Optimizing In-Pit Crushing and Conveying Systems for Cost-Effective Open Pit Mine Scheduling – A Sensitivity Analysis on Material Throughput and Haulage Costs

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ABSTRACT

In open pit mining, in-pit crushing and conveying (IPCC) systems offer significant advantages over traditional truck-shovel (TS) methods, particularly as haul distances grow with increased mine depth. IPCC reduces the need for extensive truck haulage, cutting down on fuel consumption, maintenance, and carbon emissions by transporting material via conveyors. Placing crushers within the pit streamlines material handling and stabilizes haulage costs over time, providing a more cost-effective and sustainable operation. This study develops a model to optimize IPCC placement and relocation to minimize haulage costs and maximize Net Present Value (NPV) in long-term mine scheduling. To examine the sensitivity of our model, we vary two key parameters: the tonnage of material processed while the crusher remains in the optimal panel and the dollar-per-ton-kilometer cost of haulage. By adjusting the processed tonnage, we evaluate how throughput levels influence haulage requirements and crusher relocation strategies. Altering the haulage cost, meanwhile, offers insight into how changing market conditions impact the economic viability of crusher relocations and the overall robustness of the model. The methodology utilizes a two-stage clustering approach, combining k-medoids and hierarchical algorithms, to define crusher panels and mining cuts precisely, integrating road and conveyor networks. Tested on real mine data, this approach shows significant NPV gains across analyzing the scenarios, consistently outperforming traditional TS methods. Our findings highlight that optimal IPCC configurations depend heavily on both material tonnage and haulage costs, underscoring the importance of these factors in sustainable and cost-efficient mining practices. This scalable model provides a flexible solution for modern mine planning, advancing IPCC as a practical alternative to traditional haulage methods.

1. Introduction

Material haulage is one of the most energy-intensive and costly components in open pit mining operations. As mines deepen and haulage distances increase, traditional truck and shovel (TS) systems become increasingly inefficient. These systems are not only limited by operational costs and greenhouse gas emissions but also by their reliance on extensive road networks and large fleets of heavy trucks. With the growing demand for sustainability and cost efficiency in mining, alternative haulage methods have garnered significant attention.

One such alternative is the in-pit crushing and conveying (IPCC) system, which offers the potential to reduce haulage distances, lower fuel consumption, and enhance productivity. By crushing materials inside the pit and transporting them via conveyors, IPCC systems can mitigate many of the

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inefficiencies associated with conventional trucking. Among the various configurations of IPCC systems, semi-mobile solutions are particularly attractive due to their balance of flexibility and cost-effectiveness. These systems can be periodically relocated within the pit to adapt to the spatial and temporal dynamics of long-term mine planning.

Despite their potential advantages, implementing semi-mobile IPCC systems requires careful strategic planning, particularly in terms of their integration with truck-based systems and the long-term scheduling of extraction activities. Furthermore, the economic viability of IPCC systems is highly sensitive to factors such as truck haulage costs, conveyor costs, and the capacity thresholds required for crusher relocation or installation. Capital and operating cost assumptions, in particular, are often chaotic and vary widely across studies and practical implementations, leading to uncertainties in critical decision-making. Consequently, there is a need for a systematic approach that identifies optimal system configurations under different material throughput requirements, while acknowledging how haulage cost factors may affect the project's economic outlook. This paper addresses that need by presenting a comprehensive methodology for optimizing IPCC layouts within open pit mines and by providing sensitivity analyses on throughput and hauling costs to highlight robust strategies for cost-effective and flexible mine scheduling.

In several studies, researchers have explored the implementation of IPCC systems to reduce haulage costs and improve operational efficiencies in both small and large-scale mines. In small surface pits of dolomite, mobile crushers were shown to yield lower costs compared to stationary units, primarily by reducing haul and set-up requirements [13]. Similar conclusions emerged from investigations on multiseam open cut coal operations, where fully mobile IPCC lowered equivalent unit costs to US$1.22–1.39/t [15]. Analyses of lignite mines incorporating both roads and conveyor ramps further underscored the importance of conveyor design, noting that installation costs of around €3520/m could be offset by long-term savings [23]. Larger metalliferous operations, adopting fully mobile units with capacities of 4000–10 000 t/h, reported capital investments ranging from US$180 million to US$250 million [7], though high-level economic assessments indicated notable reductions in truck fleet requirements.

Subsequent work has highlighted the pivotal roles of crusher relocation timing and location in achieving cost savings. In a conical iron ore pit processing 8 kt/d of ore and 12 kt/d of waste, a semi-mobile 907 t/h IPCC required investment outlays of US$48.8 million plus US$1300/m for conveyors yet delivered significant haulage cost reductions [6]. Studies on copper operations, including the Sungun Mine in Iran, validated similar trends, showing that crusher relocation (US$1.5 million each move) and conveyor construction (US$3000/m) must be carefully scheduled for optimal benefit [20, 21]. At Chuquicamata, adding a third gyratory crusher (5600 t/h) at a cost of US$15 million, with US$35 million for installation and about US$2500/m for conveyors, demonstrated how additional IPCC capacity could reduce reliance on trucking [30]. Further evaluations of simplified copper deposits [17] and the Kahnuj titanium mine [22] confirmed that both semi-mobile and fully mobile IPCC significantly influence total haulage economics, although capital requirements may reach US$200 million in deeper pits.

Recent investigations have reinforced these findings while examining expanded material handling and practical deployment considerations. A hypothetical copper project employing a 3000 t/h semi-mobile crusher recorded relocation costs of US$1 million and conveyor rates of US$0.20–0.42/t, significantly reducing truck haul distances (Abbaspour, Drebenstedt & Dindarloo, 2018). Similarly, a Brazilian copper–gold mine with a 20 year life found that an IPCC system, rated between 3805 and 2718 t/h, cut total haulage expenditures by 28 per cent [19]. Research on large copper porphyries and smaller-scale operations also highlighted cost benefits, indicating that even at lower capacities, IPCC can relieve truck fleet demands, especially if relocation and conveyor charges (eg US$1 million per move, US$0.30/t per level) are optimized [5, 14]. Iron ore mines exhibited similar trends, with semi-mobile crushers around 2700 t/h and conveyor rates of US$0.25/t/km achieving meaningful reductions in truck haulage. In scenarios involving both ore and waste handling, discounted cash flow gains were observed over purely truck-based operations [11], underscoring that careful planning of crusher configuration and conveyor can offer considerable economic advantages across diverse resource settings.

Gong et al. [9] presented a MILP model for long-term open-pit scheduling, comparing the Near Face Stockpile (NFS) method with conventional mining and showing higher NPV and reduced head-grade deviations in an iron ore case study. A related study by Gong, Moradi Afrapoli, et al. [10] further introduced the NFS concept by integrating IPCC with a pre-crusher stockpile, demonstrating improved operational stability and equipment utilization in an oil sands mine.

It is crucial to develop practical and computationally manageable units in order to incorporate the additional physical constraints required by the IPCC system. For this reason, blocks are aggregated into mining cuts, and bench phases are subdivided to create crusher panels through a two-stage clustering process. Although the crusher panel is a new concept introduced in the current framework, mining cuts have been widely used in previous research [1-4, 8, 16, 18, 24-29].

Kamrani, Pourrahimian & Askari-Nasab [12] provided a comprehensive framework that was developed to optimize the long-term mine scheduling problem while simultaneously integrating road network design and in-pit conveyor configurations. Their two-step mathematical model introduced a novel approach that allowed the strategic placement and relocation of semi-mobile crushers in alignment with material movement and infrastructure development. The study demonstrated significant cost savings and reductions in truck travel distances when comparing IPCC-enabled scenarios against conventional TS systems. While this study provided important insights into the advantages of IPCC systems, their work focused on a fixed set of cost and capacity assumptions. However, these parameters can vary widely across mines and over time. Therefore, a comprehensive sensitivity analysis is essential to assess the robustness of such models and to provide mine planners with actionable insights under varying operational conditions.

This paper builds upon the foundational work of [12] and extends it by conducting an extensive scenario-based sensitivity analysis. Specifically, we evaluate how changes in truck haulage costs, conveyor costs, and crusher capacity thresholds affect the overall system performance and haulage cost outcomes. We consider four primary operational configurations: TS only, ore-IPCC, waste-IPCC, and combined ore and waste-IPCC across 32 distinct cost and capacity scenarios. The aim of this study is to provide mine planners and decision-makers with a better understanding of the conditions under which IPCC systems outperform traditional TS methods and how key cost drivers influence strategic planning. The remainder of this paper is organized as follows. Section 2 outlines the methodology, mathematical model and scenario generation process. Section 3 presents the case study and experimental set-up. Section 4 discusses the results, and Section 5 summarizes the conclusions and suggests directions for future research while interprets the findings in light of practical planning implications.

2. Methodology

The methodology builds upon the first model formulation presented by [12], which uses a two-step optimization approach to identify optimal crusher locations and integrate them into the mine schedule while considering haulage network constraints. The methodology begins by optimizing a traditional block model to establish the ultimate pit boundary, pushbacks, and a preliminary long-term schedule. From here, each bench-phase within the pushbacks is subdivided into smaller units, storing relevant geological and economic data for every block. Two rounds of clustering then follow. First, a k-medoids clustering method defines ‘crusher panels,’ each large enough to accommodate the in-pit crusher, its feeder, and conveyor loading areas. Next, a hierarchical clustering algorithm groups blocks into workable ‘mining cuts, ensuring spatial adjacency and uniformity in rock characteristics.

In parallel, dedicated road and conveyor ramps are designed for the open pit, allowing for accurate travel-distance measurements by applying a shortest-path algorithm.

After these preparatory steps, two main optimization models are employed. The first model, aims to select the most cost-effective crusher panel(s) to minimize material transport and installation expenses, accommodating operational configurations that are explained. The second model is a mixed-integer linear program that fine-tunes the long-term production schedule while respecting capacity, grade, and precedence constraints among the mining cuts and crusher panels. It also determines when crushers should be relocated to maximize net present value. Collectively, these models integrate clustering-based block aggregation, in-pit crushing and conveying placement, and operational scheduling, aiming to produce a practical and economically robust open pit mine plan.

2.1. Crusher Integration and Movement

In IPCC-enabled scenarios, semi-mobile crushers are assigned to pre-identified panels called crusher panels, which serve as candidate locations for installation. Once installed, a crusher must remain in a panel until a predefined amount of ore or waste material has been processed. The movement of the crusher is allowed only when the cumulative processed tonnage exceeds the lower bound and does not exceed the upper bound.

Ore and waste crushers operate independently, and their placement is modelled through additional binary variables. Truck haulage is required to move material from the mining face to the crusher location, after which it is transported via conveyor to the destination (eg processing plant or waste dump).

2.2. Scenario Structure

To understand the effect of economic and operational parameters on the performance of IPCC systems, we constructed a full factorial design involving three key parameters:

- Truck haulage cost: four levels:
    - Horizontal: [0.1,0.3,0.5,0.7] \$/t/km
    - Vertical: [0.6,0.8,1.0,1.2] \$/t/km
- Conveyor haulage cost: four levels:
    - [0.1,0.3,0.5,0.7] \$/t/km
- Crusher capacity bounds: two configurations:
    - Lower bounds: 8 Mt (ore), 22 Mt (waste)
    - Lower bounds: 16 Mt (ore), 44 Mt (waste)

These combinations result in 4 × 4 × 2 = 32 unique scenarios, each defined by a specific set of cost and capacity assumptions.

Each of the 32 scenarios is applied to four broader system configurations to assess how IPCC deployment strategies influence outcomes:

- A: No crusher or conveyor (truck-shovel system only).
- B: One semi-mobile crusher and conveyor for ore.
- C: One semi-mobile crusher and conveyor for waste.
- D: Two semi-mobile crushers and conveyors for both ore and waste.

These configurations reflect varying degrees of IPCC integration, from conventional haulage to full IPCC deployment. In all configurations involving crushers, trucks are still required for short-distance haulage to the in-pit crusher.

2.3. Crusher Panel Optimizer Model

To identify the optimal locations for in-pit crushers throughout the mine's operational timeline, it is essential to evaluate material haulage costs between different locations. These costs are computed by multiplying distance matrices by cost coefficients tailored to each scenario. In the base scenario, traditional truck and shovel operations, there is no need to implement the first optimization model. However, for scenarios that incorporate IPCC, a tailored version of the first model is required.

While this model offers flexibility across different IPCC configurations, technical requirements specific to each material type and scenario must be considered. These include conveyor system components like belts, rollers, drives, pulleys, and more. Each scenario demands a custom formulation with slightly different objectives and constraint sets.

Three primary IPCC configurations are considered:

1. Ore IPCC: A single in-pit crusher handles ore, with conveyors installed on a ramp for ore transport. Waste continues to be hauled by trucks.
2. Waste IPCC: One in-pit crusher is dedicated to waste, using conveyors on a ramp on the same pit side, while ore is trucked out.
3. Ore and Waste IPCC: Two crushers (for ore and waste) are placed on the same crusher panel, using separate conveyors spaced adequately on the same ramp.

The general model designed for the combined Ore and Waste IPCC case is presented in Equations 1 to 7. This version integrates the objective functions and constraints for both ore and waste simultaneously. To adapt the model to single-material scenarios, the *MT* index should be adjusted to only include Ore (O) or Waste (W) material type.

Across all three models, a shared objective component accounts for the cost of installing a crusher at a given panel. This cost may vary based on location, accessibility, and geological factors but is never zero.

$$\min \sum_{p=1}^{P} (f_p \times y_p) + \sum_{MT=\{O,W\}} \sum_{k=1}^{K} \sum_{p=1}^{P} \begin{bmatrix} (hoTC \times hoKm_{k,p}) + (veTC \times veKm_{k,p}) \\ + (cc \times cKm_{p,mt}) + cCR_{mt} \end{bmatrix} \times z_{k,p,mt} \tag{1}$$

Subject to:

$$\sum_{p=1}^{P} z_{k,p,mt} = do_{k,mt} \quad \forall\ k \in \{1,...,K\}, mt \in \{O,W\} \tag{2}$$

$$lM_{p,mt} \times y_p \le \sum_{k=1}^{K} z_{k,p,mt} \le uM_{p,mt} \times y_p \quad \forall\ p \in \{1,...,P\}, mt \in \{O,W\} \tag{3}$$

$$z_{k,p,mt} \le do_{k,mt} \times y_p \qquad \forall\ k \in \{1,...,K\},\ p \in \{1,...,P\}, mt \in \{O,W\} \tag{4}$$

$$\overline{pu} \times \sum_{k=1}^{K} z_{k,p,mt=W} - \overline{mu} \times \sum_{k=1}^{K} z_{k,p,mt=O} \le 0 \ \forall\ p \in \{1,...,P\}, mt \in \{O,W\} \tag{5}$$

$$z_{k,p,mt} \geq 0 \ \forall \ k \in \{1,...,K\}, \ p \in \{1,...,P\}, mt \in \{O,W\} \tag{6}$$

$$y_p \in \{0,1\} \ \forall \ p \in \{1,...,P\} \tag{7}$$

Where:

$p \in P$	is the index for crusher panels
$k \in K$	is the index for the mining cuts
$mt \in MT$	is the index for the material types being either Ore (O) or Waste (W)
f_p	is the cost of installing crusher in the crusher panel p. It could be different for the crusher panels if they were not chosen within the same bench phase. Otherwise, it has the same value for all the crusher panels
y_p	is a binary decision variable that is equal to one if the crusher is located in crusher panel p, otherwise zero
$hoTC$	is the horizontal unit cost of truck transporting each tonne of material 1 km
$hoKm_{k,p}$	is the horizontal distance between the mining cut k to crusher panel p
$veTC$	is the vertical unit cost of truck transporting each tonne of material 1 km
$veKm_{k,p}$	is the vertical distance between the mining cut k to crusher panel p
cc	is the unit cost of conveyor conveying each tonne of material 1 km towards its destination
$cKm_{p,mt}$	is the distances on the conveyor ramp between the crusher panel p and the material destinations which are mill or waste dump
cCR_{mt}	is the unit cost of crushing one tonnage of ore or waste material
$z_{k,p,mt}$	is a continuous decision variable representing the tonnage of ore or waste from mining cut k sent to crusher panel p
$do_{k,mt}$	is the ore or waste tonnage of mining cut k
$\overline{pu}$	is the average of the upper bounds on the tonnage of ore processing capacity in all the periods
$\overline{mu}$	is the average of the upper bounds on the tonnage of mining capacity in all the periods
$uM_{p,mt}$	is the upper bound on the total ore or waste tonnage milled or dumped during the time that either/both crusher/s is/are located on the crusher panel p
$lM_{p,\,mt}$	is the lower bound on the total ore or waste tonnage milled or dumped during the time that the either/each crusher/s is/are located on the crusher panel p

As mentioned, Equation 1 serves as the objective function of Ore and Waste IPCC scenario which in the given formulation aims at minimizing the cost of installing the crusher and transporting ore and waste materials. Equation 2 ensures that all ore and waste tonnages from each mining cut are extracted and assigned to a crusher panel. Equation 3 establishes lower and upper limits for ore and waste, on the total ore tonnage milled or the total waste tonnage dumped during the time that the crusher is located on crusher panel p. Equation 4 sets an upper bound for variable z to ensure the feasibility of the solution. Equation 5 is specific to the Ore and Waste scenario, ensuring that both crushers in the selected optimal crusher panel are fed with an equal amount of material relative to the average upper bound of mining and processing capacities across all periods. Finally, Equations 6 and 7 represent the decision variables' boundaries for z, and y, respectively.

In this study, the scheduling model from Kamrani, Pourrahimian & Askari-Nasab [12] remains unchanged and is executed only once. Our primary interest lies in assessing how variations in cost and throughput parameters influence haulage costs, rather than examining changes in net present value. Therefore, while the same schedule is used across all 32 scenarios, each operational configuration (eg ore-only in-pit crushing, waste-only, or both) adopts a unique schedule to reflect its respective haulage approach. This maintains a consistent comparative basis yet ensures that the underlying long-term production schedule is internally coherent for each configuration.

3. Case Study

To evaluate the long-term scheduling performance of semi-mobile IPCC systems under various economic and operational assumptions, a real-size iron ore open pit mine was used as the basis for the case study. The selected mine represents a typical large-scale operation with substantial production volumes, variable topography, and multiple haulage constraints, making it suitable for testing both traditional and IPCC-based haulage strategies.

The mine is divided into 2208 mining cuts, each associated with known tonnage, grade, material type (ore or waste), blocks, sizes and spatial coordinates. These cuts are preprocessed into 215 crusher panels using a hybrid approach that combines K-medoids clustering and hierarchical agglomerative clustering (HAC). This panel-based approach significantly reduces the problem size, allowing the optimization model to handle multi-year schedules and infrastructure placement decisions effectively.

Each panel and cut are defined such that its constituent blocks are spatially contiguous and geologically coherent. Clustering also supports the definition of feasible haulage routes and ensures that crusher panel candidates are positioned in geologically stable zones that can accommodate crusher installation and operation since they are created within a designed pit.

In IPCC-enabled scenarios, the model optimally selects when and where to install the ore and/or waste crusher, subject to tonnage-based movement constraints. The planning horizon spans 20 years, and all results are expressed in cumulative terms unless stated otherwise.

Key economic assumptions include:

- discount rate: 10 per cent
- fixed processing and dumping costs: assumed equal across all scenarios
- truck haulage costs: vary across scenarios based on horizontal and vertical components in \$/t/km
- conveyor haulage costs: vary across scenarios in \$/t/km
- crusher capacity bounds:
  - upper bounds: 40 Mt (ore), 110 Mt (waste)
  - lower bounds: either 8 Mt/22 Mt or 16 Mt/44 Mt

These cost and capacity settings were combined factorially to produce 32 unique scenarios per system configuration.

The optimization models for each scenario were implemented in Python, using a combination of MILP formulations and scenario-specific cost inputs. Each of the four system configurations (A, B, C, D) was run across all 32 scenarios, resulting in a total of 128 optimized schedules.

Each model run produced time-series outputs for truck usage, haul distances, tonne-kilometers (TKM), and total haulage cost, which were aggregated and compared across scenarios. These outputs were then analysed to determine which configurations and parameter settings resulted in the most cost-effective solutions and when IPCC systems demonstrated significant advantages over the conventional TS set-up. Figure 1 shows a plan view of the case study with the positioning of the road and conveyor networks, two waste dumps, crusher panels for one bench-phase and mill.

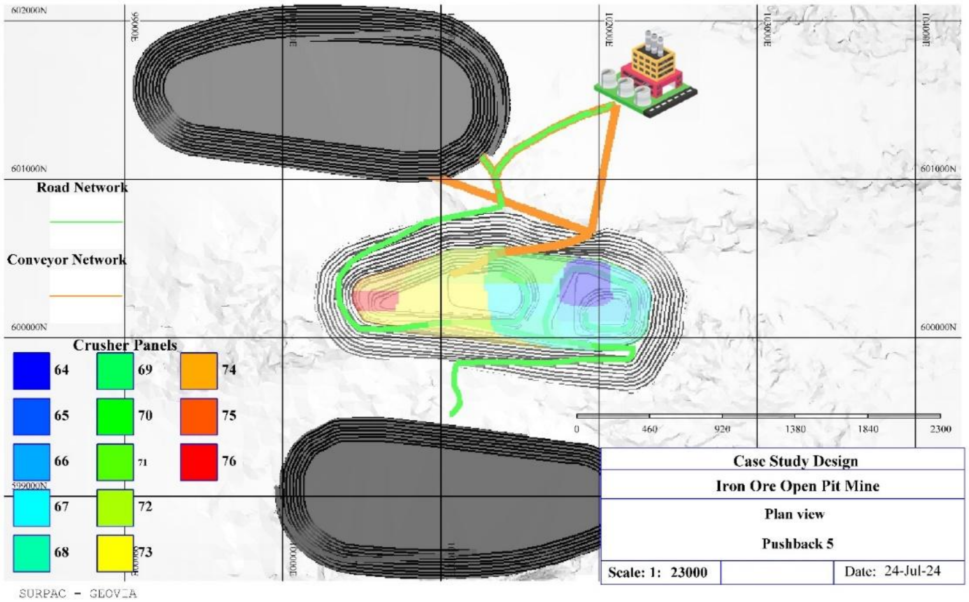

Figure 1: Plan view of the case study.

4. Results and Discussion

Figure 2 summarizes the total cumulative haulage costs (ore + waste) for all scenarios and configurations. As expected, CP00 (without any crusher and conveyor) scenarios consistently incur the highest haulage costs due to reliance on long-distance truck transport. Across 32 scenarios, CP02 (dual IPCC) achieves the most significant cost reductions, with savings ranging from 25 per cent to over 40 per cent compared to CP00, depending on the cost assumptions.

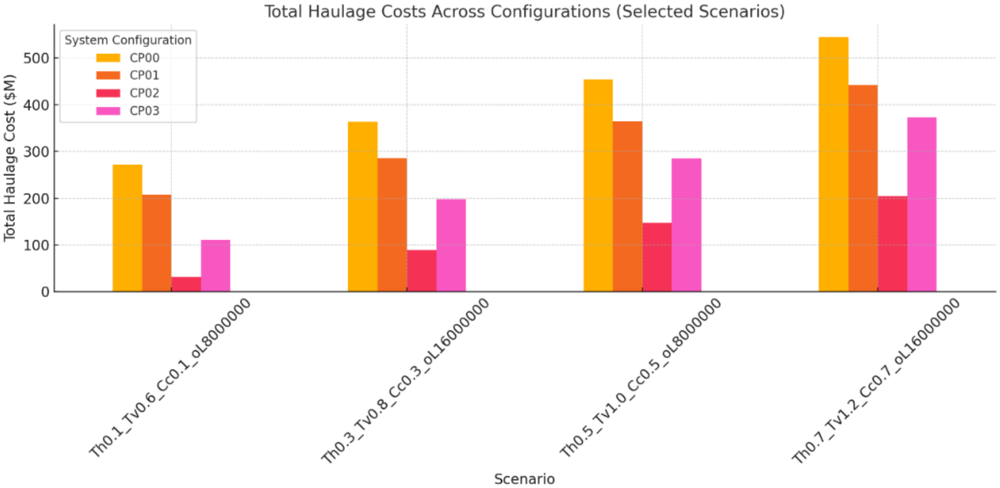

Figure 2: Total cumulative haulage costs for selected scenarios.

Table 1 provides a detailed breakdown of total haulage cost (in million USD) across configurations and scenarios. Scenario names follow the format Th{H}_Tv{V}_Cc{C}_oL{L}, where {H} is the horizontal truck cost, {V} is vertical truck cost, {C} is conveyor cost, and {L} is ore crusher lower bound.

Table 1: Detailed breakdown of total haulage cost across configurations and scenarios.

Scenario	**CP00 ($M)**	**CP01 ($M)**	**CP03 ($M)**	**CP02 ($M)**
Th0.1_Tv0.6_Cc0.1_oL8000000	272.5	232.1	213.4	188.6
Th0.1_Tv0.6_Cc0.1_oL16000000	272.5	234.8	216.0	192.4
Th0.1_Tv0.6_Cc0.3_oL8000000	272.5	238.7	213.4	188.6
Th0.1_Tv0.6_Cc0.3_oL16000000	272.5	241.4	216.0	192.4
Th0.1_Tv0.6_Cc0.5_oL8000000	272.5	245.2	213.4	188.6
Th0.1_Tv0.6_Cc0.5_oL16000000	272.5	247.8	216.0	192.4
Th0.1_Tv0.6_Cc0.7_oL8000000	272.5	251.6	213.4	188.6
Th0.1_Tv0.6_Cc0.7_oL16000000	272.5	254.2	216.0	192.4
Th0.3_Tv0.8_Cc0.1_oL8000000	309.3	256.1	240.5	213.2
Th0.3_Tv0.8_Cc0.1_oL16000000	309.3	258.9	243.1	216.9
Th0.3_Tv0.8_Cc0.3_oL8000000	309.3	262.6	240.5	213.2
Th0.3_Tv0.8_Cc0.3_oL16000000	309.3	265.3	243.1	216.9
Th0.3_Tv0.8_Cc0.5_oL8000000	309.3	269.0	240.5	213.2
Th0.3_Tv0.8_Cc0.5_oL16000000	309.3	271.7	243.1	216.9
Th0.3_Tv0.8_Cc0.7_oL8000000	309.3	275.5	240.5	213.2
Th0.3_Tv0.8_Cc0.7_oL16000000	309.3	278.2	243.1	216.9
Th0.5_Tv1.0_Cc0.1_oL8000000	340.4	274.8	262.6	231.0
Th0.5_Tv1.0_Cc0.1_oL16000000	340.4	277.5	265.2	234.8
Th0.5_Tv1.0_Cc0.3_oL8000000	340.4	281.3	262.6	231.0
Th0.5_Tv1.0_Cc0.3_oL16000000	340.4	284.0	265.2	234.8
Th0.5_Tv1.0_Cc0.5_oL8000000	340.4	287.8	262.6	231.0
Th0.5_Tv1.0_Cc0.5_oL16000000	340.4	290.5	265.2	234.8
Th0.5_Tv1.0_Cc0.7_oL8000000	340.4	294.2	262.6	231.0
Th0.5_Tv1.0_Cc0.7_oL16000000	340.4	296.9	265.2	234.8
Th0.7_Tv1.2_Cc0.1_oL8000000	394.2	305.2	289.7	258.1
Th0.7_Tv1.2_Cc0.1_oL16000000	394.2	308.0	292.4	262.0
Th0.7_Tv1.2_Cc0.3_oL8000000	394.2	311.7	289.7	258.1
Th0.7_Tv1.2_Cc0.3_oL16000000	394.2	314.4	292.4	262.0
Th0.7_Tv1.2_Cc0.5_oL8000000	394.2	318.2	289.7	258.1
Th0.7_Tv1.2_Cc0.5_oL16000000	394.2	320.9	292.4	262.0
Th0.7_Tv1.2_Cc0.7_oL8000000	394.2	324.6	289.7	258.1
Th0.7_Tv1.2_Cc0.7_oL16000000	394.2	327.3	292.4	262.0

The results show that the inclusion of either ore or waste IPCC (CP01 or CP03) yields substantial haulage cost reductions. However, CP02 generally outperforms both, especially under higher truck cost assumptions and when crusher relocation thresholds are moderate (ie lower bounds of 8 Mt/ 22 Mt).

Figure 3 presents the cumulative TKM for ore and waste materials under different configurations. In CP00, trucks are responsible for all material movement, resulting in the highest TKM values. The use of conveyors in CP01, CP03, and CP02 substantially reduces truck travel distances, with CP02 demonstrating the lowest combined TKM. The reductions are particularly pronounced for waste TKM in CP03 and CP02, highlighting the benefit of applying IPCC to high-tonnage, low-value material like waste. For instance, in high-cost scenarios, waste TKM under CP02 is reduced by over 60 per cent relative to CP00.

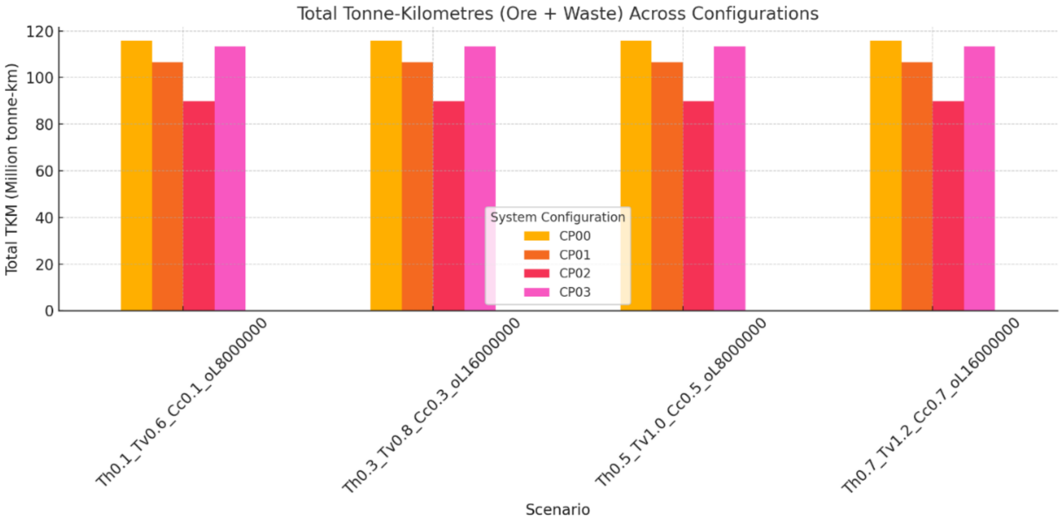

Figure 3: Cumulative TKM for ore and waste materials under different configurations.

Figure 4 compares the number of ore and waste trucks required over the 20 year horizon. In CP00, truck demand is consistently high due to the need for full-pit haulage. Introducing IPCC systems results in a measurable reduction in truck requirements:

- CP01: Ore truck demand drops significantly, while waste remains unchanged.
- CP03: Waste truck demand drops sharply, especially in low-capacity scenarios.
- CP02: Both ore and waste truck demands are minimised.

This directly translates to savings in capital expenditure (CAPEX) and maintenance costs, as well as reduced traffic congestion and environmental impact within the pit.

Across all configurations involving crushers, scenarios with the lower capacity threshold (8 Mt ore/ 22 Mt waste) tend to perform better in terms of cost and TKM. The increased frequency of crusher relocation allows the system to remain closer to the active mining face, thereby reducing truck haul distances. However, this benefit comes at the cost of increased logistical complexity and potential downtime during crusher moves. Thus, there is a trade-off between cost efficiency and operational stability that must be evaluated in practice.

While conveyor cost influences overall system cost, its effect is less pronounced than truck haulage cost. Even at the highest tested conveyor rate ($0.7/t/km), IPCC systems remain cost-competitive under medium-to-high truck haulage costs. This suggests that conveyor cost inflation does not significantly undermine the value of IPCC, especially when trucks are expensive to operate.

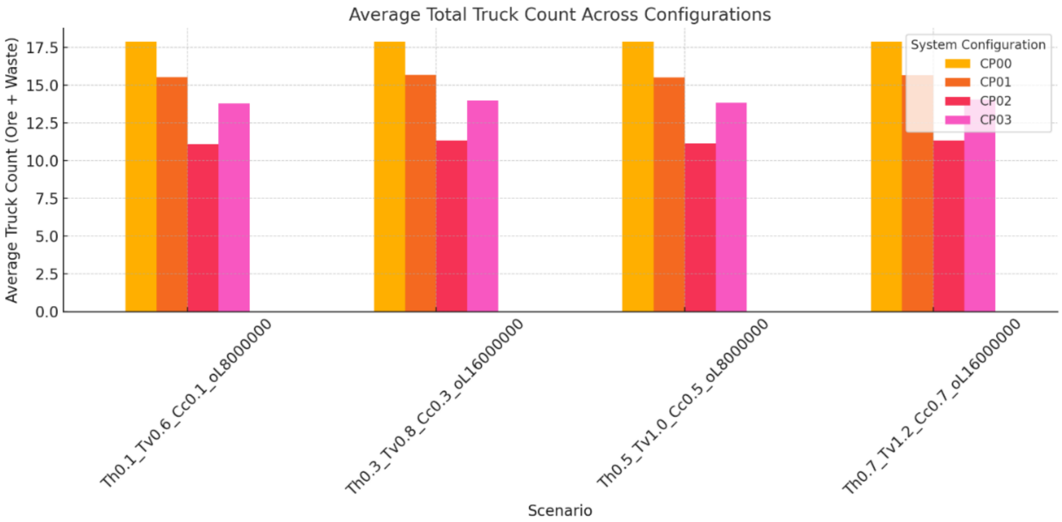

Figure 4: compares the number of ore and waste trucks required over the 20 year horizon.

Figure 3 shows that CP00 consistently produces the highest TKM due to full-distance truck haulage. CP02 significantly reduces TKM, demonstrating the efficiency of combining ore and waste IPCC systems particularly in high-cost scenarios. Also, Figure 4 shows that CP00 requires the largest truck fleet throughout the mine life. The introduction of IPCC systems, especially in CP02, substantially reduces the average number of trucks needed, lowering CAPEX and operational complexity.

The results of the sensitivity analysis reveal clear and consistent trends that reinforce the benefits of incorporating semi-mobile in-pit crushing and conveying (IPCC) systems into long-term open pit mine planning. One of the most prominent patterns observed across all scenarios is the increasing effectiveness of IPCC systems as truck haulage costs rise. In scenarios with high horizontal and vertical truck costs (eg Th0.7_Tv1.2), total haulage costs in the TS-only configuration (CP00) escalated dramatically. Conversely, configurations involving conveyors (especially CP02) demonstrated resilience to these increases, primarily due to the reduced dependence on long-distance trucking. These findings imply that in regions where fuel prices are high, haul roads are long and steep, or environmental regulations impose strict emission limits, IPCC becomes not just an alternative but a strategic imperative. The ability to relocate crushers closer to active mining zones helps stabilize haulage costs and enhances system adaptability over time.

Among the three IPCC-enabled configurations, CP02, where both ore and waste are handled by dedicated crusher-conveyor systems, consistently delivered the lowest total haulage cost and truck fleet requirement. The simultaneous reduction in ore and waste TKM demonstrates the operational synergy achieved when both material streams are supported by IPCC infrastructure. While CP01 and CP03 also provide benefits, their advantages are material specific. CP01 is more effective in reducing ore-related TKM and truck use but offers no benefit for waste movement. CP03, conversely, is particularly effective in reducing haulage costs in waste-dominant scenarios. The choice between these configurations should depend on the relative tonnages of ore and waste, crusher relocation feasibility, and haulage profiles in each mine.

The scenarios involving lower tonnage thresholds for crusher relocation (8 Mt for ore and 22 Mt for waste) resulted in better performance across most metrics. These scenarios allowed more frequent repositioning of the crushers, keeping them close to the mining face and minimizing truck travel distances. However, frequent relocation introduces logistical challenges. Even if modelled as instantaneous or costless in an optimization framework, real-world relocations require downtime, workforce planning, and coordination with other operations. Therefore, while lower thresholds may improve cost performance in the model, planners must assess whether their operations can realistically accommodate such frequent movements.

The analysis also shows that while conveyor costs influence the total system cost, they are not as critical as truck haulage costs. Even in scenarios where conveyor costs reach \$0.7/t/km, the IPCC-enabled configurations remain economically favorable in medium-to-high truck cost environments. This result is crucial for planners concerned about the capital and operating costs of conveyor systems, as it underscores the robustness of IPCC's value proposition even under less favorable conveyor pricing.

5. Conclusions

This study presented a comprehensive sensitivity analysis of semi-mobile IPCC systems integrated into long-term open pit mine scheduling. Building upon the optimization framework introduced by Kamrani, Pourrahimian & Askari-Nasab [12], we evaluated 32 distinct cost and capacity scenarios across four major system configurations: conventional truck-shovel only (CP00), ore IPCC (CP01), waste IPCC (CP03), and dual IPCC for both ore and waste (CP02).

The results demonstrate that IPCC-enabled configurations consistently outperform the conventional truck-shovel system in terms of total haulage cost, tonne-kilometers, and truck fleet requirements. These advantages become particularly pronounced under high truck haulage cost conditions, where IPCC systems, especially CP02, offer substantial cost savings and operational efficiency.

Key findings from the analysis include:

- The dual IPCC system (CP02) yields the greatest cost savings and reductions in truck use, supporting its role as a strategic long-term haulage solution.
- Crusher relocation thresholds significantly affect system performance, with lower thresholds enabling better proximity to active mining zones and reducing haul distances.
- While conveyor costs influence overall haulage expenses, their impact is less critical than that of truck-related costs, affirming the economic resilience of IPCC strategies.
- IPCC integration supports broader sustainability goals, reducing fuel consumption, emissions, and pit traffic congestion.

The results offer guidance for mine planners evaluating the trade-offs between conventional TS and IPCC systems. The detailed scenario analysis provides a decision-support framework to help determine when and where IPCC operational costs become cost-effective, based on-site-specific parameters and market conditions.

Future research may focus on incorporating the second-stage model from Kamrani, Pourrahimian & Askari-Nasab [12] for relocation timing, scheduling optimization, modelling downtime and capital costs associated with crusher moves, or integrating stochastic elements to account for material and price uncertainty. Additionally, expanding the framework to consider emissions, energy consumption, and social impact metrics would enhance its applicability in modern sustainability-focused mine planning.

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