%	2%	2%	-2%	0%
Empty Distance	10%	114%	-2%	-4%	-6%	-6%	9%	-9%
Full Distance	13%	101%	-5%	-7%	-1%	-1%	16%	1%
Empty Travel Time	14%	0%	0%	0%	-3%	-5%	26%	1%
Full Travel Time	13%	0%	-3%	-4%	-3%	-3%	22%	0%
Spot Time	17%	0%	2%	2%	-5%	-7%	-4%	-1%
Loading Time	12%	76%	0%	-4%	-3%	-7%	1%	1%
Dump Time	16%	0%	2%	2%	-3%	-3%	11%	2%

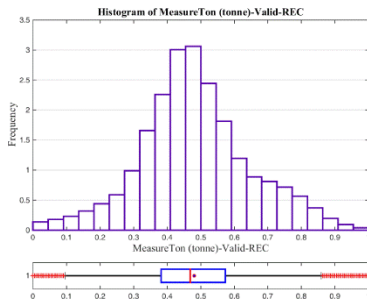


Fig. 7. Recorded Measureton

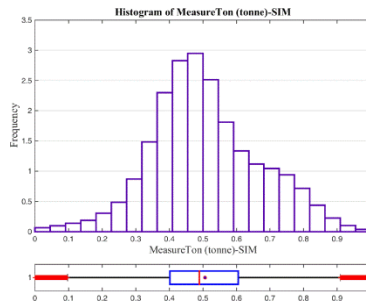


Fig. 8. Simulation Measureton

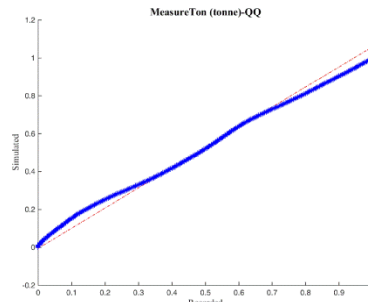


Fig. 9. Measureton QQ Plot

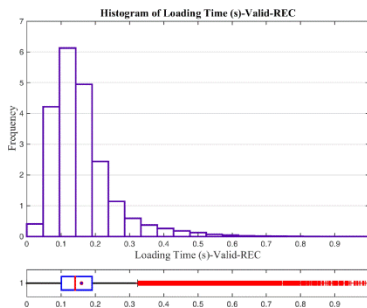


Fig. 10. Recorded Loading Time

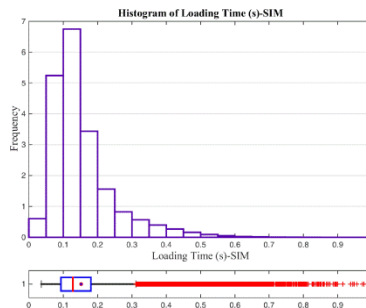


Fig. 11. Simulation Loading Time

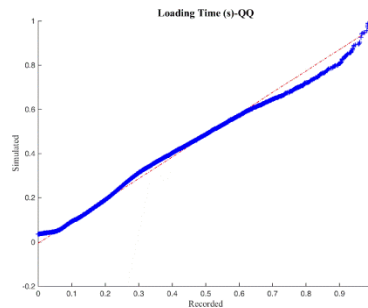


Fig. 12. Loading Time QQ Plot

In addition to the general histograms our codes create the plots and statistics grouped by truck type, shovel type and material type. We have replaced the actual truck type and shovel types with numbers. Truck tonnage values for recorded and simulated values are plotted and compared for shovel type 1 loading ore on truck type 3 in Fig. 13 to Fig. 15.

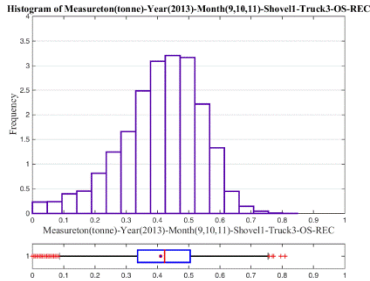


Fig. 13. Recorded Measureton

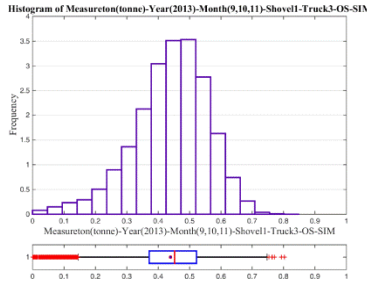


Fig. 14. Simulation Measureton

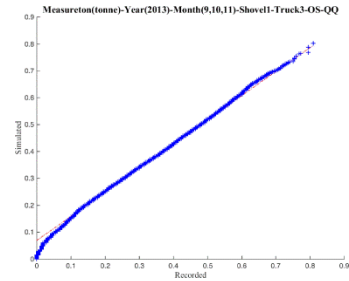


Fig. 15. Measureton QQ Plot

5.2. Three-month multiple replications

We used the same parameters from the single replication model and ran 20 replications. The production schedule is the same as the single replication and the simulation results are compared against the same set of historical records. The difference between the single-replication and multi-replication reports is in reporting the values with half widths. The half width is a statistical measure to understand the uncertainty around an output parameter. The half widths presented in the following tables and graphs are calculated based on 95% statistical confidence level. For confidentiality reasons, the simulated measures and their half widths are divided by the historical recorded value and presented as percentage. For example, the average summation mined tonnages in 20 replications is equal to the recorded summation and the 95% confidence interval for it is $\pm 0.78\%$ of the recorded tonnage. Some of the major validation measures and truck KPIs are presented in Table 4 and Table 5. The corresponding plots are presented in Fig. 16 to Fig. 21.

Table 4. Multiple Replication Results

	Mean	H. W.	Median	H. W.	ST.Dev.	H. W.	Summation	H. W.
Measureton	102%	0.05%	102%	0.04%	99%	0.21%	100%	0.78%
Empty Distance	93%	0.42%	93%	0.84%	108%	0.57%	90%	0.80%
Full Distance	97%	0.46%	95%	1.18%	114%	0.62%	99%	0.96%
Empty Travel Time	96%	0.51%	94%	0.66%	126%	0.68%	100%	0.82%
Full Travel Time	97%	0.40%	96%	0.61%	124%	1.34%	99%	0.84%
Spot Time	94%	0.13%	94%	0.13%	93%	0.29%	99%	0.73%
Loading Time	98%	0.31%	95%	0.21%	101%	0.88%	101%	0.66%
Dump Time	93%	1.28%	95%	0.24%	110%	5.17%	98%	1.63%

Table 5. Shovel KPI Results

	Mean	H. W.	Median	H. W.	ST.Dev.	H. W.	Summation	H. W.
Total Hours	100%	0.00%	100%	0.00%	100%	0.00%	100%	0.00%
Work	100%	1.46%	98%	1.79%	63%	4.49%	100%	1.46%
Ops Delay	106%	1.37%	104%	2.68%	54%	2.86%	106%	1.37%
Ops Standby	100%	3.36%	94%	4.15%	85%	6.89%	100%	3.36%
Short Down	78%	1.14%	84%	1.89%	30%	2.81%	78%	1.14%
Down Service	99%	9.08%	97%	24.30%	86%	4.78%	99%	9.08%
Down Technical	96%	2.95%	155%	6.13%	21%	2.05%	96%	2.95%
Down Waiting	132%	19.50%	100%	0.00%	42%	5.06%	132%	19.50%

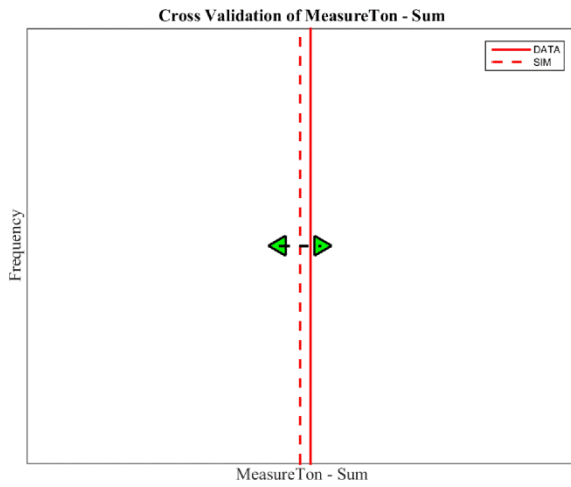


Fig. 16. Measureton Summation

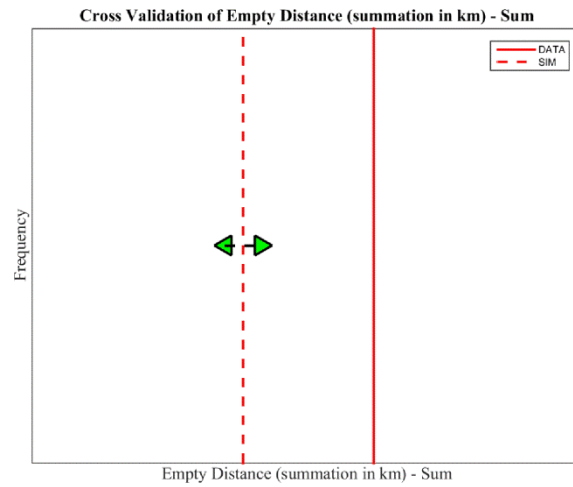


Fig. 17. Empty Distance Summation

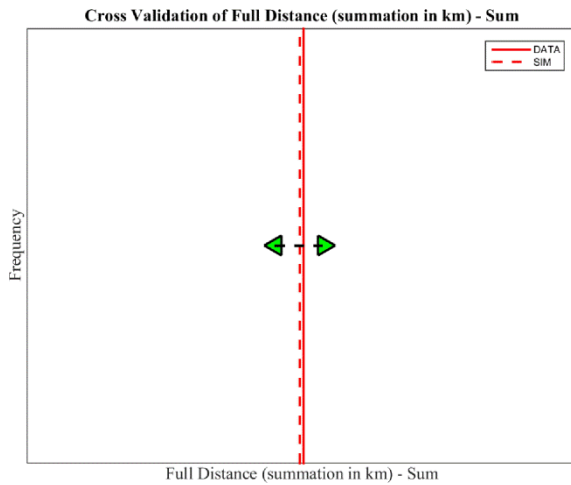


Fig. 18. Full Distance Summation

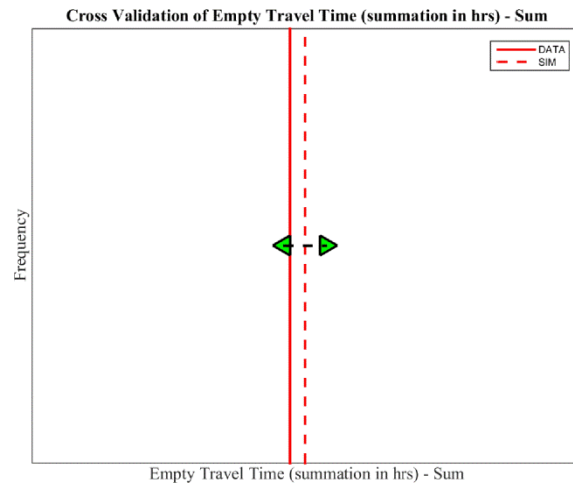


Fig. 19. Empty Travel Time Summation

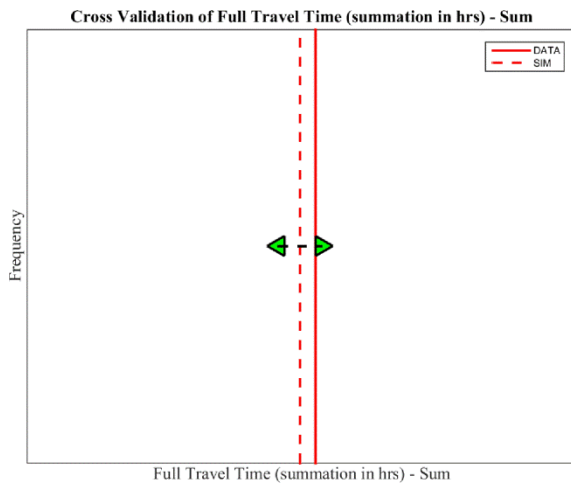


Fig. 20. Full Travel Time Summation

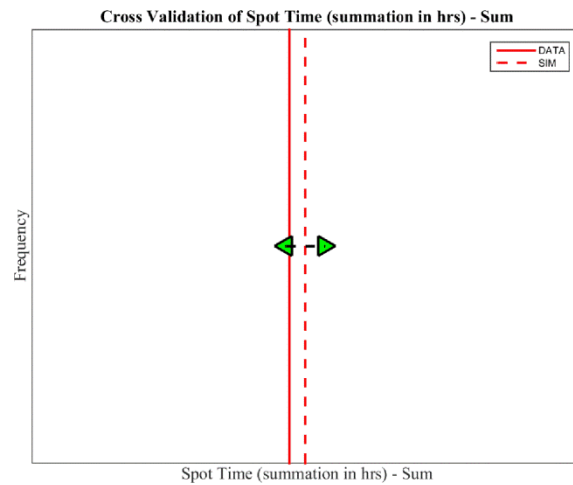


Fig. 21. Spot Time Summation

6. Conclusion and future work

Discrete event simulation is a powerful technique for studying complex systems that change states over time. Truck-shovel operation in an open pit mine is one of those complex systems that is affected by large number of uncertain parameters. Therefore, in this paper, we presented the steps to build a simulation model for an open pit mining operation. We have developed the model in Arena simulation software and used SQL databases, Matlab codes, Excel interfaces and VBA programs to create a dynamic framework to analyze the historical data and evaluate various expansion and modification scenarios. The simulation tool inputs the production schedule, road networks and other operation parameters and simulates the current operation as well as planned scenarios. Travel sub model coupled with rimpull curve characteristics of trucks and haul road characteristics enabled the model to capture realistic truck travel times and truck interactions.

In this paper, we presented the conceptual diagrams of the operation and the simulation model and the details of the modeling procedure. We showed that our model is able to mimic the current operation by comparing the statistics and histograms of the historical data and the simulation results. Moreover, we showed how we can build a confidence interval around the performance measures of the operation by running multiple replications of the simulation model in order to capture the existing uncertainty in the operation as well as proposed scenarios.

For future studies, we recommend developing more accurate dispatching modules that incorporate optimization engines to improve truck allocations. On the other hand, decreasing the runtime for the simulation model can improve the usability of the model.

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