Discrete Event Simulation Modelling versus TKM Analysis of a Mine Operating with a Hybrid Material Movement Practice Consisting of Truck Haulage and Skipping

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Abstract

The work in this paper describes the theory, development and analysis of a computer model simulating a mine operation moving material using concurrent decline ramp truck haulage and skipping practices. This simulation was designed specifically to assess the performance of the truck haulage component and to expand on the scope and capabilities of traditional TKM fleet calculations. Haulage fleet simulation results were similar to TKM calculations for the lower to moderate production rate cases. However, comparisons of ramp-up and high production rate scenarios indicated that the simulation model was significantly more sensitive to operating practices and factors not accounted for by calculations derived when using a single TKM figure. Given the proper calibration of inputs and logic, the simulation model was additionally capable of providing information associated with general mine operations efficiency. Further benefits of the simulation model over a TKM approach included logistical assessments such as production schedule feasibility, productivity trade-off quantifications for proposed operating practices, and the validation of mine resource utilization scheduling. The simulation model was able to expand on traditional methods to approach planning and logistics by considering factors such as truck queuing, real-time traffic interactions, random events, and competition for resources on mine productivity.

Biography

Kris Shelswell is a Simulation Specialist working for Labrecque Technologies Inc., specializing in creating simulation models for both surface and underground mining operations. He has a Ph.D. in Microbiology and Immunology from the University of British Columbia, with a focus on population dynamics, complex interactions, and data management. His experience is in discrete event simulation to plan for future expansions, evaluate mine design options, assess operational logistics, and identify process bottlenecks.

Introduction

Mine planning is a key operational factor driven by the design, logistics, operations, and productivity of all mines. Traditional planning techniques include spreadsheet-based approaches that use static values and isolated mine components to predict the returns from operational practices and overall mine operations. The current suite of software tools available for mine planning expand on traditional principles by considering the effects of multiple mine aspects at once, accounting for interaction factors that evaluate the operation as a whole rather than from the viewpoint of each isolated system. The Rockwell Automation Arena® software provides a modular programming platform to model dynamic interactions which allows for a flexible approach to the creation of discrete simulations.

Material movement methods for sub-surface mining operations

One of the key downstream logistical hurdles for any underground mining operation is how to efficiently transfer production and development material to surface. Typical material transfer methods include rail haulage networks, conveyor assemblies, truck haulage fleets, and shaft hoisting. While the transfer process used to move material to surface in underground mining operations is influenced by the size of the operation, it is primarily driven by the overall mine design and the access method used to reach the sub-surface reserves. The access method used for sub-surface mining can be used to group operations into three basic classes: a) drift operations with horizontal access methods, b) slope operations with inclined access methods, and c) shaft operations with vertical access methods. Conveyors, haulage trains, and truck haulage perform well in the long horizontal tunnels of drift access mines, but haulage trains are not well-suited to accesses with inclines greater than 2-4% and a conveyor system is more economical for operations with transfer distances greater than one kilometer (Filas, 2002). While conveyors and truck haulage are appropriate for inclined access operations, typical conveyors are limited to inclines of no more than 15-20% (with specialized conveyor assemblies available for slopes up to 70-80%). Conveyor belt systems are not ideal for turning corners and are most appropriate for long linear runs (Pathak, 2011). Truck haulage is suited for inclined access operations to steep orebodies that generally require an access ramp, although shaft hoisting becomes more effective at depths greater than 350-500 meters, and shaft hoisting is the most appropriate recourse for moving material to surface vertically in shaft operations (de la Verne, 2003).

Sub-surface material movement at Young-Davidson Mine

The current Young-Davidson Mine sub-surface mine design follows a steeply dipping orebody along an inclined access ramp with a gradient of up to 17% for approximately 5 kilometers to a depth of around 800 meters. To accommodate this design, the underground at Young-Davidson will be a hybrid operation consisting of an inclined truck access haulage ramp working concurrently with twin vertical shafts; the MCM and Northgate shafts. The MCM shaft is intended primarily for the movement of personnel and materials while the Northgate shaft is designed for ore and waste skipping from midshaft and shaft bottom loading pockets. This paper compares the truck haulage fleet requirements estimated for the projected quarterly development-production schedule derived from tonne-kilometer (TKM) calculations and discrete simulations with an Arena® model. Analysis revealed that estimated TKM truck fleet estimates diverged from truck fleets estimated by the Arena® model under ramp-up and high production rate scenarios because historically-based TKM calculations do not adequately account for changing operational factors included in the simulation model. Sensitivity of the simulation to operating practices not addressed by traditional calculation methods allowed the value of the model to extend beyond truck haulage fleet requirements. The Arena® model was also used to test the feasibility of alternate production-development schedules, predict resource utilization, and perform trade-off analyses on operating practices.

Fleet Requirement Calculations, Model Logic, and Simulation Analysis

TKM fleet requirement calculations

Tonne-kilometre (TKM) calculations provide a fundamental approach to determining fleet requirements for trucking operations. The basic TKM calculation was used to evaluate the haulage demand over a specific distance (Przhedetsky, 2010). The fundamental TKM unit was derived by multiplying the amount (t) of material to be moved during a defined period of operation by the 1-way distance (km) of the haul cycle for that material [a modified TKM unit can be derived by accounting for the round trip distance of the haul cycle] (see Eq. 1). The TKM unit was then factored by the average cycle speed (km/hr) to generate a time-based function (see Eq. 2), and modified to reflect the average payload (t/truck) of the haulage fleet (see Eq. 3). The available truck hours (hrs.) of the defined period of operation were then used to determine the fundamental truck capacity and consequent fleet requirements to meet the target production (see Eq. 5).

$$TKM = (t_a)(km_a) + (t_b)(km_b) + (t_c)(km_c) + (t_d)(km_d) + \cdots \qquad \textbf{Eq. 1}$$

$$Tonnes\ Hours\ (TH) = \left(\frac{TKM_a}{{}^{km}/_{hr_a}}\right) + \left(\frac{TKM_b}{{}^{km}/_{hr_b}}\right) + \left(\frac{TKM_c}{{}^{km}/_{hr_c}}\right) + \left(\frac{TKM_d}{{}^{km}/_{hr_d}}\right) + \cdots \qquad \textbf{Eq. 2}$$

$$Total\ Truck\ Hours\ (TTH) = \left(\frac{TH_a}{{}^{t}/_{truck_a}}\right) + \left(\frac{TH_b}{{}^{t}/_{truck_b}}\right) + \left(\frac{TH_c}{{}^{t}/_{truck_c}}\right) + \cdots \qquad \textbf{Eq. 3}$$

$$Traffic\ Truck\ Hours = (TTH) + \left[\left(\frac{TH_a}{{}^{t}/_{truck_a}}\right)(delay_a) + \left(\frac{TH_b}{{}^{t}/_{truck_b}}\right)(delay_b) + \cdots\right] \qquad \textbf{Eq. 4}$$

$$Fleet\ Requirement = \left(\frac{Traffic\ Truck\ Hours}{(hrs.)(avail.)}\right) \qquad \textbf{Eq. 5}$$

Basic TKM calculations focus on truck properties and must be modified to reflect site operations. Additional site-specific factors must be added to the calculation to determine the effects of mine factors such as the average duration of traffic delays per kilometer (delay [in hr/km]) and haulage truck availability (avail.) on TKM-derived truck productivity (see Eq. 2 and Eq. 4, respectively). The TKM approach employed for the study used a historically-derived TKM value considered to be representative of changing conditions in the future.

Arena® simulation fleet requirement calculations

Simulations were carried out to determine the haulage truck fleet size required to meet the proposed quarterly schedule targets for ramp-up and steady-state production operations. Model analysis factored the effects of quarterly schedule profiles, ramp traffic, and resource competition (the use of mine components such as loadouts or tip sites by multiple trucks) on truck utilization to determine fleet trucking capacities and mine productivity. The maximum truck utilization was capped to reflect the operating conditions expected on site.

Simulated truck fleets were deemed to have met the quarterly schedule requirements if the average daily truck productivity met, exceeded, or was within 150 tonnes of the scheduled daily target and the average truck utilization did not exceed the maximum threshold of 5,100 engine operating hours per year. For simulations that failed to meet the quarterly schedule requirements within the model constraints, fleet size was optimized by plotting diminishing returns (Hirschey, 2009) to determine the saturation point for ramp traffic and resource competition.

Arena® simulation model boundaries

The simulation was limited to haulage activity on the main access ramp and midshaft level. Production and development activities were not explicitly modelled, and it was assumed that material was efficiently transferred to the muck bays servicing the truck haulage portion of the operation. Similarly, rehandling activities were not modelled for material transfer to the skips and from surface stockpiles.

The upstream boundary of the simulation was the daily scheduling of production and development material to transfer nodes throughout the mine. The transfer nodes represented mine level loadouts and midshaft level passes for ore and waste where the haulage trucks acquired payloads. The downstream boundaries of the simulation were the dumping of material at/in ore and waste stockpiles. The ore and waste stockpiles consisted of separate surface stockpiles for ore and waste trucked out the portal, separate midshaft level ore and waste stockpiles servicing the midshaft loading pocket, and separate shaft bottom ore and waste stockpiles servicing the shaft bottom loading pocket.

Arena® simulation scheduling and haulage truck dispatch

Development and production schedules were used to determine the total tonnes of material to be trucked during each quarter. Ore and waste calls were scheduled to loading nodes at the beginning of each day. Loading nodes represented truck loadouts at mine levels or orepasses and wastepasses servicing material movement at the midshaft and shaft bottom levels. Ore and waste tonnes were scheduled additively, such that daily calls were combined with any material scheduled from previous days but not yet trucked from that node. Production and development activities were indirectly simulated with the scheduling of material for haulage. Quarterly targets were converted to daily values by converting the total quarterly tonnes of ore and waste for each node into average daily targets (1/91st). A triangular distribution with a limit of ±25% (Robinson, 2004) was then applied to the average ore and waste targets for each level during the scheduling period to generate daily variability.

Haulage trucks were dispatched to mine levels designated as active if there was a Load-Haul-Dump Vehicle (LHD) present to load trucks. The number of LHDs available to load trucks varied based on the quarterly schedule profile. LHDs were dispatched to mine levels if the loadouts had ore or waste scheduled for haulage by the ramp trucks. Each loadout had separate ore and waste stockpiles with material further designated for the midshaft raises, to surface, or to sub-surface tip points feeding shaft loading pockets. Material scheduled for loading from the midshaft raises was transferred automatically to these raises from the daily call of the corresponding mine level. Truck payloads were dispatched from the loadout stockpile or raise with the largest quantity of material.

Arena® simulation haulage truck availability

Haulage truck availability was modelled dynamically throughout simulation by using discretely modelled variables (Robinson, 2004) for shift seat-time, planned maintenance, refueling, and unplanned maintenance (random breakdowns). Maintenance was carried out underground if the truck was at or below the midshaft level and the underground maintenance shop was available (dictated by mine and ramp development). Otherwise, all trucks were sent to surface for maintenance activities. Fuel depots were located at the portal on surface and in the shop underground. Both depots each had one pump so queues were established if multiple trucks arrived concurrently to refuel at either depot.

Shift availability was modelled based on seat-time data collected from site. Pre- and post-shift downtime accounted for events such as safety meetings, personnel movement, lineups, equipment checks, and blasts. Planned maintenance was staggered evenly between the trucks based on the frequency of the maintenance regime and the haulage fleet size. An average service delay was taken by each truck for the duration of the planned maintenance event. Refueling availability was sampled from a uniform distribution (Forbes *et. al.*, 2011) to randomly stagger truck refuelling activity throughout a window in the final third of each shift. The duration of refuelling was modelled as an average delay calculated from data acquired on site. The unplanned maintenance availability was modelled as a mean time between failure

(MTBF) and mean time to repair (MTTR) using a triangular distribution (Forbes *et. al.*, 2011) that sampled a min/mode/max function (Onyango and Plews, 1987) generated from random breakdown industry benchmarking data. A midshaft LHD was specifically modelled to transfer material from the midshaft level wastepass to the midshaft waste stockpile. The midshaft LHD availability was modelled with a similar availability to that of the haulage trucks (see above).

Arena® simulation haulage truck and light vehicle traffic interactions

Dynamic traffic interactions between mine vehicles were simulated by discretely modelling the movement of both the haulage trucks and the service vehicles. Service vehicles included a) equipment travelling from surface such as scissor lifts, lube/fuel trucks, crane trucks, personnel carriers and light vehicles, and b) production and development equipment travelling between levels such as LHDs, jumbos, bolters, secondary breaking rigs, and service vehicles. The fleet sizes and average daily number of trips made for each type of service vehicle were estimated based on the quarterly production and development profiles provided for the simulation. The frequency of daily service vehicle dispatching was randomized by using a uniform distribution (Forbes *et. al.*, 2011) that sampled a range centered on the average number of trips per day with a maximum deviation of ±0.5 fold (Onyango and Plews, 1987). Service vehicle dispatching was limited to mine levels scheduled for production and development activity during the simulated quarter to ensure traffic was localized to the appropriate areas of the mine.

Right of way logic was designed to regulate underground traffic by limiting passing along the access ramp and midshaft level to prevent vehicles from travelling along the same ramp section in opposite directions. To mimic the traffic behaviour on site, the access ramp and midshaft level were respectively separated into segments that spanned the distance between consecutive mine levels and midshaft service drifts. The upper ramp consisted of long decline segments with passing bays, and traffic priority was given to haulage trucks travelling between levels in the upper ramp. Traffic priority in the lower ramp and across the midshaft level was given to the vehicle already in transit on that segment of the roadway. Movement along each segment was restricted to one direction at any time, although vehicles could convoy along any roadway segment in the same direction. Passing activity was limited to along the access ramp and midshaft level at passing bay and mine level pullouts. Light vehicles were allowed to exit at either pullout while haulage trucks were only permitted to pull off at mine levels.

Discussion

A dynamic truck haulage model was developed to estimate the haulage truck fleet requirement for the quarterly mine waste and ore development-production planned for the sub-surface Young-Davidson operation. The simulation was further used to model the feasibility of alternate steady-state production levels by evaluating the haulage truck fleets required to meet those scenarios. These results were compared to traditional tonne-kilometer (TKM) calculations to quantify the sensitivity of the model to operational practices on site.

Comparisons of TKM-calculated and simulation-derived truck haulage fleet requirements

The quarterly haulage fleet requirement was determined for three separate schedule profiles; a base case schedule for the currently proposed operations and two elevated steady-state production rates. The two higher production rate schedules were designed to increase steady-state ore production by 1.3 and 1.6 fold with respect to the base case. The ramp-up period was extended in the higher production rate schedules to meet the 1.3 and 1.6 fold steady-state targets (see Figure 1). The amount of light vehicles and mine equipment travelling throughout the mine was increased accordingly to support the elevated production and development activities for the 1.3 and 1.6 fold scenarios.

Fleet requirements determined by TKM calculations and the model were similar for the base case scenarios. The simulation fleet requirements differed from the TKM calculations by only one truck in ~28% (ten of the final 28 quarters) of the ramp-up and steady-state periods (see Figure 1). Discrepancies in fleet requirement were scattered mainly through the steady-state production periods for the base case comparisons, whereas fleet requirement discrepancies for the 1.3 and 1.6 fold comparisons were also evident in the early and middle stages of the ramp-up period. When the schedules changed to the 1.3 fold mine production rate, a larger discrepancy between fleet requirements calculated using TKMs and simulation results was observed. Fleet requirement calculations differed for ~42% (15 of 36 quarters) of the scenarios; with nine of the 15 (60%) quarters exceeding the TKM calculated fleet requirement by more than one truck (see Figure 1). The majority of the fleet requirement discrepancies were noted in the early steady-state period. Comparisons of TKM and simulation fleet sizes reported significant discrepancies in fleet requirements for the 1.6 fold scenario. The increased quarterly fleet requirement predicted by the model varied between one and eight trucks in 58% (21 of 36 quarters) of the scenarios. Differences in fleet requirement calculations were noted across most areas of the schedule profile including early ramp-up, late ramp-up, and throughout the steady-state periods (see Figure 1).

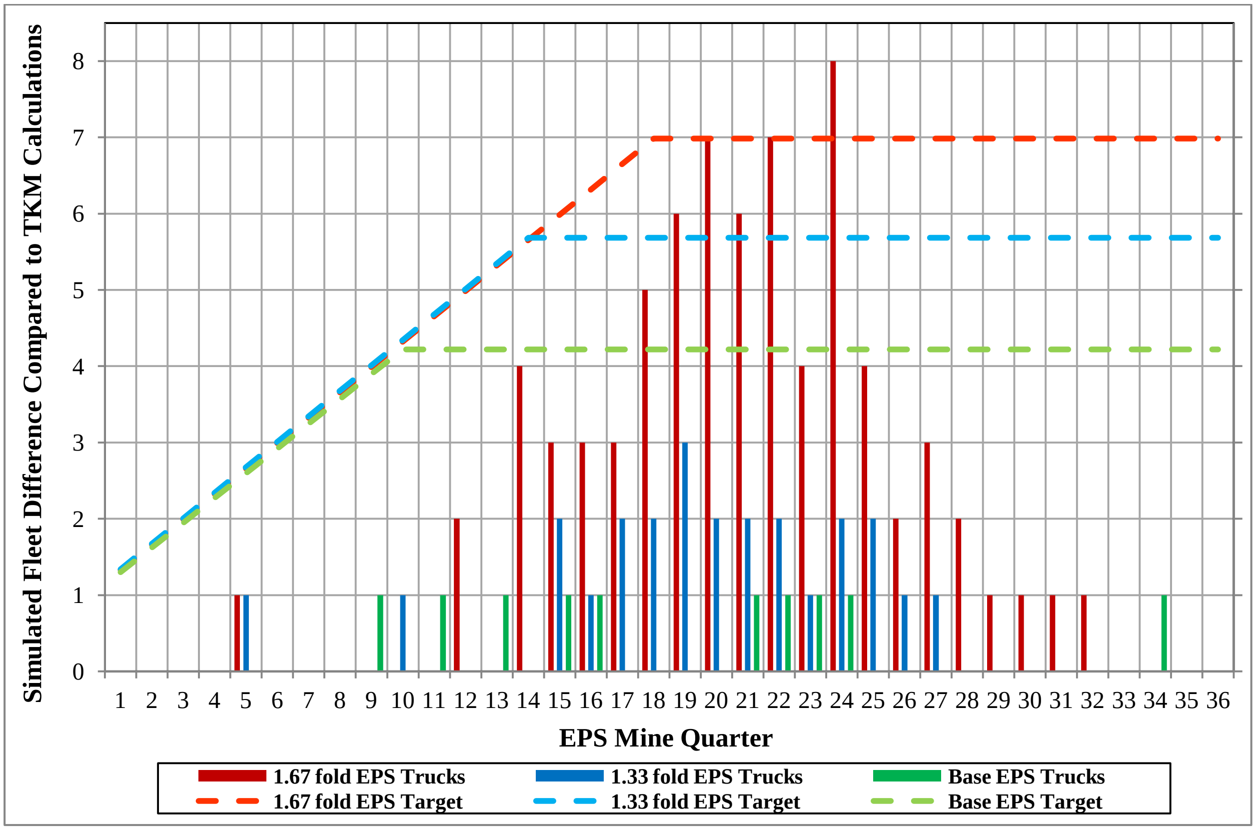

Figure 1: Quarterly simulation-derived truck requirements compared to TKM-derived fleet calculations. (green) base case targets and related fleet requirements; (blue) 1.3 fold targets and related fleet requirements; (red) 1.6 fold targets and related fleet requirements. Bars represent the fleet difference in the number of trucks required to meet the schedule targets from simulation runs versus TKM calculations. Dashed lines represent the ramp-up and steady-state schedule profiles for the base case, 1.3 fold, and 1.6 fold schedule targets plotted on a secondary axis (not shown).

Simulation model sensitivity to truck haulage activity

The TKM calculations do not account for the compound effects of additional trucks on haulage activities, whereas the discrete simulation approach dynamically modelled the effects of the feedback loop created by increasing the truck fleet. The simulation indicated that the fleet size feedback loop was associated with traffic and resource competition. Analysis of the traffic-related trucking delays from the base case schedule highlighted the greater sensitivity of the simulation model (see Figure 2).

The increase in fleet size for quarters 9, 13, 15, and 16 were the product of pronounced traffic delays resulting from haul distances and dump dispatching (see Figure 2). Longer hauls equated to more ramp traffic events, while the localization of all dumping at the midshaft further increased traffic delays due to congestion in the midshaft haulage drift. Quarters 11, and 21 through 24 required an additional truck with marginal traffic delays; indicating that truck efficiency was reduced by both traffic and resource completion (see Figure 2). Haulage efficiency was partly reduced by traffic generated by consolidating active mine areas. Haul distances were not particularly long, but the localization of haulage activity resulted in ramp congestion. Haulage of material only to the midshaft further decreased haulage efficiency by increasing truck queue delays at the tip site (resource competition). Quarter 34 reported decreased truck efficiency with only marginal traffic delays (see Figure 2). Haulage activity was centralized in the lower mine region but the scheduling distribution did not generate any significant ramp traffic. Haulage efficiency was reduced by an increased queuing of trucks for muck transfer at loadouts and tip sites (resource competition) not accounted for with the TKM calculations; due to a historic (actual) TKM value being used to estimate future fleet requirements.

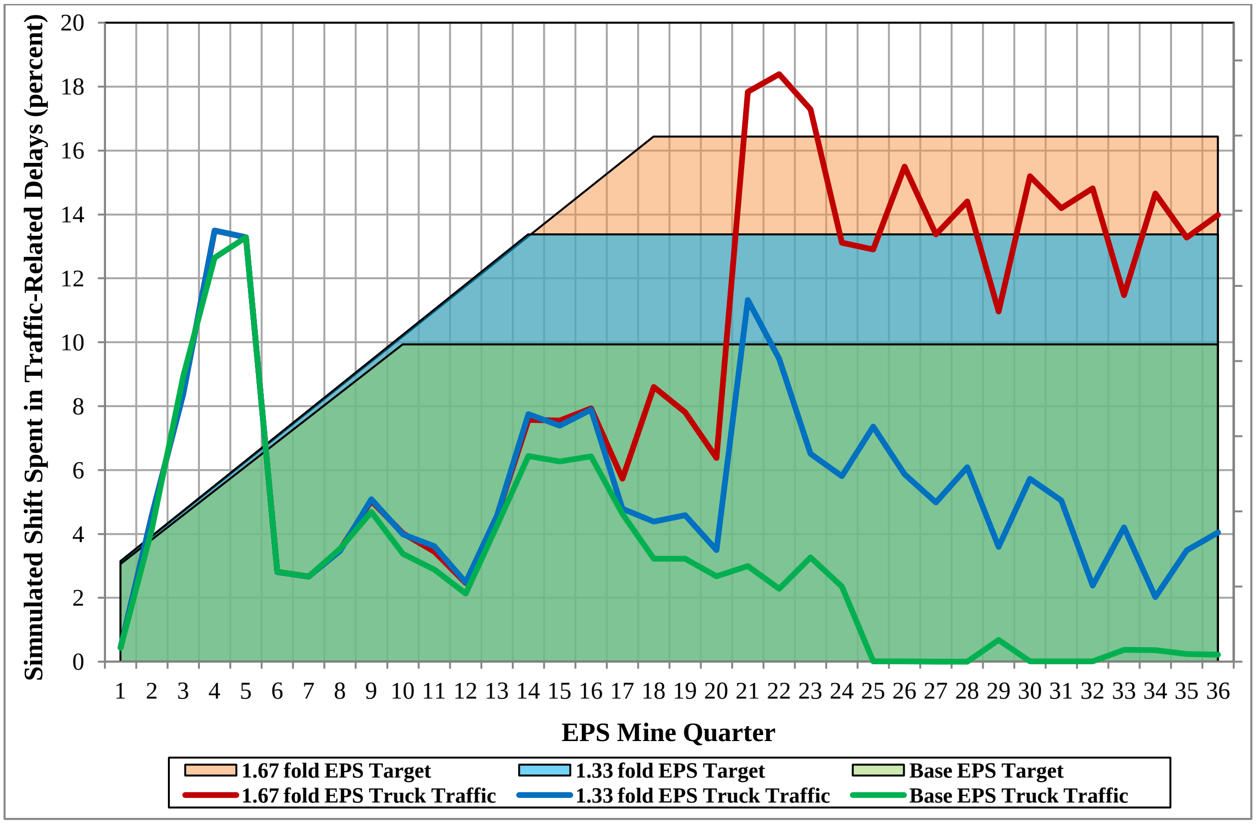

Figure 2: Quarterly average traffic-related haulage traffic delays derived from data for truck fleet requirement simulations. (green) base case targets and related fleet traffic; (blue) 1.3 fold targets and related fleet traffic; (red) 1.6 fold targets and related fleet traffic. Solid lines represent the simulated average percentage of each shift spent by haulage trucks in traffic-related delays. Area graphs represent the ramp-up and steady-state schedule profiles for the base case, 1.3 fold, and 1.6 fold schedule targets plotted on a secondary axis (not shown).

Similar patterns were observed when comparing fleet discrepancies between the base case, 1.3, and 1.6 fold schedules. Increased fleet requirements associated with a minimal increase in traffic delays relative to the base case were attributed to increased resource competition by trucks for loading and dumping activity (see quarter 5, Figure 1 and Figure 2). Quarters with significantly higher traffic delays and increased fleet requirements were attributed to increased haul distances and traffic congestion from the consolidation of active mine areas (see quarter 24, Figure 1 and Figure 2). Alternatively, some increases in fleet requirements were the product of a moderate increase in traffic delays and increased resource competition (see quarter 15 and 17, Figure 1 and Figure 2).

Assessments of operational constraints affecting haulage truck efficiency

Operational practices on site often affect the efficiency of haulage trucks, which can in turn influence the overall mine productivity. The hybrid nature of the material movement operations was particularly sensitive to dumpsite (or destination) dispatching because the haulage trucks were used to move material both to surface and to the shaft stockpiles. The fleet efficiency was also affected by both the amount and distribution of material scheduled throughout the mine. Cemented rock and paste backfill techniques have different distribution systems so the model was also used to quantify the effect of the backfill technique on fleet requirements.

The model simulated skipping from the midshaft or shaft bottom loading pockets based on the state of mine development. The ramp-up and early steady-state quarters used midshaft skipping, while later steady-state quarters used shaft bottom skipping which coincided with increased lower mine production and development activities. Material from loadouts below the midshaft level was trucked to either the midshaft skip stockpiles or to surface during quarters with midshaft skipping. However, when skipping switched to the shaft bottom most material from below the midshaft level was trucked to raises at the midshaft and throughout the lower mine area for transfer to shaft bottom. Simulation analysis indicated that bringing the changeover period for shaft bottom skipping forward by four quarters decreased traffic-related truck utilization by 0.8 to 12.1%, which was associated with a concurrent reduction in the haulage truck fleet (see Table 1). These decreases were the product of shorter haul cycles, fewer ramp traffic events, and decreased tip site queuing when material from the lower mine was skipped from the shaft bottom.

Table 1: Difference in haulage truck fleet requirement and traffic-related truck haulage delays associated with an earlier changeover from midshaft to shaft bottom skipping, and changing from cemented-rock backfill practices to paste backfill.

Simulated Quarter	Shaft Bottom Skipping Fleet Reduction	Shaft Bottom Skipping Traffic-Related Delay Reduction (%)	Paste Backfill Fleet Reduction	Paste Backfill Traffic-Related Delay Reduction (%)
Quarter 24	0	0.8	3	0.5
Quarter 25	6	12.1	5	5.1
Quarter 26	4	8.3	4	6.4
Quarter 27	5	11.5	6	4.5
Quarter 28	1	2.5	6	6.8

Cemented rock backfill scheduling often employs schedule profiles with concentrated mining activity due to the smaller stope size and shorter backfilling time, whereas paste backfill schedule profiles generally segregate work areas to accommodate larger stopes and longer backfilling times. Segregating work areas can reduce traffic congestion by spreading the haulage fleet across mine areas and ramp segments. Results were shown for quarters 24 through 28 to demonstrate the compound effect of the shaft bottom skipping practice and the paste backfill scheduling. The paste backfill schedule further reduced the simulated haulage fleet requirement by three to six trucks, while reducing the associated haulage-related traffic by 0.5 to 6.8% (see Table 1). The increased haulage fleet efficiency was primarily associated with a reduction in resource competition. The increased segregation of active mine areas translated to decreased truck queuing delays both at the mine level loadouts and truck tip points.

Conclusions

Analysis indicated that TKM calculations were suitable for static trucking operations with low to moderate production targets and modest fleet sizes, while TKM fleet calculations were less than those estimated by the simulation under ramp-up and high production rate scenarios. This was attributed to several factors included in the simulation but not accounted for in the TKM calculations. The additional operational factors accounted for by the discrete simulation approach provided sensitivity to potential constraints in the proposed quarterly schedules, and the dynamic nature of the model further increased the sensitivity by providing input from feedback loops on haulage truck efficiency.

The simulation approach demonstrated the capacity of the mine to move the scheduled material under low, moderate, and high production rate targets with a range of fleet sizes by modelling trucking activity in context with other critical operational factors. Several potential operational constraints not evident in TKM calculations were highlighted by the simulation. Analysis of the simulation data allowed for the characterization of these constraints and the identification of mitigation strategies to optimize mine performance with respect to schedule targets, truck fleet requirements, and operational practices.

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