# DISCRETE SIMULATIONS QUANTIFYING THE EFFECTS OF MATERIAL HANDLING CONVEYORS IN SERIES OR PARALLEL OREFLOW STREAMS

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## Abstract

This work describes the design, analysis, and comparison of discrete simulation and static spreadsheet models developed to compare the oreflow efficiency of two conveyor-based material handling systems; one approach with a conveyor stream in series and one with parallel conveyor streams. Analysis and comparison indicated that daily rates were significantly affected by random conveyor failures in both designs. The compound effect of random failures limited the effectiveness of long belt assemblies in series, while the parallel conveyor stream design partially alleviated this constraint. The static spreadsheet model predicted a lower average daily oreflow rate for the series conveyor stream design and a higher average daily oreflow rate for the design with parallel conveyor streams when compared to the discrete simulation results. These discrepancies were the product of model sensitivity to operational factors incorporated in the system and provided the opportunity to further use the discrete simulation models for trade-off comparisons and sensitivity breakdowns of mine operating practices and material handling system efficiencies in both the series and parallel belt stream designs

## Introduction

A fundamental aspect of an efficient mining operation is the steady movement of material throughout the mine system; particularly the flow of muck from the upstream excavation point to the downstream processing or stockpile site(s). The material handling approach used for a mining operation is dependent on factors such as the orebody geometry, target production rates, the general mine layout, and the scale of the operation. These material handling methods may include mobile transfer systems such as haulage fleets or fixed transfer systems such as shaft hoisting, rail haulage networks, and conveyor systems. Mobile transfer systems are well-suited for low to moderate production rate targets in mine designs with small defined areas or sprawling orebodies that dictate multiple segregated work areas. Fixed conveyors systems are ideal for moderate to high production rate targets from long life of mine plans or mine designs with orebodies that allow for operations to be localized in centralized work areas for long periods of time.

Mobile truck or scoop based haulage and fixed train haulage networks are inherently batched processes with competition for resources such as drift or ramp access, whereas conveyors offer the potential for an uninterrupted material handling stream from a dedicated oreflow infrastructure. While requiring a substantial capital expenditure, conveyors are considered to be the most efficient means of material handling along inclines with slopes between 4% and 20% (Pathak, 2011) when the transfer distance is more than one kilometer (Filas, 2002). However, the key to conveyor efficiency is downstream oreflow availability, and the availability of any conveyor-based material handling system is dependent on the mine design and operating conditions. Site-specific factors such as rock quality and fragmentation, operational resources like maintenance crews, and the design of the conveyor system itself play a large role in determining the material handling availability.

The discrete simulation was modelled to emulate the movement of material from an underground mining operation to surface level stockpiles. The material handling conveyor system was designed to tie the production from a new sub-level work zone into an existing conveyor-based oreflow infrastructure feeding a vertical access shaft (Shelswell *et. al.*, 2013) installation hoisting material to surface. Muck was extracted using a block cave simulation by LHDs and trammed to panel crushers servicing two separate work zones. Feeder conveyors acted as the input point for oreflow from the crushers into conveyor stream linking the expansion to the existing material handling assembly feeding the shaft. A surface conveyor system was also used to transfer muck from the shaft installation to surface stockpiles. Analysis of the material handling system with discrete simulation and static spreadsheet approaches revealed the effects of conveyor availability constraints on oreflow when using a series or parallel conveyor stream design. The discrete simulation model was further used to quantify the effects of operating procedures, operating conditions, and system designs on the efficiency of the conveyor-based material handling oreflow systems.

## Model Boundaries, Model Logic, and Conveyor Availability Calculations

### *Model boundaries*

The upstream boundary used for the study was a discrete simulation of an extraction level for a block cave mine. The block cave model encompassed extraction activities from the drawpoints through the crusher which included; a) daily drawpoint call and shift scheduling, b) LHD dispatch and mucking, c) drawpoint secondary breaking events, d) secondary breaking fleet dispatch and oversize/hangup resolution, e) coarse ore crusher processing, and f) planned maintenance routines and random failure-associated availabilities for extraction level equipment. Development activities, material resupply, and interactions with service and utility equipment were excluded from the discrete extraction level model.

The extraction level simulation was tied directly to the discrete material handling model to feed the conveyor-based oreflow system, whereas the average daily rate predicted by the extraction level simulation was used to define the influx value for the conveyor assembly system of the static spreadsheet model. The downstream boundary of the simulation was the dumping of material from the conveyor system on surface at an ore stockpile. The surface ore stockpile was given an unlimited capacity and imposed no constraints on the material handling system.

### *Arena® simulation conveyor and hoist logic*

The conveyor components of the material handling system were modelled as unique non-accumulating (Rockwell Automation, 2005) belts. Muck in the oreflow system was broken down into packets that moved through system as discrete entities (Robinson, 2004) on the conveyors relative to the position on the belt at which they were deposited. Oreflow was modelled as single tonne muck packets exiting the crusher fine ore bins, surge capacity rock bins, or muck silos onto the belts of the conveyor assembly. Packets in the system occupied a defined portion of the belt corresponding to an area related to the capacity of the conveyor, determined by the specified length and width of each specific conveyor. Packets could only enter a conveyor if the available space was large enough and not already occupied by another entity. Movement of the muck along the conveyors occurred relative to the position at which the material was deposited on the belt at speeds corresponding to the specified rate of each conveyor in the system. Muck packets were moved from the head of each belt assembly to the tail of the conveyor to be transferred either to a downstream belt through a transfer chute or to a rock bin or silo for surge capacity stockpiling. If insufficient space was available for downstream transfer to conveyors or stockpiles once a muck packet reached the end of the belt assembly, the belt stopped until the muck packet at the tail of the conveyor could be transferred further along the oreflow stream.

The hoist was modelled as a parallel conveyance system with dual winders hoisting two in balance skips (Hartman, 1992). The skips from each winder were fed from a dedicated loading pocket (one for each winder) which was filled from parallel conveyor streams using diverters. Hoist operations were carried out such that each winder operated independently to convey skipped muck from a single loading pocket to the corresponding transfer bin under the headgear bin. Muck was not transferred to the skips until there was a full skip payload in the loading pocket. Full skips were not hoisted from the loading pocket unless there was sufficient space in the headgear bin to transfer the full muck payload from the skips. Muck was transferred from the headgear bins by independently modelled feeder conveyors dedicated to either winder stream (see Figure 1).

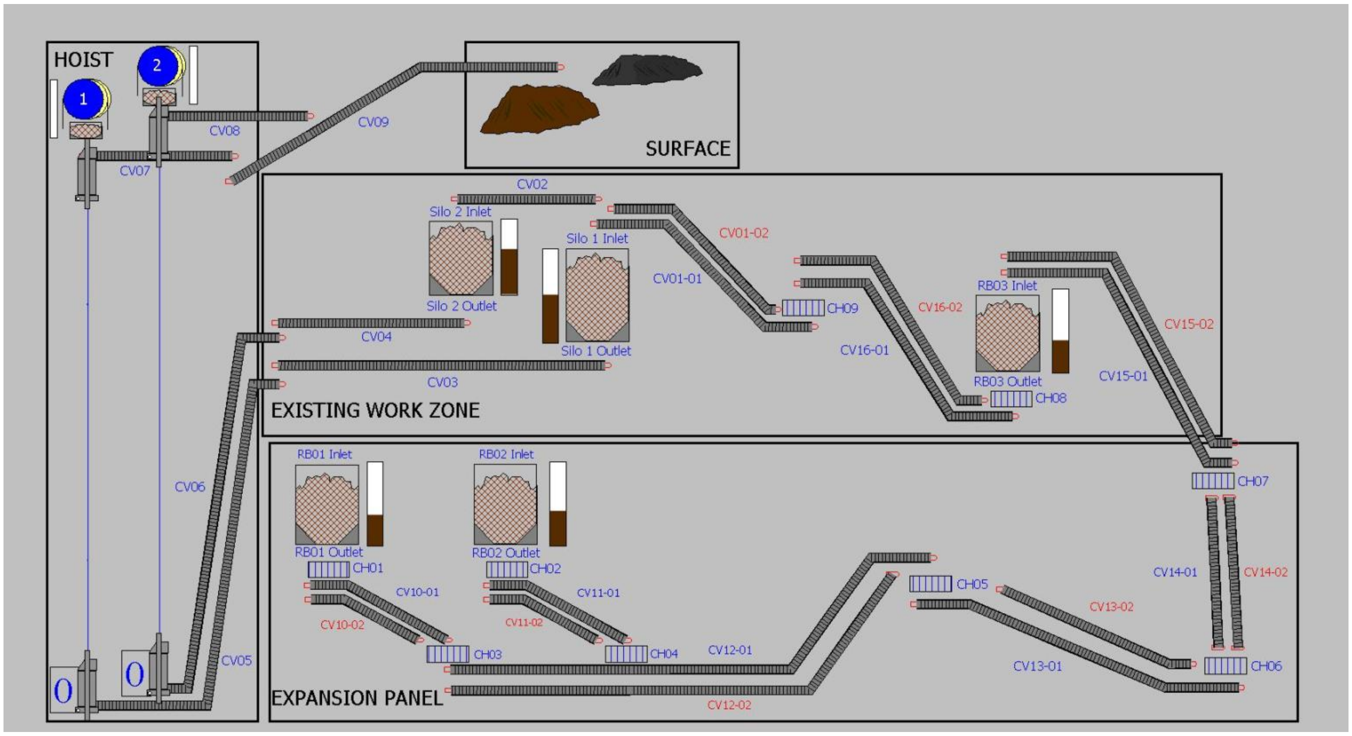


**Figure 1. Conveyor-based material handling layout for the discrete simulation model. Muck entered the system at RB01 and RB02 in the expansion panel from crushers servicing a simulated block cave extraction panel. Muck was transferred by conveyors from the expansion panel to RB03 in the existing work zone where it was tied into the existing infrastructure by feeder conveyor CV16. Material stockpiled in the existing work zone was transferred to the skips by parallel conveyor streams for hoisting to surface. The model was designed to run from either conveyor stream in series or using both conveyor streams in parallel: (blue text) conveyors from the series conveyor assembly design representing the primary oreflow stream; (red text) conveyors added for the parallel conveyor assembly design representing the secondary oreflow stream.**

***Arena® simulation conveyor and hoist availability***

Discrete variables for planned and unplanned (random failure) maintenance (Robinson, 2004) were used to dynamically model the material handling availability. Availabilities were programmed for each individual segment in the system, with scheduled downtime and independent random failures modelled for each conveyor and either hoist winder. Planned maintenance schedules were generated based on industry benchmarking data to simulate conveyor and hoist downtime associated with daily and weekly preventative maintenance routines on the oreflow system. A triangular distribution (Forbes *et. al.*, 2011) was used to sample min/mode/max functions (Anyang and Plows, 1987) to determine the mean time between failure (MTBF) and mean time to repair (MTTR) for both the conveyor and hoist unplanned maintenance.

Maintenance was carried out using a resource-based approach to limit the capacity of work performed during a shift. Each maintenance/repair crew resource was given a fixed capacity such that each crew could only work on one conveyor at a time (Karnon *et. al.*, 2012) and only during the available hours defined by the daily shift schedules. Shift availability was modelled based on a three shift day with pre- and post-shift factors such as safety meetings, personnel travel, equipment inspections, and blasts reducing the workable shift hours (lost shift time). Shift availability was based on industry benchmarking, with lost time resulting in surface and sub-surface availabilities of 95% and 80% of the total shift duration, respectively.

***Ore flow availability calculations***

The static spreadsheet model was used to predict the average daily rate of the material handling system from the crusher fine ore bins through to the surface stockpiles. The design used for the spreadsheet approach mimicked the layout created for the discrete simulation model (see

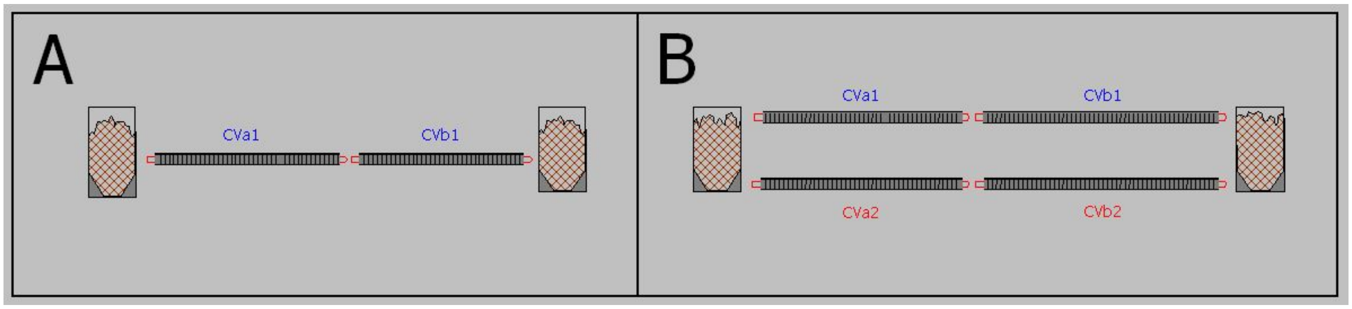


**Figure 2. Oreflow segment designs with material removed from an upstream stockpile by conveyor CVa for transfer to conveyor CVb and deposited in a downstream stockpile. (A) oreflow segment design with a series conveyor stream involving direct transfer from CVa1 to CVa2; (B) oreflow segment design with parallel conveyor streams involving direct transfer either from CVa1 to CVa2 or CVa2 to CVb2.**

Figure 1). The material handling system was subdivided into oreflow segments which were defined by conveyance streams between potential stockpiling points such as rock bins and silos. The unplanned maintenance availability of each oreflow segment was calculated separately based on the conveyor/material handling design of the segment itself (see Figure 2) and the MTBFs and MTTRs of conveyor or hoist components in the oreflow segment.

$$A_s = (A_{CVa1})(A_{CVb1})$$ **Eq. 1**

$$A_p = (1 - [1 - (A_{CVa1})(A_{CVb1})][1 - (A_{CVa2})(A_{CVb2})])$$ **Eq. 2**

Unplanned maintenance (random failure associated) availabilities for each oreflow segment was calculated either as single-failure or compound-failure models (Pham, 2006). Availabilities for oreflow segments with series designs ($A_s$) were treated as single-failure models (see **Error! Reference source not found.**) with the probability that the material handling stream was halted was dependent on the likelihood that at least one component in the oreflow stream was down for unplanned maintenance. Oreflow segments with parallel designs ($A_p$) were treated as compound-failure models (see **Error! Reference source not found.**) with an overall probability that material handling was halted dependent on the likelihood that at least one component in both streams were down for unplanned maintenance simultaneously. The existing work zone infrastructure, the hoist, and the surface conveyors were all treated as parallel oreflow segments, whereas the calculation used for the expansion panel was dependent on the modelling of the material handling as a single series or parallel conveyor design. All of the oreflow segments in the material handling system from the crusher fine ore bins through to the surface stockpile were then combined to predict the overall system availability and average daily production rates for the models.

## Discussion

A discrete simulation model was created to compare the effects of alternate conveyor-based material handling designs on daily oreflow rates from a simulated block cave expansion mine panel. Discrete simulation results were compared to predictions generated using a spreadsheet model in order to quantify the sensitivity of the models to operational practices programmed into the simulations. The two discrete model designs were also compared to each other to quantify the effects of the conveyor designs on daily oreflow rates, and the simulations were used to perform sensitivity analysis to determine the effects of operational practices and conditions on material handling efficiency.

It is understood by the authors that fixed transfer systems such as conveyor assemblies are costly and that a parallel conveyor stream design would require a significant increase in capital expenditure over a conveyor design in series. It should be noted that a cost analysis was not factored in the assessment of the series versus parallel conveyor design analyses for this work, as it remains an exercise specific to the scope of each particular mining operation.

***Comparisons of discrete simulation and static spreadsheet models***

The discrete expansion panel block cave extraction model linked to the material handling conveyor design models was also used to provide the upstream input values for the static spreadsheet modelling. The average daily rate of the stand-alone block cave extraction model was used as the input value for material entering the conveyance stream in the spreadsheet analysis. The spreadsheet approach factored the conveyor stream design, the planned maintenance availability of the scheduled conveyor and hoist downtime, and the unplanned maintenance-associated availability of each component of the oreflow designs to predict the average daily amount of material moved to surface by the material handling system. These values were used to calibrate the discrete model results against predicted oreflow rates. Discrete simulation results for the series and parallel conveyor designs were normalized against the spreadsheet results and are presented in Table 1.

**Table 1. Comparison of normalized static and discretely modelled average daily oreflow rates.**

| Expansion Material Handling Oreflow Design | Spreadsheet Approach | Simulation Approach |
|---|---|---|
| series conveyor streams | 1 | 1.07 |
| parallel conveyor streams | 1 | 0.96 |

The discrete simulation models calibrated well against the static spreadsheet approach with a minimal deviation from the traditional approach for predicting average daily rates from availability specifications. The spreadsheet model predicted an average daily rate of 7% less than the simulation model for the series conveyor stream design, while it returned a 4% higher rate prediction than the simulations for the design with parallel conveyor streams. A conservative approach to predicting basic oreflow rates for a conveyor based material handling mine design indicated that a spreadsheet model would be suitable for conveyor designs in a series stream. In a series stream the spreadsheet method calculated the worst case scenario based on the underlying assumption that concurrent conveyor failures occurred infrequently. The discrete event simulation model that was used for this analysis dynamically modelled concurrent conveyor failures at a higher frequency of occurrence and therefore outperformed the spreadsheet model for a series design. On the other hand, a discrete simulation model would be the preferable approach to predict the rates from a more complicated design with parallel conveyor streams. The spreadsheet model overestimated the performance of a parallel conveyor system by over-simplifying the interaction between the conveyors and the storage bins. The deterministic spreadsheet model was not able to capture the complex interaction between parallel conveyor streams. The lack of a direct relationship between the results from the two models indicated that the simplified approach taken by the static spreadsheet model lacked several of the dynamic interactions between components of the material handling oreflow system captured by the discrete simulations.

***Comparisons of discrete simulations modelling material handling oreflow streams in series and in parallel***

The primary purpose of this study was to compare the benefits of adding a parallel conveyor stream to alleviate the constraint of unplanned maintenance downtime in a material handling system with several conveyors transferring material in a series-designed oreflow stream. If any of the conveyors in the series configuration failed the oreflow was halted, whereas the parallel design required at least one conveyor from both streams of a single oreflow segment to undergo a failure for muck transfer to be halted. The overall availability and average daily oreflow rate of the parallel stream design was normalized against that of the series conveyor stream design for the discrete simulation models (see Table 2) to determine the benefit from a parallel conveyor stream design.

**Table 2. Comparison of normalized discretely modelled oreflow availabilities and average daily oreflow rates.**

| Expansion Material Handling Oreflow Design | % of Maximal Theoretical Panel Yield | Overall System Availability | Average Daily Oreflow |
|---|---|---|---|
| series conveyor streams | 66.8 | 1 | 1 |
| parallel conveyor streams | 76.1 | 1.27 | 1.14 |

The parallel conveyor stream design had an overall availability (from crusher fine ore bins through to surface stockpiles) that was 27% higher than that of the series conveyor design. The increased parallel conveyor stream availability partially mitigated the random failure-associated unplanned maintenance downtime in the system. This resulted in fewer oreflow segment stoppages

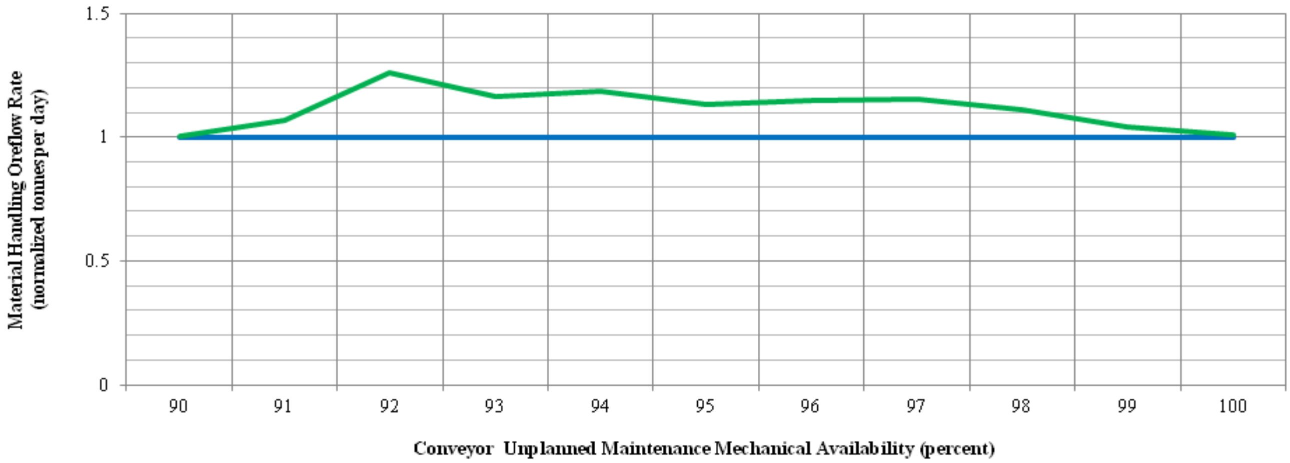


**Figure 3. Conveyor unplanned maintenance (random failure) sensitivity analysis on daily material handling rates from crusher fine ore bin through to surface stockpiles for discrete simulations models of conveyor systems with series and parallel oreflow stream designs. Average daily rates from the parallel conveyor stream design are normalized against the results from the design with a series conveyor stream: (blue line) series conveyor stream design; (green line) parallel conveyor stream design.**

and increased the average daily rate by 14%. It should be noted that a further potential benefit of the increased availability from a parallel conveyor stream design is associated with the opportunity to reduce belt size while still achieving the target rates of a single series design conveyor system (data not shown).

The maximum benefit of a parallel conveyor stream design (without increasing rates from the block cave expansion panel) was realized during adverse operating conditions that increased the stress and damage applied to the conveyor assemblies. The sensitivity of the models to operating conditions was quantified by carrying out a conveyor failure sensitivity analysis. The sensitivity analysis illustrated the benefit of the increased oreflow availability associated with the parallel conveyor stream design (see Figure 3). Partial mitigation of the oreflow segment downtime by the parallel stream design was prominent for operating conditions with conveyor failure rates between 2% and 8% (98% to 92% availability) – the effects of the improved material handling availability was observed with prominent increases between 11% and 25% of the daily rates.

***Discrete simulation application for dynamically modelled sensitivity analysis***

The adverse operating conditions modelled above (see Figure 3) were associated with an increased frequency of conveyor failure, which required more planned maintenance. The discrete modelling approach was used to perform sensitivity analysis on resource-based operating practices incorporated in the simulations – specifically the availability of maintenance crews for unplanned conveyor maintenance. The simulated maintenance crews had a fixed capacity which limited each crew to work on only one conveyor at a time during the available shift hours. Sensitivity analysis was performed on the number of underground crews available for maintenance on conveyors in the existing work zone and the expansion panel (see Table 3). Oreflow rates were normalized to the worst case scenario (one crew per zone) from the model operating with the series conveyor stream design.

The sensitivity analysis results indicated that the oreflow rate was dependent on a critical number of crews for the unplanned maintenance. The efficiency of both conveyor design systems was significantly improved by the availability of two crews per work zone, and reached a maximum with two crews in the existing zone and three crews in the expansion panel. The results indicated that there was a significant occurrence where two conveyors within a zone were down for failure concurrently, and some occasions when three conveyors on the expansion level failed at the same time. When there was not enough maintenance crews available the conveyor availability decreased due to an increase in the mean time required to facilitate repairs. These results demonstrate the power of a discrete simulation model to assess the impacts of operational constraints due to the dynamic nature of the interactions programmed into the models.

**Table 3. Conveyor maintenance sensitivity analysis of average daily material handling rates normalized to the base case of one crew per work zone for a series conveyor oreflow stream design.**

| Existing Zone Crews | Expansion Panel Crews | Series Stream Average Daily Rate | Parallel Stream Average Daily Rate |
|---|---|---|---|
| 1 crew | 1 crew | 1 | 0.93 |
| 1 crew | 2 crews | 1.08 | 1.23 |
| 2 crews | 2 crews | 1.10 | 1.30 |
| 2 crews | 3 crews | 1.14 | 1.32 |
| 3 crews | 3 crews | 1.15 | 1.33 |
| 3 crews | 4 crews | 1.14 | 1.35 |

## Conclusions

The static spreadsheet model and the discrete simulation model approaches calibrated well to predict the average daily oreflow rates from conveyor-based material handling systems with belt designs both in series and in parallel. However, the discrete simulation approach was more sensitive to dynamic interactions between the components of the system. This sensitivity provided an opportunity to assess the impacts of operating conditions and practices on the efficiency of the material handling system. A comparison of discretely modelled conveyor system designs indicated that a potential benefit could be realized in a system with series oreflow segments by introducing parallel material handling streams with increased oreflow segment availabilities. The extent of this benefit was found to be dependent on the operating conditions of the conveyor system and the availability of resources such as maintenance crews to carry out planned and unplanned maintenance on the system.

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