Discrete event simulation to design open-pit mine production policy in the event of snowfall

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Snowfall can lead to the cessation of production in a truck-shovel mining system. A snow road removal procedure that is performed simultaneously with the production operation is introduced to avoid this situation. A discrete-event simulation model is built to evaluate both operations under different configurations. An operation policy is designed based on the simulations results. This policy defines the manner in which production and snow removal operations are conducted depending on the intensity of the snowfall. The operational policy demonstrates that production can be maintained at high snowfall intensities.

Keywords: discrete-event simulation; open-pit mines; truck-shovel mining system; operational mine planning.

Introduction

The most common method used for material transport in open-pit mines is the truck-shovel system. Production continuity is the key aspect for any open-pit mine operation because it is directly related to productivity and, therefore, to the mining cost. For example, material transportation may contribute about 50–60% of the total operating cost in an open pit mine [1,2]. Therefore, the main goal of operators is indeed to keep the mine running by eliminating interruptions and interferences so that loss of time is reduced and the system remains productive for as long as possible.

Unfortunately, adverse weather conditions may result in the slowing or even stopping of production in an open-pit mine. For example, snowfalls can affect the safety of the operation owing to the accumulation of snow on the roads. Such events may lead to the stopping of mine production for several days. Therefore, there is interest in determining ways to continue operation during such bad weather conditions or to reduce the time required to restart operation.

In the case study presented, we considered the introduction of special equipment to continue operation for as long as possible during snowfall and to reduce the cleaning time required to restart operation after the storm has passed. The equipment we considered was snowpushers which are front-end-loaders coupled with a pusher in the front; this equipment can be operated as trucks haul the minerals. However, for this to solution to be effective, the planning must be accurate because the additional interference between the two types of equipment may affect these operations in such a way that there is no net gain. Thus, we investigated ways to optimize the operation to maintain the production for as long as possible.

A truck-shovel mining system can be modelled in several ways. According to [3], the main methods are mathematical programming, stochastic methods (e.g. queuing theory) and simulation. For example, [4–6] used mathematical programming to optimize production scheduling and truck-dispatching problems in the same framework. On the other hand, stochastic methods such as the queuing theory have been applied to evaluate truck and shovel systems (See [7–15]).

As it turns out, both mathematical programming and stochastic methods cannot comprehensively capture all the necessary aspects of the shovel-truck system by themselves [3]. This is because they do not consider the stochastic nature of these systems, the economics involved, or the multi-period nature of mining operations [6]. In fact, [16] indicates that simulation is the only reliable method for evaluating the multiple possible scenarios that exist for complex systems, which is the case of the problem addressed in this article. The complexity of the interaction between different types of equipment and the dynamics of snowfall do not allow the application of mathematical programming or stochastic methods.

In this study, we applied discrete-event simulation (DES) for modelling mine operation under conditions of snowfall, designed the operation of the mine under complex weather conditions and, then, devised an operational strategy that was subsequently tested against real past snow events. The necessity for DES arose from the fact that alternatives such as algebraic formulas or optimisation models fell short for our purposes because they do not capture the complex interaction between different pieces of equipment, variable precipitation and operational uncertainty, which are the key elements in our study.

Related work

The DES was used to evaluate the performance of open-pit mining systems in many studies. The application of simulation in the mining sector can be traced back to the 1940s [17]. The first application of DES to fleet management can be found in [18], where the Monte Carlo simulation technique was used to solve hauling problems in mining operations.

The DES was applied for evaluating dispatch policies in open-pit mining systems. [19] studied the impact of dispatching rules for assigning trucks and shovels, such as minimizing shovel idle time, maximizing truck use and assigning trucks to shovels to meet specific production objectives. [20] also studied the impact of several dispatching rules, such as fixed trucks, maximum trucks and maximum loaders. Simulation was used to assist the management of the Aitik mine in decision-making regarding the purchase of new trucks, installation of in-pit crushers and route selection for efficient ore and waste transportation. [2] developed a simulation model to compare different dispatch policies in terms of total production.

Other applications of the DES tool have been reported. [21] discusses the construction of simulation models using a general-purpose simulation system. The authors mention that a separate program has to be written for each system to be simulated as illustrated by three case studies of actual open pit mines located in Australia. [22] illustrates the use of DES for determining the optimum number of trucks in the mine, the number of repair crews and the number of spare trucks required. [23] used a deterministic-stochastic model to compare an automated system with a manual to predict the benefits of an autonomous haulage system. [24] developed a simulator called the open-pit production simulator. They report that artificial intelligent simulators can be very efficient and helpful for modelling the dynamicity of processes and randomness of input parameters.

Although mathematical programming has limitations regarding capturing all the complexities of a mining system, it has been successfully integrated with DES in some studies. For example, [25,26] integrate optimisation and simulation; the optimisation model performs equipment assignment (assigning shovels to extraction polygons and trucks to shovels) and, then, a simulation model evaluates the allocation results. [27] obtained feasible, reliable and accurate short-term mine plans for open-pit operations by integrating simulation and optimisation during the system simulation execution; an optimisation model was used for decision-making in the ongoing simulation. [28] proposed a tool that integrated the simulation of discrete events of a material-handling system in an open-pit mine with a mixed-linear integer programming (MILP) assignment of transport equipment to productive circuits. The objective function of the MILP maximized the expected throughput of the system. [29] offers an excellent review of simulation studies in open-pit and underground mining systems.

In this case study, we are interested in a shovel-truck system whose route conditions dynamically change over time because of snow precipitation. We search for the best operational strategy for this truck-shovel system under these considerations. This is the novelty of this work since most applications of DES consider the uncertainty that is inherent to the system (and not exogenous as in our case) and do not explore how the system should respond to these dynamic changes.

We use the DES to model the material handling system and use it as follows: First, we explore different operational configurations (in particular, fleet); then, we evaluate these configurations to determine the critical snowfall intensity (the maximum value in centimetres per hour of snow that the system can withstand and stay operational). Next, we design an operational policy to address heavy snowfall events; finally, we evaluate this policy against past occurrences of snowfalls.

The remainder of this paper is organized as follows. The next section provides a full description of the truck-shovel mining system integrated with snow removal and simulation model implementation. Thereafter, we describe the case study in which the simulation model was used. Then, we discuss the obtained results. Finally, we present the conclusions of this work.

Mining system description

In this section, we briefly describe the truck-shovel system that is to be evaluated under standard and snowfall conditions.

Under the standard condition, i.e. when there is no snowfall, the system follows the usual truck-shovel operation. The system layout considers the loading points, destination and travel routes and a truck shop. Load equipment charges material from a loading point onto the trucks, which haul the material through travel routes to the primary crusher. Then, the empty trucks return to the shovel to be loaded again. Route intersections are zones where two or more routes join, causing other equipment to stop or yield transit. Whenever a truck fails or needs maintenance, it goes to the truck shop. Whenever a load equipment fails or needs maintenance, it stays at the loading point, and no trucks are loaded until the appropriate repair or maintenance operation is completed. The truck that was assigned to an unavailable shovel is reallocated to another operative shovel or put in reserve, depending on the operation configuration.

Under snowfall conditions, snow accumulates along the routes and intersections depending on the actual intensity of the snowfall, preventing their utilization if the accumulated reaches certain a critical height. Thus, the production operation is interrupted. To avoid this scenario, additional equipment (snow-pushers and snow-melters) is introduced to perform a snow removal operation, which is performed simultaneously with production. A snow-pusher (Figure 1a) is a front-end-loader coupled with a pusher at its front and is used to collect snow from the travelling routes and carry it to snow-collection points. A snow-melter (Figure 1b) is a static piece of equipment located at each of the snow collection points and is used for melting the accumulated snow. Because of the integrated operation of the truck-shovel with the snow removal operation, the trucks and snow-pushers travel simultaneously along the routes, creating complex interactions between the two operations.

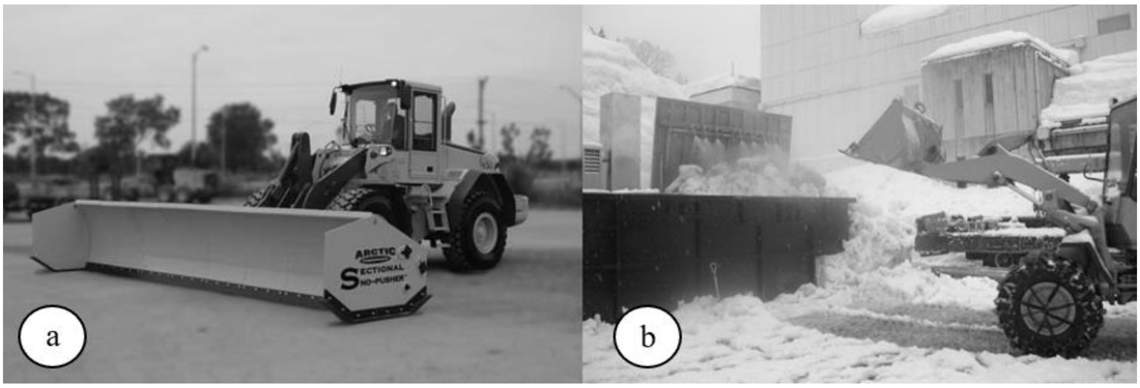


Figure 1. (a) Snow-pusher and (b) snow-melter

Materials and Methods

We adopted the following methodology and employed DES to identify the best operational strategy for the truck-shovel system under heavy snowfall.

- We developed a DES model that emulates the truck-shovel production with simultaneous snow removal operation in an open-pit mine.
- We used the DES model to simulate different strategies (Full production, full snow removal and production and snow removal) and operational configurations (layout, type and quantity of equipment).
- For each of the defined configurations, we ran the DES model to estimate the critical snowfall intensity, which is the maximum snowfall (in centimetres per hour) that the system can withstand and stay operational.
- We designed an operational policy that defines how to carry out the operation depending on snowfall intensity.
- Finally, we validated the operational policy against past occurrences of snowfall.

Simulation modelling

We developed the simulation model using DSim (DELPHOS Mine Planning Lab) [30], discrete event simulation software. DSim is DES software used to simulate mine systems, such as material-handling systems in open pit mines and production and preparation in underground mines. It is coded in Python® [31] using a specific simulation library called SimPy® [32]. This software implements a set of functions that allow easily defining a layout and modelling of movement of equipment; several agents (trucks, shovels, etc.) that can be used as is or extended to model more complex situations and reports that are customized to mine operations (e.g. cycle times and production).

The main simulation objects to be considered in the simulation model are described below (quantitative information is provided in the case study section).

- **Loading point**: The location where trucks are loaded with material by the loading equipment
- **Dumping point**: The location where production material is unloaded from the truck
- **Mining truck**: The mobile equipment that transports ore from a loading point to a dumping point; whenever some load equipment is unavailable, the simulation model reallocates the operative trucks to the remaining load equipment depending on the maximum number of trucks that can be assigned to each load equipment. For example, in a mine system with three loading points and a fleet of six trucks, when all the trucks and loading equipment are in production, two trucks are allocated to each of the three pieces of load equipment (i.e. three shovels). When one of these three is unavailable and when the maximum number of trucks per circuit is set to three, the trucks that were assigned to the unavailable shovel are reassigned to the remaining two available production circuits. Thus, three trucks are assigned to the remaining two productive circuits. Instead, when the maximum number of trucks is set to two, the two trucks assigned originally to the unavailable shovel are put in reserve and not allocated to the remaining operative circuit.

- **Load equipment**: The equipment that loads the material from the loading points onto the truck.
- **Route**: The path along which the trucks and snow-pushers travel; snow accumulates on the route depending on the actual snowfall intensity, and when a snow-pusher circulates over the route, the snow is removed
- **Route intersection**: The points where two or more routes join, causing other equipment to stop or yield transit; snow is accumulated at intersections depending on the actual snowfall intensity and is removed by snow-pushers
- **Truck shop**: The locations where trucks are maintained and repaired; trucks placed in reserve are parked at this place
- **Primary crusher**: Crushes the ore unloaded at dumping points
- **Snowfall**: Models the intensity of the snow accumulated on the transportation routes; the snowfall intensity (in centimetres per hour) can vary over time.
- **Snow-pusher**: A front-end-loader coupled with a pusher in the front; pushes snow out of the transportation routes and into snow-collection points. The maximum capacity of snow volume that can be pushed is based on the dimensions of the pusher (width and height); this equipment does not fail nor needs maintenance, because it is used during snowfall events only. A snow-pusher needs to clean the left and right sides of the route to completely remove the snow from the route because the road width is twice the width of the snow-pusher. Snow-pushers cannot change the side of the route that they are currently cleaning.
- **Snow-collecting point**: The location where the snow swept by the snow pushers is accumulated
- **Snow-melter**: Static equipment located at the snow-collecting points to melt the accumulated snow

Figure 2 shows the locations of the aforementioned elements in an open-pit layout.

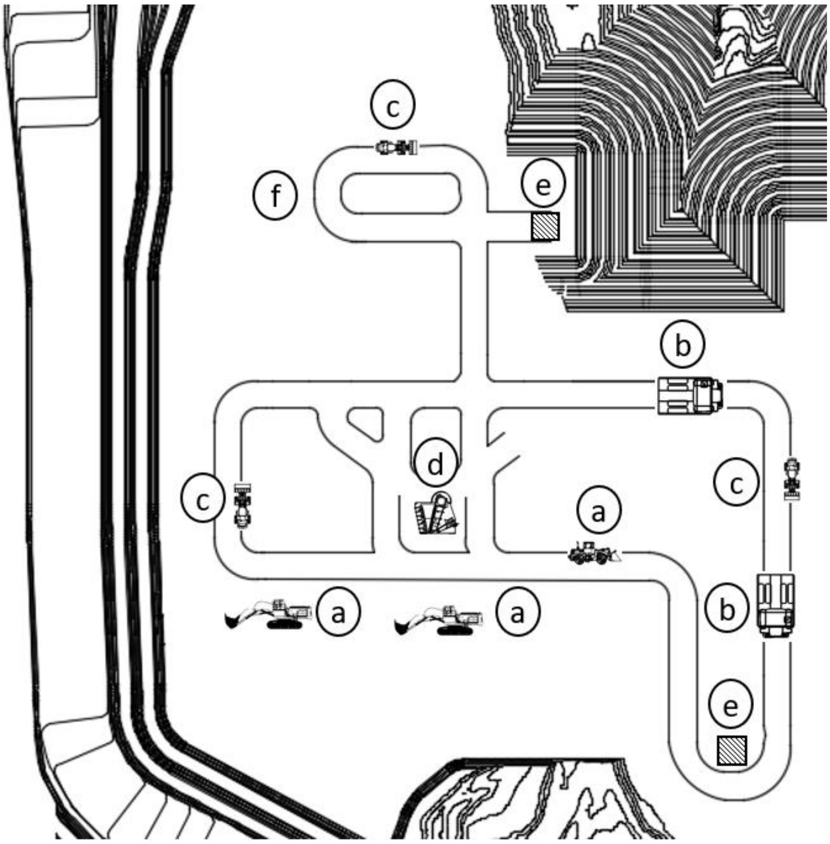


Figure 2: Isometric view of the simulated layout with the main simulation elements: (a) Loading point, (b) mining truck, (c) snow-pusher (d) crusher, (e) snow-collecting point and (f) truck shop

Operational strategies and configurations

We consider three different *operational strategies* in the simulation process. The full production strategy (P) refers to the scenario when only the production operation is carried out. Similarly, the full snow removal strategy (R) corresponds to the scenario when only the snow removal operation is carried out. Finally, the production and snow removal strategy (P&R) corresponds to the scenario when production and snow removal are carried out simultaneously.

Furthermore, an operational configuration defines completely the way in which the production and snow removal operation are carried out. In production configurations, we specify the type and location of load equipment at the loading points, the maximum number of trucks that can be allocated to the load equipment and the number of trucks. In snow removal configurations, we establish the location of the snow-melters, the number of snowpushers and the snow removal circuit of each snow-pusher.

Given the above definitions, each operational strategy may be carried out by following an operational policy, which selects a configuration to adapt the system to the operational state and, in particular, the weather conditions.

Production and critical precipitation

In our study, we considered two main indicators to evaluate these configurations: production and precipitation intensity. Production is estimated as the average tonnage of material delivered to the crusher, obtained over the replications run for each simulated scenario. The critical precipitation intensity of a certain operation configuration is the snowfall intensity [cm/h] should meet the following snow capacity constraints over all the replications, at each moment in time (hence, the criterion is very conservative):

- The total snow carried by each snow-pusher at each collection point must be less than or equal to its capacity.
- The height of the snow layer at each point along the transport routes must not exceed the critical height throughout the time horizon.
- The amount of snow carried per hour at each collection point must not exceed the melting capacity of the snow-melter.

Then, the critical precipitation capacity was obtained by the following procedure:

(1) We selected a snowfall intensity ρ, which corresponds to the maximum historical value of the snowfall intensity.

(2) We simulated several replications for the actual snowfall intensity ρ.

(3) If in all the replications, the snow capacity constraints were met, ρ was reported as the critical precipitation intensity, and the procedure is completed.

(4) We reduced the actual snowfall intensity by a small amount and went back to step 2.

Design and validation of operational policies

An operational policy defines the way in which production and snow removal are carried out depending on the snowfall intensity. We used the evaluated configurations, production and critical precipitation to propose several policies. Then, these policies were evaluated and validated under real historical snowfall events.

Case study

The case study corresponds to a real truck-shovel mining system located 3,500 m above sea level. This system combines truck-shovel production with snow removal operations when heavy snowing conditions arise.

The production operation uses trucks that are loaded with ore from three loading points (FC_STS_O, FC_STS_E y FC_STE) by the loading equipment (three pieces) that may be either front-end-loaders (F) or hydraulic shovels (H). Then, the load trucks travel on the transport routes to the primary crusher (CR), where they discharge ore at one of the two dumping points available (FD_O, FD_E). Thereafter, the empty trucks travel along the travel routes to one loading point to be reloaded.

We consider two load equipment configurations, one with two front-end-loaders and one shovel (FHF) and the other with one loader and two shovels (FHH) (Table 1). For each load equipment configuration (FHF and FHH), there are three production circuits, each defined by one loading and dumping point and one piece of load equipment. Two to three trucks can be allocated to each production circuit. In all, the truck fleet has six trucks.

Table 1. FHH configuration (1 Front-end loader and 2 hydraulic shovels)

Loading equipment configuration	**Load point**	**Loading equipment**	**Dump point**
FHH	FC_STS_O	Front-end-loader (F)	FD_O
	FC_STS_E	Hydraulic shovel (H)	FD_E
	FC_STE	Hydraulic shovel (H)	FD_E
FHF	FC_STS_O	Front-end-loader (F)	FD_O
	FC_STS_E	Hydraulic shovel (H)	FD_E
	FC_STE	Front-end loader (F)	FD_E

In the two above-mentioned load equipment configurations, snow removal operation is carried out by three snow-pushers that clear snow from the travel routes up to the two snow collection points PA_N and PA_S. Figures 3 and 4 show both load equipment configurations, FHH and FHF, together with the closed cycles of layout and snow-pushers.

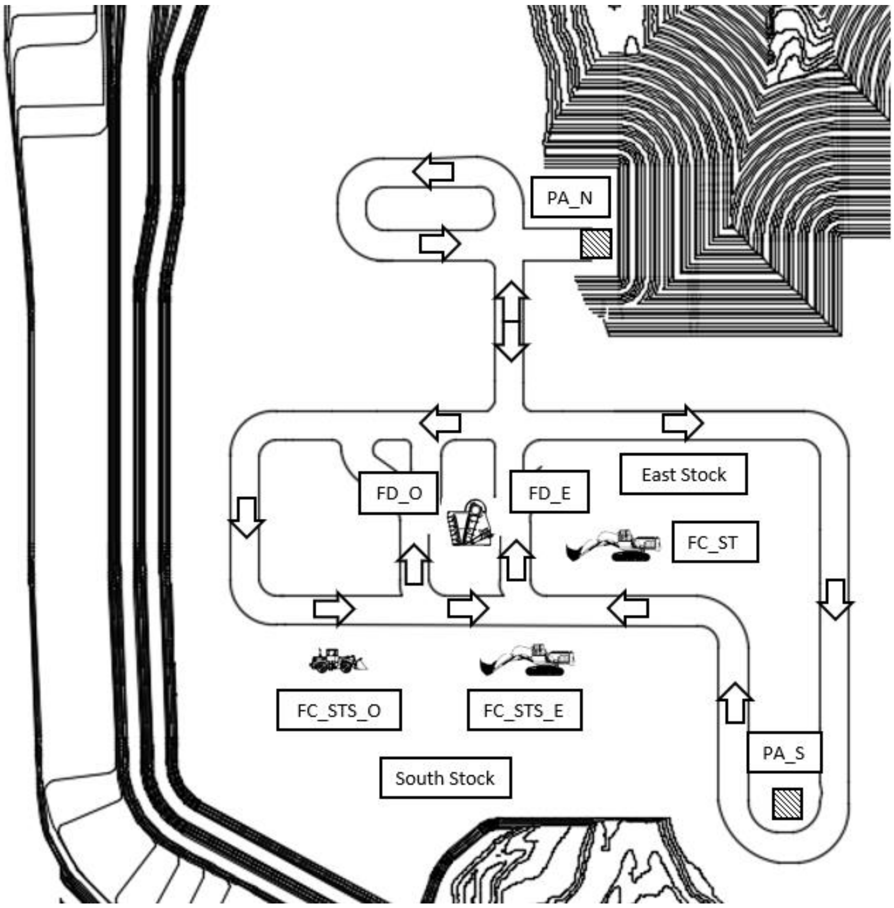


Figure 3. Layout and route directions of the FHH loading equipment configuration (one front-end loader and two shovels).

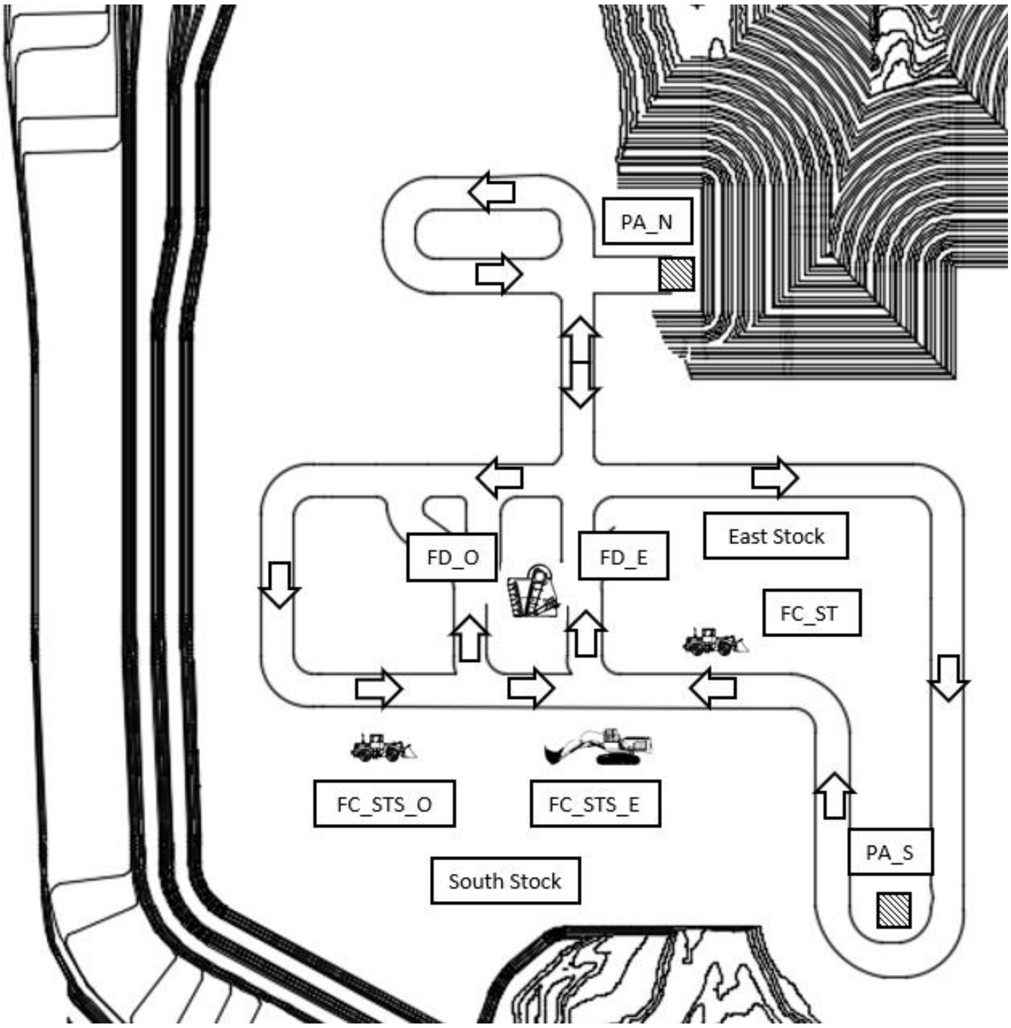


Figure 4. Layout and route directions of the FHF loading equipment configuration (two front-end-loaders and one shovel).

The operational parameters were modelled using probability density functions that consider the intrinsic variability of the operational parameters in a real mining operation. Each of the functions was adjusted based on data from a real mining operation using StatFit ® [33] and based on weather conditions—with snowfall (SF) or without snowfall (WS). Table 2 lists the means of the operational parameters of the mining equipment that performed the production operation. Tables 3 and 4 present the probability density distributions of the mining equipment. In Tables 3 and 4, $\boldsymbol{W}(\alpha, \beta)$ represents a Weibull distribution; $\boldsymbol{T}(a, b, c)$, a triangular distribution; $\boldsymbol{N}(\mu, \sigma)$, a normal distribution and $\boldsymbol{U}(a, b)$, a uniform distribution.

Table 2. Equipment parameters

Parameter / Condition	**Without snowfall (WS)**		**With snowfall (SF)**	
	Front-End-Loader (F)	**Hydraulic Shovel (H)**	**Front-End-Loader (F)**	**Hydraulic Shovel (H)**
Load time [min]	5,65	4,85	7,65	6,85
Spotting time for loading [min]	0,67	0,5	1,84	1,37
Dump Time [min]	0,58		0,58	
Spotting time for dumping [min]	0,42		1,71	
Truck payload [t]	285	285	285	285
Truck velocity [km/h]	12	12	10	10
Crusher capacity [ktpd]	180		180	

Table 3: Probability density distribution of equipment parameters without snowfall (WS)

Parameter / Condition	Loading equipment	
	Front-End-Loader (F)	Hydraulic Shovel (H)
Load time [min]	$2.82 + 12.1 \cdot \left(\frac{1}{1 + exp\left(-\frac{(\boldsymbol{N}(0,1) - 2.19)}{2.17}\right)}\right) - 0.49$	$2.82 + 12.1 \cdot \left(\frac{1}{1 + exp\left(-\frac{(\boldsymbol{N}(0,1) - 2.19)}{2.17}\right)}\right) - 1.29$
Spotting time for loading [min]	$-0.365 + 1.12 \cdot \left(\frac{1}{\left(\frac{1}{\boldsymbol{U}(0,1)} - 1\right)}\right)^{\frac{1}{4.64}} - 2.24$	$-0.365 + 1.12 \cdot \left(\frac{1}{\left(\frac{1}{\boldsymbol{U}(0,1)} - 1\right)}\right)^{\frac{1}{4.64}} - 2.207$
Dump time [min]	$\boldsymbol{T}(0.533,0.583,0.633)$	
Spotting time for dumping [min]	$-1.2 + \left(\frac{1}{0.443}\right) \cdot \left(-\log\left(\boldsymbol{U}(0,1)\right)\right)^{-\frac{1}{11.9}} - 1.60$	
Truck payload [t]	$\mathbf{W}(328,14.2) - 31.2$	
Truck velocity [km/h]	$\boldsymbol{T}(10.2,12.1,13.8)$	
Crusher capacity [ktpd]	180.0	

Table 4: Probability density distribution of equipment parameters with snowfall (SF)

Parameter / Condition	Loading equipment	
	Front-End-Loader (F)	Hydraulic Shovel (H)
Load time [min]	$2.82 + 12.1 \cdot \left(\frac{1}{1 + exp\left(- \frac{(\boldsymbol{N}(0,1) - 2.19)}{2.17} \right)} \right) + 1.51$	$2.82 + 12.1 \cdot \left(\frac{1}{1 + exp\left(- \frac{(\boldsymbol{N}(0,1) - 2.19)}{2.17} \right)} \right) + 0.71$
Spotting time for loading [min]	$-0.365 + 1.12 \cdot \left(\frac{1}{\left(\frac{1}{\boldsymbol{U}(0,1)} - 1 \right)} \right)^{\frac{1}{4.64}} + 0.27$	$-0.365 + 1.12 \cdot \left(\frac{1}{\left(\frac{1}{\boldsymbol{U}(0,1)} - 1 \right)} \right)^{\frac{1}{4.64}} - 0.2$
Dump time [min]	$\boldsymbol{T}(0.533, 0.583, 0.633)$	
Spotting time for dumping [min]	$-1.2 + \left(\frac{1}{0.443} \right) \cdot \left(-\log(\boldsymbol{U}(0,1)) \right)^{-\frac{1}{11.9}} - 2.89$	
Truck payload [t]	$\mathbf{W}(328, 14.2) - 31.2$	
Truck velocity [km/h]	$\boldsymbol{T}(10.2,12.1,13.8)$	
Crusher capacity [ktpd]	180.0	

Table 5 lists the utilization (the ratio of effective time and nominal time) values of the production equipment, and Table 6 presents the operational parameters of the snow-pusher fleet.

Table 5. Utilization values of production equipment

Equipment	**Winter (WI)**	**Summer (SU)**
Mining truck	54.50%	69.10%
Front-end-loader	51.40%	60.90%
Hydraulic shovel	58.60%	69.30%

Table 6. Snow-pusher parameters

Parameter	Value
Capacity [m³]	43.4
Width [m]	9.2
Height [m]	1.52
Velocity [km/h]	10
Snow dumping time [min]	0.33

For snow removal operation, the capacity of the snow-melter is 1171.0 m^3/h, and the maximum height of the snow layer is 10.0 mm.

The full production (P), full snow removal ® and production and snow removal strategies (P&R) were evaluated under four possible weather conditions: summer without snowing (SU_WS), summer with snowfall (SU_SF), winter without snowing (SI_WS) and winter with snowfall (WI_SF) to measure both the impact of operational parameters and weather conditions on the production.

All the simulations have a time horizon of one day (24 h), performing a total of 100 replications per simulation. This number was calibrated in such a way that the estimated production accumulated averages were stable.

Results

In this section we present the numerical results obtained from the experiments. The results are divided into two categories. First, we present the results for understanding the behaviour of the system for different operational strategies; the base case is defined in terms of productivity and critical precipitation. Second, we present the results related to the designed operational policies and their testing against past snowing events. A discussion on all these results is presented in the following section.

Operational strategies results

Figure 5 shows the results for the full production strategy. Tables 7 and 8 present the results for the full removal strategy.

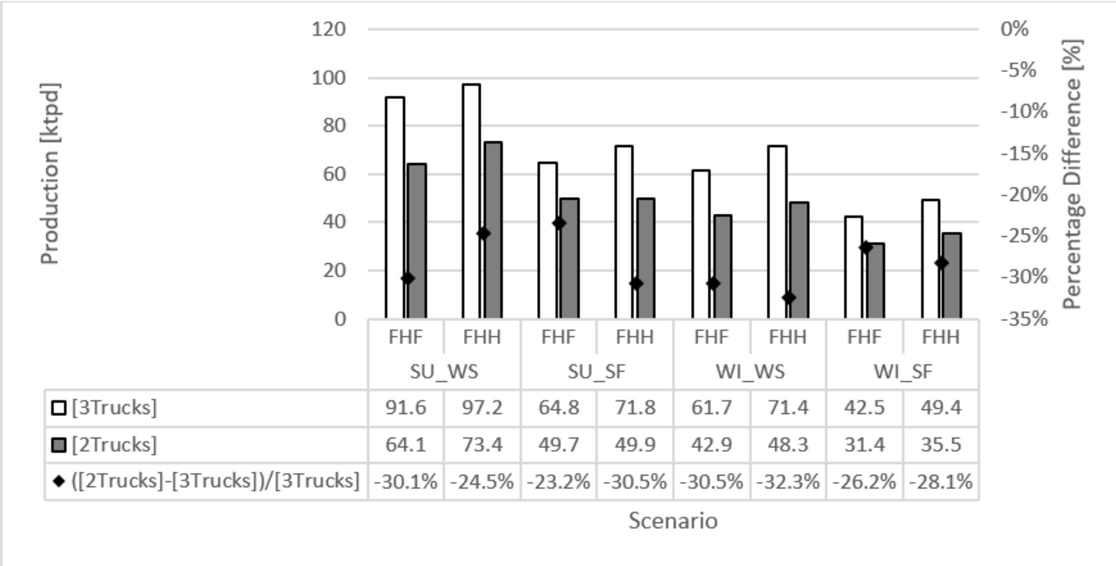


Figure 5. Production assessment in the full production strategy for loading equipment configurations (FHF—with two front-end-loaders and one shovel; FHH—with one loader and two shovels) for all weather scenarios: summer (SU), winter (WI), without snowfall (WS) and with snowfall (SF).

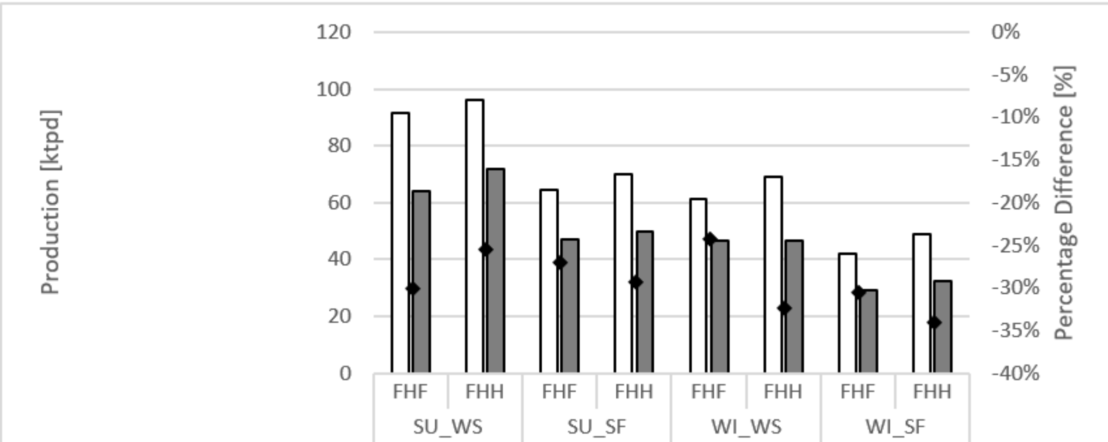
Table 7. Snow height and snow-pusher capacity utilization versus required limits.

Snow-pusher	Snow collection points	Maximum height of snow layer [cm]	Maximum snow volume pushed per cycle [m^3]
SP_01	**PA_S**	2,13	18,51
SP_01	**PA_N**	1,97	34,37
SP_02	**PA_S**	2,23	23,18
SP_02	**PA_N**	2,05	37,60
SP_03	**PA_N**	4,94	41,81
Maximum		4,94	41,81
Required limits		10,0	43,40

Table 8. Snow-melter throughput in Full Snow Removal strategy

Snow collection point	**Maximum amount of melted snow [m³/h]**
PA_S	229.0
PA_N	789.0
Snow-melter capacity [m³/h]	1171.0

We now present the results of combined production and snow removal operations to compare against the reference strategies over the 16 simulated scenarios wherein the production and the snow removal are operated simultaneously (Figures 6 and 7).



	FHF	FHH	FHF	FHH	FHF	FHH	FHF	FHH
	SU_WS		SU_SF		WI_WS		WI_SF	
[3Trucks]	91.36	96.15	64.4	70.11	61.26	69.08	42.2	48.89
[2Trucks]	64	71.8	47	49.7	46.4	46.7	29.3	32.3
([2Trucks]-[3Trucks])/[3Trucks]	-29.9%	-25.3%	-27.0%	-29.1%	-24.3%	-32.4%	-30.6%	-33.9%

Figure 6. Production assessment under the production and snow removal strategy, for loading equipment configurations ((FHF—with two front-end-loaders and one shovel; FHH—with one loader and two shovels)) for all weather scenarios: summer (SU), winter (WI), without snowfall (WS) and with snowfall (SF).

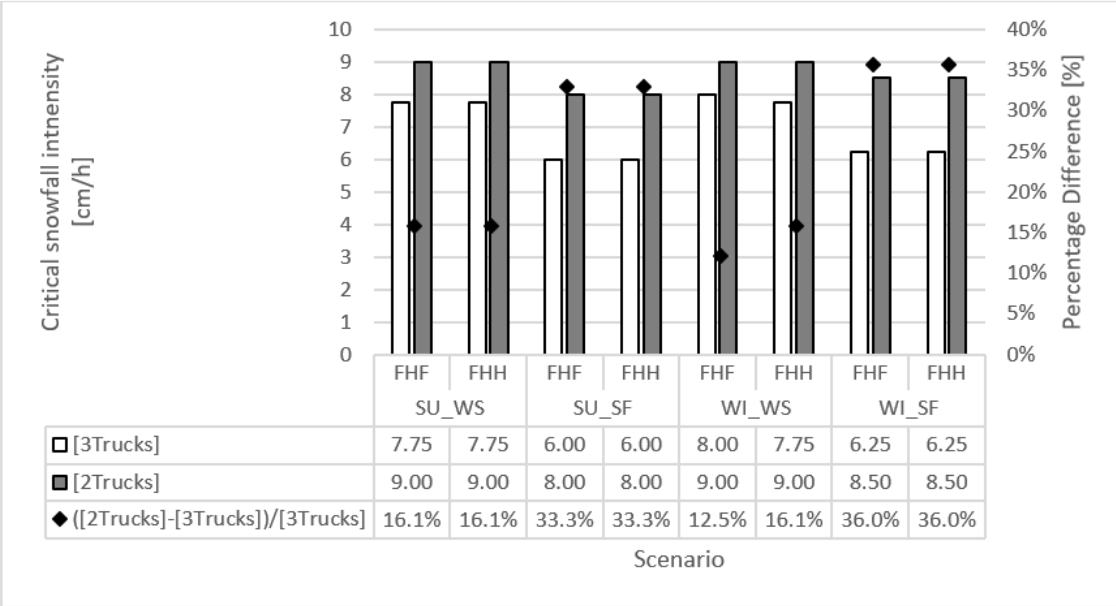


Figure 7. Critical snowfall intensity under the production and snow removal strategy

Finally, we compared the production between the full production strategy and production and snow removal strategy (Figures 8 and 9).

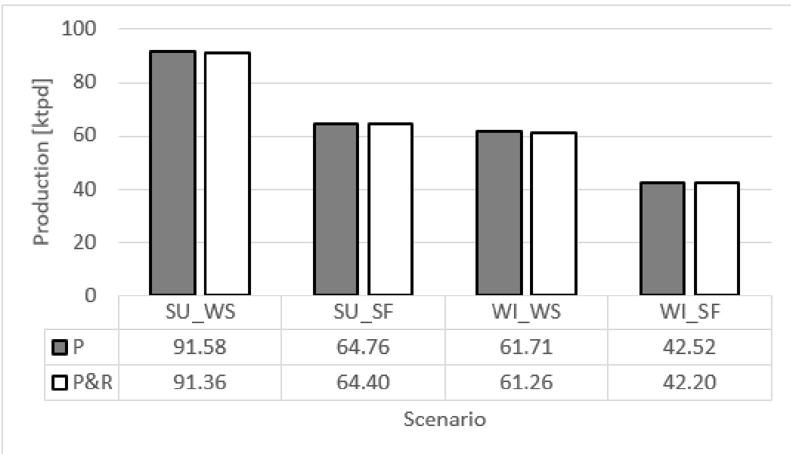


Figure 8. Comparison between the production strategy and production and removal strategy in the FHF (two front-end-loaders and one shovel) load equipment configuration

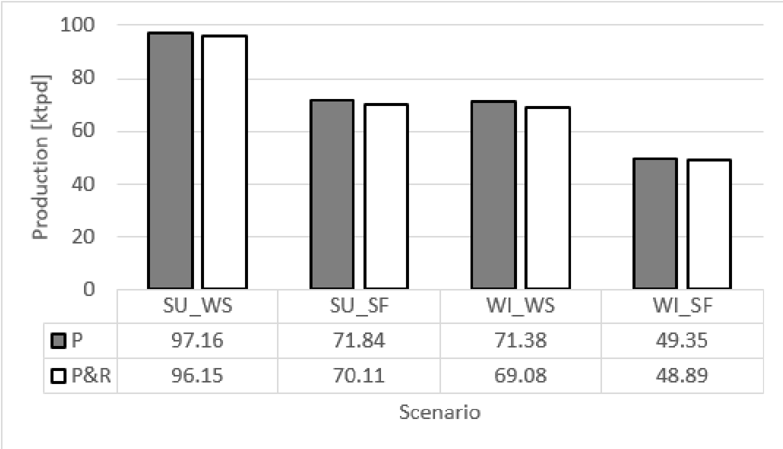


Figure 9. Comparison between the production strategy and production and removal strategy in the FHH (with one loader and two shovels) configuration

Design of an operational policy for production and snow removal during snowing events

We analysed the results for different operation strategies and configurations to devise an operational policy for operating the mine under heavy snowfall conditions. Here since this configuration exhibited higher productivity levels, we limit ourselves to the case of winter conditions and the FHH configuration.

The policies to be compared are as follows:

- **Base operational policy (OP1):** This corresponds to the current operation in which production and removal operation are carried out simultaneously when snowfall intensities are lower than 4.0 cm/h; however, the production completely stops when the snowfall intensity exceeds this value.
- **Full fleet operational policy (OP2):** The results provided in the previous section indicate that for snowfall intensities less than 6.25 cm/h, the system can operate under the production and snow removal strategy with a maximum of three trucks per circuit.

Therefore, for this policy, production occurs until this threshold is reached, and from that point until a snowfall intensity of 9.75 cm/h, operation is limited to snow removal strategy only (with the hope that this will reduce the re-starting time later). At snowfall intensities exceeding 9.75 cm/h, there is a complete shutdown of both production and snow removal operations.

- **Flexible fleet operational policy (OP3):** This policy is based on the observation that when the precipitation intensity exceeds 6.25 cm/h, the system may still be operational with fewer trucks. Therefore, in this operational strategy, we allow production to continue up to a precipitation level of 8.50 cm/h. While snow removal continues up to an intensity of 9.75 cm/h, all operations are halted beyond this value.

Note that while OP1 and OP2 were envisioned by the mine operators, OP3 became apparent as an alternative only when simulations showed that production affected snow removal. This effect could be mitigated by reducing the number of trucks, hence allowing operations to continue at a lower level of production. Furthermore, it is important to mention that these operational policies can be used only as a guide in practise, in the sense that the actual rules are applied by observing the saturation of the limiting capacity (snow-pushers) and not precipitation level, which is difficult to measure.

Evaluation of operational policies under past snowing scenarios

The operational policies described above were tested against four historical events regarded as high snowfall event. Table 9 lists the results in terms of average productivity and gains.

Table 9. Comparison of production corresponding to different operational policies

Snowfall Event	Production [ktpd]			Relative percentage increment		
	OP1	OP2	OP3	(OP2-OP1)/OP1	(OP3-OP2)/OP2	(OP3-OP1)/OP1
E1	38.63	40.67	40.67	5%	0%	5%
E2	24.40	36.60	40.64	50%	11%	67%
E3	0.00	0.00	2.69	-	-	-
E4	8.13	10.17	12.86	25%	26%	58%

While the actual benefits depend on the event, the results show that there is a consistent benefit in using OP2 over OP1 and in using OP3 over OP2, averaging an increase of 32.5% in production when considering the benefits of OP3 over OP1.

Figure 10 shows the performance of the three operational policies for event E2 in terms of production for each of the 24 h of the event. The performance of the operational policy OP2 during snow event E2 is simulated. For each hour, the precipitation of the E2 snow event and the critical precipitation of the OP2 policy are shown.

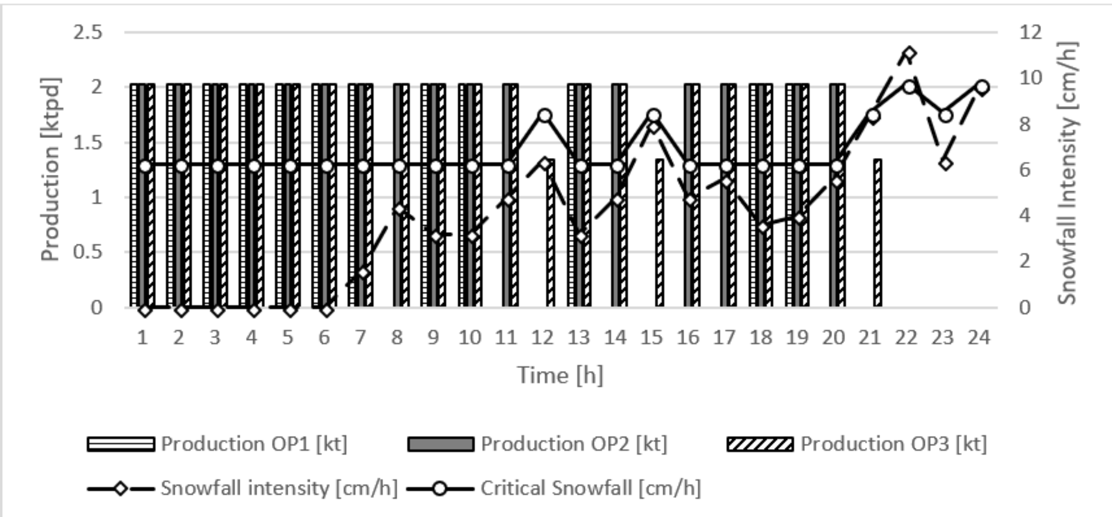


Figure 10. Production corresponding to different operational policies under snowfall event E2

Discussion

Full production strategy (P)

When considering only the production operation, the simulations show that the scenarios that use one front-end-loader and two hydraulic shovels (FHH) achieved higher production than the ones in which two front-end-loaders and one hydraulic shovel (FHF) were used; this result was expected considering the higher throughput of a shovel compared to a front-end-loader (Figure 5). For instance, in the scenarios with snowfall operational parameters (SF) and winter utilizations (WI), the production increases by 13% (4.1 ktpd) and 16% (6.8 ktpd) in the scenarios where two and three maximum trucks per circuit, respectively.

Similarly, and as expected, in scenarios with a maximum of three trucks per circuit, the production was higher than that in the scenarios with a maximum of two trucks per circuit (Figure 5). For example, in the scenarios with SF and WI, the production increased by 26% (11.1 ktpd) for FHF and 28% (13.9 ktpd) for FHH.

Full snow removal strategy (R)

When the system is set only for snow removal operation, the simulations predict a critical snowfall intensity of 9.75 cm/h, where the limiting restriction is imposed by the capacity of the snow-pushers, which is reached at this precipitation level. At this snowfall intensity, the maximum height of the snow layer is 4.94 mm, which is lower than the critical height of the snow layer—10 mm (Tables 7 and 8). However, here we recall that the critical precipitation is a very conservative value since the above must be attained in all the replications.

Production and snow route removal strategy (P&R)

Consequent with the Full production strategy, the FHH configuration consistently reaches higher levels of production than the FHF configuration (Figure 6).

The main result for the P & R strategy is that the snow-cleaning operation can be affected by the production, but surprisingly, the opposite is not true.

In terms of critical precipitation, when compared to the full snow removal strategy, in the P & R strategy, the critical precipitation is less than 9 cm/h (reduced from 9.75 cm/h) for two-truck scenarios. This effect intensifies when three trucks are allowed (Figure 7); in this case, the system cannot withstand snowfall levels greater than 8 cm/h because the loading faces have a maximum capacity of two trucks. The additional third truck must wait to be loaded on the transportation route, blocking the passing of snow-pushers and other trucks. Indeed, scenarios with a maximum of three trucks per circuit had larger productions and lower critical snowfall intensities than the scenarios with a maximum of two trucks per circuit.

The difference in production between the scenarios operated under the production strategy and under the production and snow route removal strategy is negligible (Figures 8 and 9), meaning that the snow removal operation does not affect production. This also means that the operational losses for trucks are explained by the waiting times at the loading and dumping points and by the parking, loading and dumping operations but not by on-route interference.

Design of an operational policy for production and snow removal during snowing events

The data in Table 9 indicate that while the actual benefits depend on the event, there is a consistent benefit in using OP2 over OP1 and in using OP3 over OP2. The average increase in production is 32.5% when considering the benefits of OP3 over OP1. This is very significant not only because the increment production is relevant, but also because OP3 was not envisioned before the first results of the study were available. Thus, the benefit of using DES for designing the operational policy is evident.

Conclusions

Snowfall events can result in the stopping of production operations in an operation. Therefore, mine planners and operators must devise operational policies that allow the minimisation of the effects of such events.

We demonstrated the application of discrete event simulation (DES) to devise such an operational policy for the scenario of snowfall affecting a high-altitude mining operation where production and snow removal operations may be conducted simultaneously to keep the mine operating for as long as possible. First, we studied the behaviour of the system in terms of productivity and the critical precipitation that can be handled for different configurations of loading equipment and fleet utilization. Using these data, we designed an operational policy for the mine depending on snowfall. Finally, we tested the policy against real historical scenarios.

The analysis of production and precipitation for the mine layout revealed several aspects important to mine operators:

- The expectation that higher-throughput loading equipment help realize better production levels for all the evaluated conditions was validated; the production levels were quantified.
- The capability of the system to manage snow precipitation was estimated under different configurations, and the capacity of the snow-pushers was identified as the limiting resource.
- While production may not be significantly affected by snow removal, the opposite holds true.

These observations allow us to devise different operational policies, and in particular, to consider a partial retreat of the truck fleet (which was not envisioned before the study) in order to continue production operations for longer periods of time. Indeed, this policy shows a significant potential increase of 32.5% in productivity for the case study when evaluated considering historical snowing events.

The outcomes of the work presented in this paper show the importance and the impact of techniques such as the DES on the design of the mining system with respect to the form of transportation routes, number of loading points and types of load equipment assigned to these points. Finally, the application of the DES demonstrates its capability to evaluate the operation of a highly complex truck-shovel open-pit mine system simultaneously with a snow removal operation.

Acknowledgments

The authors acknowledge CODELCO for sharing data and their valuable contribution in this work. They also express they gratitude to Nicholas Barrentine and Enrique Jélvez for his support in the revision of this document. This work is part of a PhD research, which was supported by the Advanced Mining Technology Center and the CONICYT Basal Project under Grant FB0809.

Disclosure statement

No potential conflicts of interest were reported by the authors.

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