Quantifying Operational Uncertainty: An Integrated Framework for Enhancing Efficiency in In-Pit Crushing and Stockpiling vs. In-Pit Crushing and Conveying Methods

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ABSTRACT

Conveyor operations have demonstrated significant cost advantages over truck systems for long-distance transportation, leading to the adoption of the In-Pit Crushing and Conveying (IPCC) method as a superior alternative, particularly at greater mining depths. Recently, the In-Pit Crushing and Stockpiling (IPCS) method, or near-face stockpile (NFS) mining, has emerged, separating the process into truck-to-stockpile and stockpile-to-crusher stages, which reduces the impact of mining rate fluctuations on milling and enhances system resilience. Studies indicate IPCS improves equipment utilization, stabilizes the mining system, and boosts production compared to traditional methods, but its specific enhancements over IPCC in risk resistance have not been quantified. This paper addresses this gap by developing an optimization model for IPCC using mixed integer linear programming and a discrete event simulation using Arena to simulate operations and incorporate uncertainties. Comparative analysis with real mine data shows IPCS increases equipment utilization (1.67% for shovels, 1.94% for crushers), annual output (2.28%), and reduces truck utilization (2.03%), highlighting its efficiency in managing operational uncertainties. In conclusion, IPCS enhances mining system efficiency and resilience compared to IPCC, particularly in managing uncertainty, warranting further research to refine and apply this framework across different mining environments.

Keywords: *IPCC, IPCS, stockpile, near face stockpile, discrete event simulation*

1. Introduction

Conveyor operation costs have consistently demonstrated significant advantages over trucks in long-distance transportation, as evidenced by numerous past operations and studies [1, 2]. Building on this foundation, the in-pit crushing and conveying (IPCC) mining method has emerged as the predominant alternative to the traditional truck-shovel system. Despite certain drawbacks, such as high initial investment and complex management, the appeal of IPCC increases as mining depths grow deeper, rendering truck investments less cost-effective. Consequently, IPCC has gained widespread adoption due to its superior investment returns over the mine's entire life cycle [3].

In recent years, an innovative approach combining the IPCC method with in-pit stockpiling—referred to as the In-Pit Crushing and Stockpiling (IPCS) method or near-face stockpile (NFS) mining method—has garnered attention. The layout of IPCS is illustrated in Figure 1. Unlike the IPCC

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method, in which the mining and milling systems are directly connected through the interaction of trucks and shovels to form an integrated whole, IPCS differentiates this interaction into two independent stages: truck-to-stockpile and stockpile-to-crusher. This separation significantly mitigates the impact of mining rate fluctuations on the milling system and enhances the mining system's resilience to uncertainty.

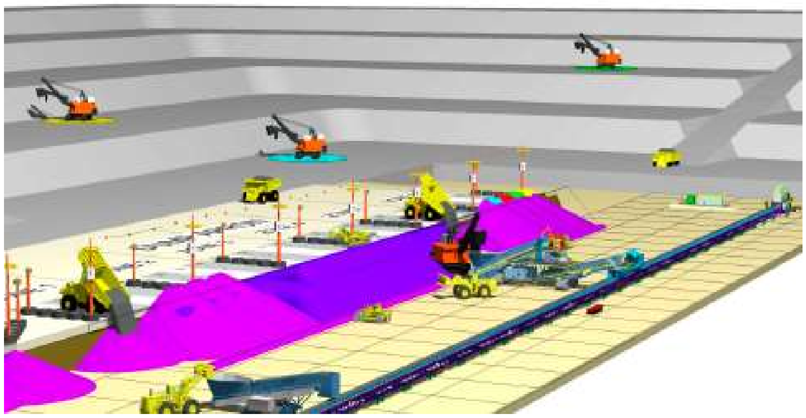

Figure 1. Pit bottom layout of IPCS mining method [4].

Previous studies indicate that IPCS, compared to the traditional truck-shovel method, improves equipment utilization, stabilizes the entire mining system, and boosts mining production [5, 6]. However, the specific enhancements in risk resistance offered by IPCS over IPCC have not been quantified. This paper aims to address this gap by quantitatively verifying the improvements of IPCS over IPCC under operational uncertainties. To achieve this, we propose a framework that integrates optimization and simulation, providing a comprehensive analysis of IPCS's advantages.

2. Literature Review

IPCC is a crucial innovation in the field of mining engineering, designed to enhance efficiency, reduce costs, and minimize environmental impacts by replacing conventional truck haulage with conveyor belt systems. The concept of IPCC dates back to the early 20th century, with initial implementations focused on reducing the reliance on haul trucks. Early systems faced significant technical and economic challenges, such as inadequate technology for efficient material handling and high initial capital costs [7]. Early studies highlighted these early challenges, emphasizing the limitations in conveyor technology and the lack of automation, which hindered the widespread adoption of IPCC systems [8].

Significant advancements in technology during the latter half of the 20th century and into the 21st century have revitalized interest in IPCC. Improvements in conveyor belt technology, automation, and control systems have addressed many of the initial challenges. Research by [9] underscores the role of these technological advancements in enhancing the efficiency and reliability of IPCC systems. For instance, modern conveyors can now handle higher capacities and longer distances, making IPCC a more viable option for large-scale mining operations.

The integration of automation and sophisticated control systems has been pivotal in enhancing the operational efficiency of IPCC. Automated control systems enable real-time monitoring and adjustments, optimizing material flow and reducing downtime. In 2015, a study [10] discussed how these advancements have made IPCC more viable and attractive for large-scale mining operations.

Several case studies demonstrate the successful implementation of IPCC systems in diverse mining operations. An early study [11] documented a copper mine where IPCC significantly reduced operational costs and enhanced productivity. Another study showed that the overall NPV of IPCC can be improved by more than 3% compared with the traditional truck-shovel hauling system [12]. A simulation study in large-scale mining operations showed that semi-mobile IPCC achieved better performance than fixed layout [13]. On top of that, some scholars have proposed a mathematical model for semi-mobile IPCC to further reduce its transportation cost [14]. In addition to the cost reduction, through conducting a Fuzzy decision-making trial evaluation laboratory, it is proved that the deployment of IPCC can significantly reduce the number of traffic accidents [15].

The focus on sustainability has driven further innovations in IPCC. Modern IPCC systems are designed to minimize environmental impact by reducing greenhouse gas emissions and energy consumption. An iron ore mine using IPCC was declared that it achieved substantial reductions in greenhouse gas emissions by replacing diesel trucks with electric conveyors [16]. Studies by [17] and [18] emphasized the environmental advantages of IPCC. Comprehensive econoamic analyses and cost-benefit studies have underscored the long-term financial advantages of IPCC systems. Despite the high initial capital expenditure, IPCC can lead to significant cost savings over time. In 2017, research [19] provided a detailed cost analysis, demonstrating the potential for substantial economic benefits, particularly for large-scale mining operations. Some scholars are committed to the optimization of mining sequence in IPCC via varied time resolution and have proposed some linear models to improve NPV and algorithm for fleet control for higher efficiency [20–28].

Although modern IPCC systems offer substantial operational and environmental benefits, making them an attractive alternative to traditional truck haulage for large-scale mining operations, high initial investment costs, lack of flexibility, and maintenance challenges remain significant barriers to widespread adoption. IPCS is a new mining method proposed based on IPCC that can partially solve the lack of flexibility and risk resistance of IPCC. Although some studies have shown that IPCS has obvious advantages over the traditional truck-shovel mining method, a direct comparison between IPCC and IPCS is still missing, which is also the gap that this paper attempts to fill.

3. Methodology

The first part of this section provides a detailed overview of the establishment of IPCC and IPCS simulation models, along with the software and technology that support them. The second part discusses the selection and introduction of case studies. The final part focuses on the verification of the simulation model, which is crucial for enhancing the credibility of the subsequent result comparison.

3.1. Simulation Modeling

This section begins by elaborating on the process of establishing simulation models for the IPCC and IPCS methods. It starts with summarizing and generalizing the similarities and differences between these methods in their operational activities, leading to the creation of corresponding frameworks. Following this, the section introduces the use of macros—a technology that addresses the limitation of the simulation models being case-specific. The application of macros allows for modular and automated construction of various components within the simulation models.

3.1.1. Framework

In a conventional surface mining system, the working area typically comprises the following elements: polygons (also known as blocks or faces to be moved), several electric shovels, a fleet of trucks, an expanding road network, crushers, processing plants, and stockpiles (positioned at various locations based on needs). Mining, therefore, is not a singular activity but rather the sum of all activities performed by these elements, which are interconnected primarily through the trucks and influence each other. For example, in an oil sands mine using the conventional IPCC method, the main activities can be summarized as follows:

1. Shovels are allocated to working polygons and request trucks by following a predetermined mining schedule.
2. Trucks haul material to shovels.
3. Shovels begin digging the assigned polygons and loading the trucks.
4. Full trucks travel to determined destinations (crusher in the pit bottom or waste dump) based on materials grade.
5. Trucks unload material carried at the designated location.
6. Trucks are assigned to a shovel for an empty return trip and are reloaded at the shovel locations.
7. The crusher processes the ore material to an acceptable particle size.
8. Crushed ore is conveyed to the slurry plant.
9. The slurry plant grinds the minerals into smaller sizes and prepares a slurry.
10. The slurry is transferred to the processing plant to produce the final product.
11. The crude oil from the processing plant is either sold in the market or sent to a refinery.

The IPCS method involves some variations in these steps. Specifically, in step 5, dumping trucks deposit material into a stockpile located in front of the crusher. As a result, trucks no longer directly feed the crusher, and an additional shovel is required to manage feeding the crusher as needed. Figure 2 illustrates the framework of the IPCS method. In the generated IPCS simulation model, there is only one stockpile divided into three zones, with four dumping spots available for each zone. A reclaim shovel retrieves materials from the stockpile zones in a specified order. These materials then proceed through the crusher, conveyor belts, and slurry plant before being pumped out of the pit.

3.1.1. Macros

A common disadvantage of simulation models is their case-specific nature and 'hard coding,' making it nearly impossible to transfer them to different scenarios. This limitation arises from various factors, including the vastly different burial conditions and physical properties of minerals in different regions. Additionally, equipment choices can significantly impact the final extraction boundary. Other influencing factors include variations in environmental policies, mining methods, capital costs, worker capabilities, and engineers' experience. As a result, automatically generating a corresponding simulation model by defining just a few key parameters is challenging. While complete automation remains unrealistic at this stage, semi-automation can enhance simulation efficiency and reduce the case-specific nature of simulation models. Given the common bottom structure of the IPCS method compared to the IPCC method, this study developed a semi-automatic model to simulate both IPCS and IPCC methods by varying stockpile capacities (either zero or a specified number) and incorporating dumping and loading logic.

Considering this, Arena, a well-established discrete event simulation software, is utilized in this research to build the simulation models due to its ability to manage both the discontinuous and continuous nature of mining activities. Additionally, its compatibility with macros and its capability to read and store data externally greatly enhance the model's establishment and operation. The macro in Arena reads equipment parameters, quantities, and road information from an Excel spreadsheet, allowing the model to be easily adapted to other mining scenarios using the same methodology. The macro performs the following functions:

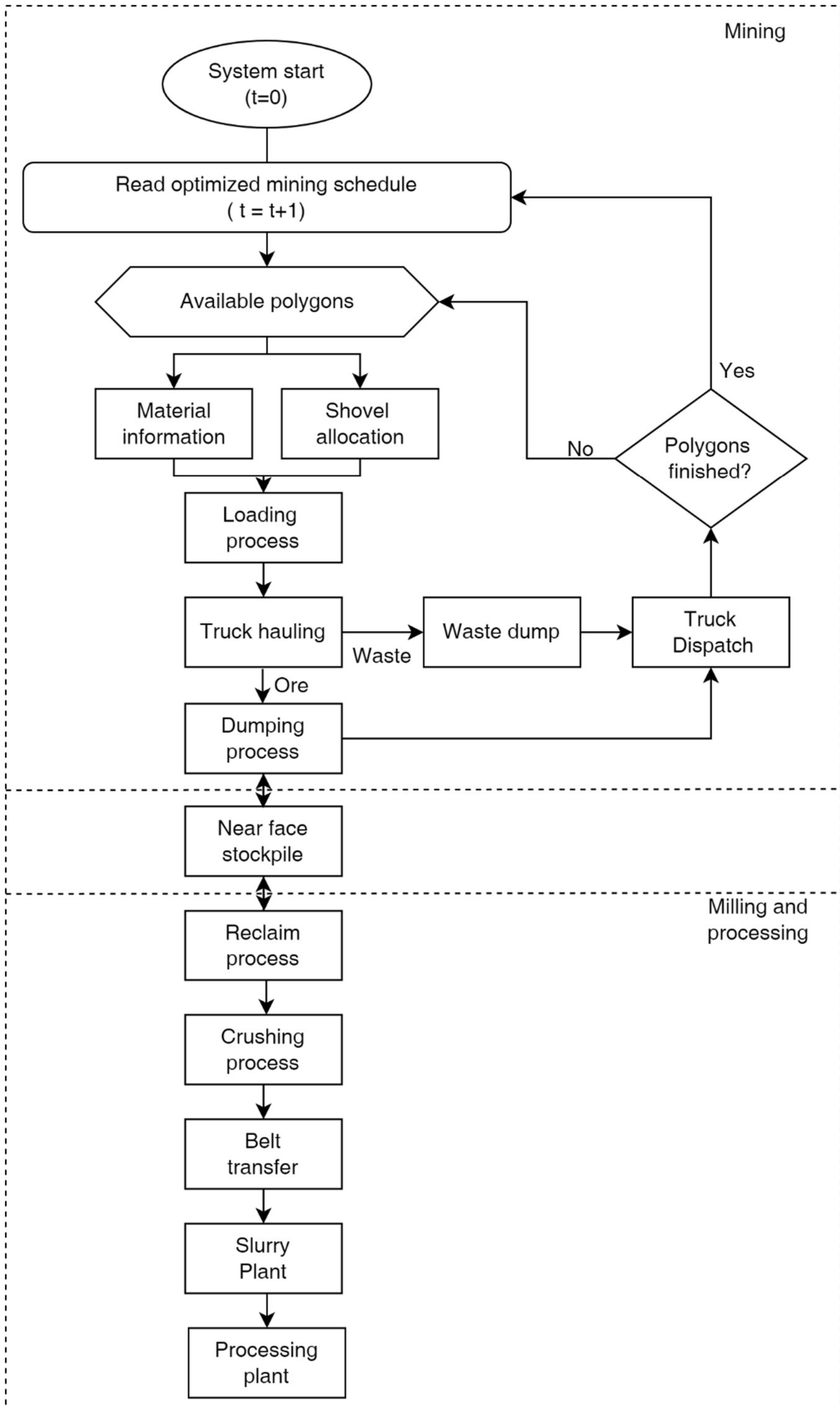

Figure 2. Framework of IPCS mining method.

1. Reads polygon data (including tonnage, grade, rock type, sequence, and coordinates) to build the polygon set.
2. Reads related data to construct 'tanks' for dumping zones, crushers, and slurry plants, and establishes corresponding regulators based on capacity and other factors.
3. Create variable sets for each dumping point to track status.
4. Develops a mining shovel resource set for the mining process.

5. Constructs a sub-model for dumping decision-making.
6. Builds a sub-model for the reclaiming process and corresponding level changes (IPCS model only).
7. Constructs a sub-model for checking the status and level changes of crushers and dumping zones.
8. Develops the conveyor system and processing system.
9. Creates stations for each mining, dumping, and processing location, establishing station sets for each branch system and classifying these stations into different sets.
10. Constructs the road network system and inputs the distances between stations.

In ARENA software, conveyors are modeled using the incorporated ready-to-use module. However, specialized simulation constructs are not always necessary for conveyor modeling. Instead, conveyors can be effectively represented using either a PROCESS module or a DELAY module with a deterministic delay. This delay parameter accurately reflects the time required for an entity to move from one location to another during sliding. The simulation models also account for uncertainties such as truck and crusher failures, which significantly contribute to operational uncertainty.

3.2. Case Study

To effectively compare the IPCS and IPCC methods, we selected an oil sand mine instance with an annual output of 93.1 Mt, of which 60.7 Mt is derived from mining, as the simulation subject. Figure 3 illustrate the road network of the chosen mine instance.

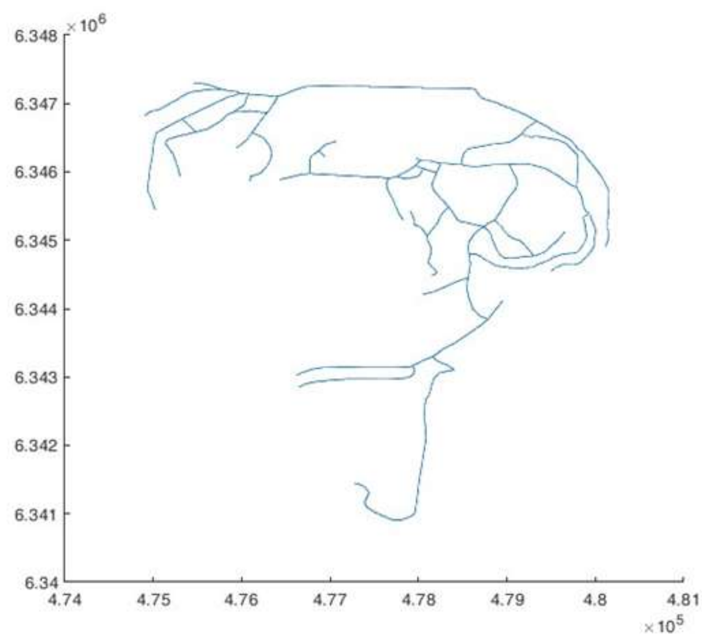

Figure 3. Road network of the oil sands mine.

While this paper primarily focuses on simulating the IPCC and IPCS methods, the mining sequence has a critical impact on mining output and can significantly affect the evaluation of a mining method. To ensure a fair comparison between the IPCC and IPCS methods, it is essential that both methods operate under an optimal or near-optimal mining sequence to enhance the credibility of the simulation results. To determine the best mining sequence, this study utilizes the mixed-integer linear programming optimization method outlined in the authors' previous work [6]. The optimized mining sequence will serve as the input for both simulation models, which will be constrained by the underlying logic to operate within an effective mining sequence, thereby ensuring credible simulation results.

By comparing the simulation results of the IPCC and IPCS methods, this study aims to quantitatively demonstrate the improvements of the IPCS method over the IPCC method while considering operational uncertainties.

3.3. Verification

Although the two methods share significant similarities and utilize the same input parameters, the software itself introduces randomness during the simulation process. Consequently, before further comparing the simulation results of the two methods, it is essential to verify the accuracy and reliability of the simulation models. This section focuses on analyzing the effectiveness of the simulation results by examining five independent variables in both models.

Table 1. Independent variables comparisons of two models.

Category	Range	Mean	Summation
Average loaded tonnage/truck(ton) - IPCC	470 ± 0	336 ± 0.45	62334106 ± 194852
Average loaded tonnage/truck(ton) - IPCS	470 ± 0	336 ± 0.28	63741722 ± 83067
Difference	0.00%	0.00%	2.26%
Loading time(min) - IPCC	5 ± 0	2.89 ± 0	536066 ± 1592
Loading time(min) - IPCS	5 ± 0	2.89 ± 0	548306 ± 1274
Difference	0.00%	0.00%	2.28%
Dumping time(min) - IPCC	1.62 ± 0.19	0.95 ± 0	176691 ± 591
Dumping time(min) - IPCS	1.64 ± 0.09	0.95 ± 0	180767 ± 361
Difference	1.23%	0.00%	2.31%
Empty speed(km/h) - IPCC	63.2 ± 5.0	28.6 ± 0.05	5309683 ± 20592
Empty speed(km/h) - IPCS	64 ± 3.3	28.6 ± 0.04	543009 ± 12366
Difference	1.31%	0.00%	2.27%
Full speed(km/h) - IPCC	58.4 ± 0.8	26.1 ± 0.03	4839876 ± 12161
Full speed(km/h) - IPCS	58.5 ± 0.6	26.1 ± 0.04	4951775 ± 7113
Difference	0.26%	0.04%	2.31%

Figure 4 presents the QQ plots for the simulation results of truck payload per cycle, truck dumping time, truck loading time, and truck empty speed for both simulation models. When combined with the data described in Table 1, it is evident that the simulation results for these independent variables are highly consistent between the two models, thereby verifying the effectiveness of the simulation models.

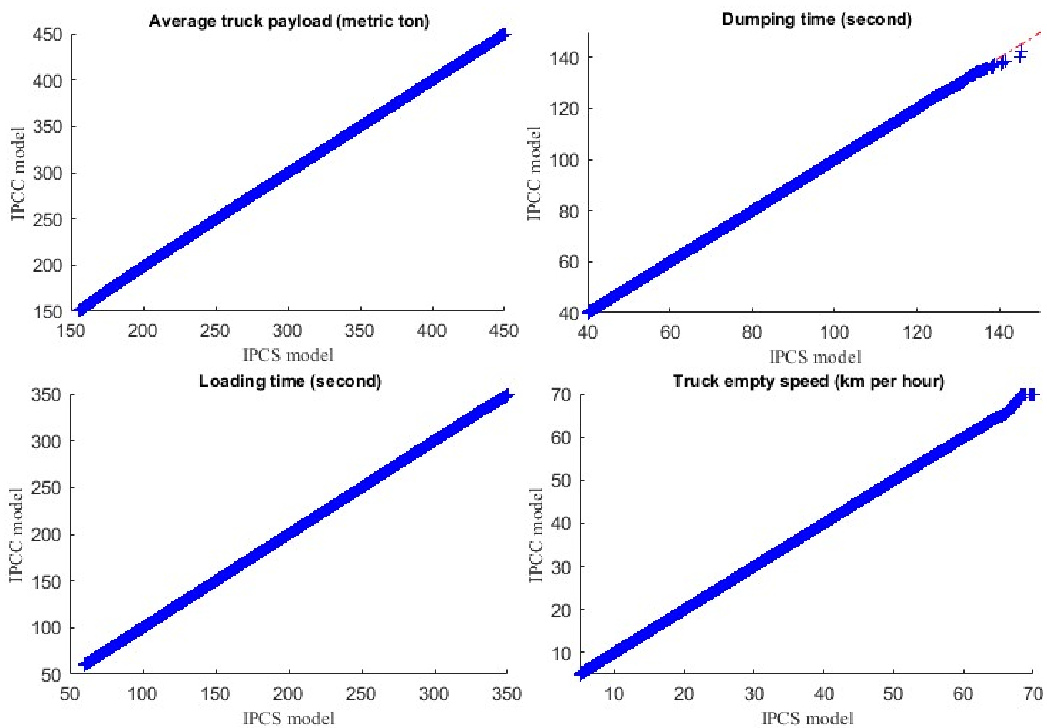

Figure 4. QQ plots of some independent variables in two models.

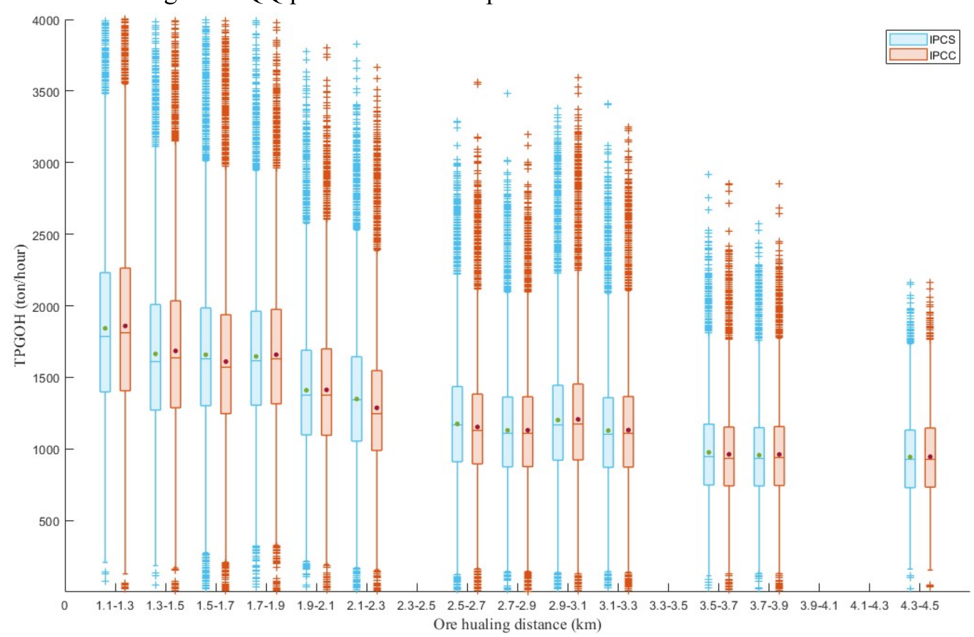

Figure 5. Simulated TPGOH of IPCC and IPCS mining methods.

In addition to independent variables, it is crucial to compare the simulation results of certain dependent variables to ensure that the simulation models accurately represent the two different mining methods. Common dependent variables include truck queuing time before shovels, empty/full truck hauling time, truck cycle ready time, and tons per gross operating hour (TPGOH), among others. For illustration, TPGOH is used to compare the simulation results of the two models. As shown in Figure 5, both the IPCS and IPCC methods exhibit a significant downward trend in TPGOH with increasing transportation distance. This trend confirms that the simulation results are consistent with actual operating results, expert assessments, and engineering expectations. Therefore, the established simulation models accurately simulate the real activities in a mine, thereby verified the correctness of the models.

4. Results

4.1. Equipment Utilization

The utilization rates for shovels and crushers exhibit some improvements in the IPCS scenario compared to the IPCC scenario. Specifically, the average utilization rates for shovels and crushers in the IPCS scenario increased by 1.67% and 1.94%, respectively, as depicted in Figure 6. These results underscore IPCS's enhanced capability to manage equipment effectively under uncertain operational conditions. Conversely, Figure 6 also shows that the utilization of trucks in the IPCS scenario declines by 2.03%. This decrease is attributed to IPCS's effectiveness in mitigating truck queuing at crusher sites and reducing overall truck occupancy rates. As a result, IPCS demonstrates a reduced dependency on trucks compared to the IPCC scenario, further emphasizing its operational efficiency amidst uncertainty.

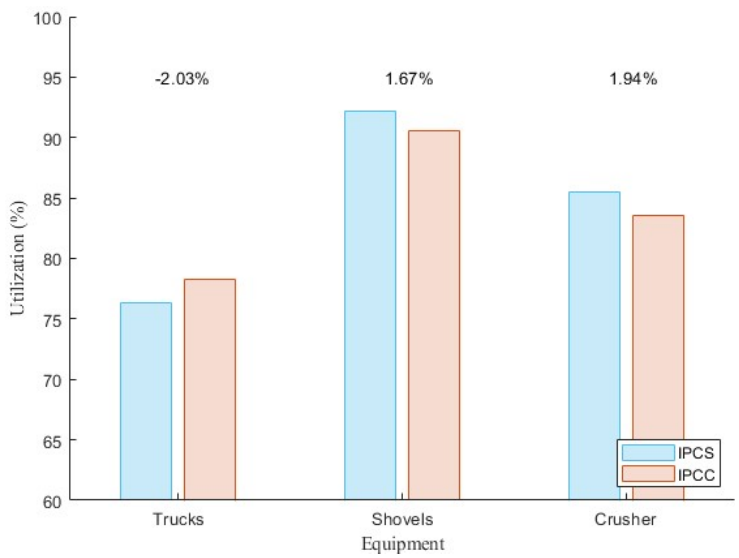

Figure 6. Trucks, shovels, and the crusher's average utilization of IPCC and IPCS scenario.

4.2. Crusher Output

This section evaluates the performance of the crusher under the IPCC and IPCS mining methods, focusing on production, defined as the output from the crusher. Figure 7 presents a comparison of crusher output performance on a yearly basis between the IPCS and IPCC methods. It is evident that the IPCS method consistently surpasses the IPCC method in crusher output, with an average annual increase of 2.28% across ten replications.

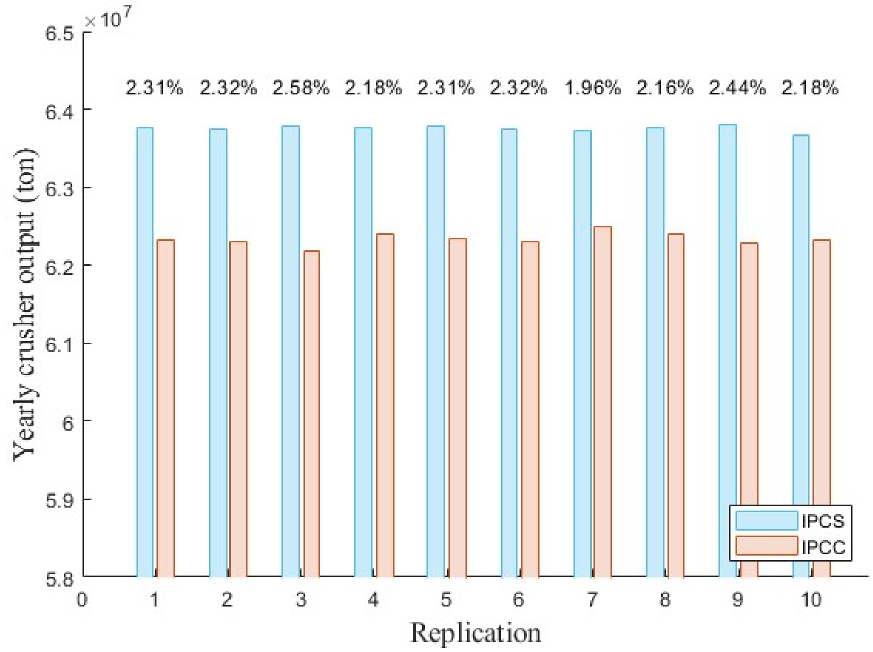

Figure 7. Shovels' annual productivity comparison of two methods.

Given that the same equipment, parameters, and mining sequence are used, the observed improvement in simulation results is primarily attributed to the inclusion of a stockpile in the IPCS method. This enhancement confirms that IPCS offers superior production and, consequently, better returns compared to the IPCC method.

4.3. Stockpile

Figure 8 illustrates the daily differences between the input and output of the near-face stockpile in the IPCS mining method, as well as the difference between the input and output of the crusher in the IPCC mining method. A positive difference indicates that the stockpile feeding tonnage exceeds the crusher's productivity, while a negative difference means the crusher's productivity is higher than the stockpile feeding rate.

In the IPCC method, which lacks a stockpile, the crusher's productivity per unit of time is expected to be less than or equal to the feeding rate. Consequently, crusher productivity will fluctuate in tandem with the feeding rate, unless a stable feeding rate is ensured. The simulation results for the IPCC method, depicted by the orange dotted line, confirm this pattern, showing a small difference between the feeding rate and productivity that fluctuates around zero, within one or two loads.

This characteristic is a common limitation of current mining methods, including IPCC, and is a problem that the IPCS method seeks to address. The IPCS method incorporates a pre-crusher stockpile, which acts as a buffer between the mining and crushing systems. The results, represented by the blue line in the figure, show noticeable volatility, indicating that the pre-crusher stockpile is functioning as intended. When the difference is positive, the stockpile holds excess ore material, while during periods of reduced feeding rates, it releases stored materials to ensure consistent crusher operation. This buffering process enhances the system's ability to manage uncertainties, significantly improving the crusher's capacity to maintain stable productivity.

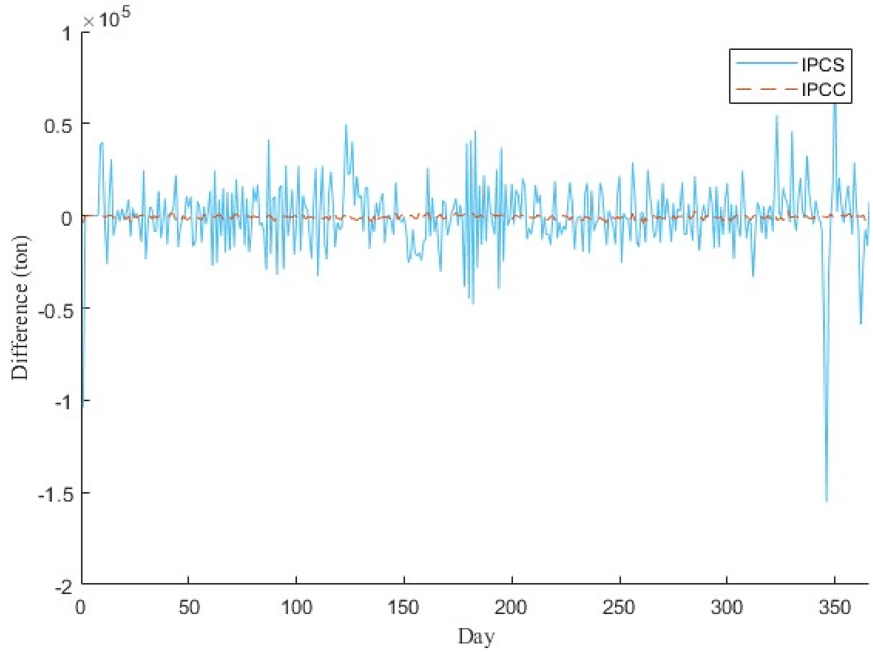

Figure 8. Stockpile/crusher input tonnage minus output tonnage on daily basis.

This stability is a key reason the IPCS method achieves higher production rates compared to the IPCC method, given the same crusher capacity. The IPCS method benefits from its ability to buffer and manage uncertainties, resulting in more consistent production rates. In contrast, the IPCC method, due to the direct linkage between the mining and crushing subsystems, lacks the capacity to effectively handle uncertain events, leading to less stability and lower production rates.

5. Conclusions

This study validates the effectiveness of the IPCS method in enhancing the operational efficiency and resilience of mining systems compared to the traditional IPCC method, with a focus on quantifying and managing operational uncertainty. By integrating a mining sequence optimization model with a discrete event simulation model, the authors developed a comprehensive framework for assessing the performance of both IPCC and IPCS methods under varying operational uncertainties.

Simulation results, based on ten replications per scenario, show that the IPCS method enhances the utilization of shovels and crushers, with average increases of 1.67% and 1.94%, respectively. Additionally, the IPCS method leads to a 2.28% improvement in annual output, underscoring its potential for greater operational efficiency in uncertain conditions. Moreover, truck utilization decreased by 2.03% under IPCS, reflecting a reduced demand for trucks and improved logistical efficiency.

These findings highlight the IPCS method's superior ability to manage and mitigate operational uncertainties, presenting a more robust and efficient alternative for future mining method selection. Future research should aim to validate the credibility of the developed model through comparison of the simulated results against historically recorded data, refine this framework and explore its applicability in diverse mining environments and conditions, further quantifying the impact of various uncertainties on operational performance.

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