An economic evaluation of a primary haulage system for a Bauxite mine: load and haul versus in-pit crushing and conveying

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ABSTRACT

The choice of a primary haulage system in mine planning remains a complex problem. Load and haul is normally utilized for material handling in open pit operations. In-pit crushing and conveying (IPCC) is a system that is not typically considered as a primary method of transportation in today's mining world. Using an IPCC system has many advantages including cost savings, safety and environmental impacts. Depending on design parameters, IPCC can achieve full or partial replacement of trucks for material transportation within and out of a mine. The objective of this research is to evaluate the life-of-mine haulage cost by comparing a truck and shovel system with a semi-mobile IPCC system as the primary material handling option. A haulage cost analysis was conducted by comparing the capital, replacement and operational costs of the two haulage systems for a Bauxite mine. In contrast, though operational flexibility is limited with the semi-mobile IPCC system, it reduces the life-of-mine haulage cost by about 60%, which has significant effect on the economic aspect and environmental footprint of the operation.

1. Introduction

It is most common for open pit operations to utilize a shovel and truck fleet as the primary haulage system. An alternate system such as In-Pit Crushing and Conveying (IPCC) is a rather new approach in dealing with the materials handling of a mine. Load and haul systems require the use of many trucks, which can increase the operating cost significantly. Material handling costs generally make up about 40% of the total mining costs. In order to reduce life-of-mine mining costs, an IPCC system can be considered. IPCC can replace the need for a full truck fleet system, or reduce the fleet size. Instead of a cycle consisting of a truck being filled by shovel and either hauling up the pit to a waste dump or to the primary crusher, fixed or semi-fixed conveyors move the material for the majority of the length.

Although there are a few varieties of IPCC systems; the main feature is that a smaller truck fleet is used, where the primary material mover is the conveying system. Shovels are used to load the material while trucks only haul a small distance to the conveyor, where the material is transported further to the respective locations depending on the material type. IPCC systems use conveyors as the primary system to move material while trucks are only used as compliment to the system. The IPCC system of choice is one that will reduce the fleet size as much as possible while being able to work with the pit's geometry and provide some level of haulage flexibility. Based on the recent research work by Dilhuydy et al. (2017), in this study the materials handling system chosen is known as the semi-mobile IPCC system. Semi mobile IPCC uses less trucks and conveyors that work hand in hand to transport ore to the crusher. The trucks are loaded close to the bench and the material transported to the in-pit crusher.

In general, IPCC reduces the reliance on haul trucks, thus reducing total life-of-mine mining costs. Fewer trucks reduce road maintenance cost as primary haulage routes are drastically reduced. On the other hand, capital cost for IPCC systems are higher than load and haul with lower operational costs. With IPCC, a more constant flow of ore is also achievable as the conveying system reduces the amount of downtimes in the cycle of ore transport from the shovel to the mill.

1.1. In-Pit Crushing and Conveying (IPCC) Systems

In-pit crushing and conveying includes three options; Fixed, Semi-Mobile and Fully Mobile. Of the three systems, fixed IPCC systems are typically located near the pit rim, thus away from the mining face. The fixed IPCC system can be moved throughout the mine life however it is beneficial to move the system as few times as possible. As this system still requires fleet of trucks to haul ore to the crusher, with the crusher near the pit rim, the realized reduction in fleet size is smaller in comparison to the other IPCC systems. Semi-mobile IPCC systems are located a short distance from the mining face. This realizes a greater reduction in fleet size. The semi-mobile IPCC system generally moves to a new mining face up to about two times per year or as required to stay close to the mining face. With a smaller fleet size than that of a fixed system, greater operational cost savings are achieved. To achieve the greatest operational cost savings, the fleet size must be minimized to the least amount possible, hence the fully mobile IPCC. Fully mobile IPCC systems require at most a small fleet for minor operational activities including ore re-handle, minor stripping and building berms. This method consists of having a track mounted mobile crusher following each shovel. A mobile conveyor moving independently of the crusher is used to connect the crusher to a fixed conveyor system which transports the ore ex-pit.

In 1956, the first mobile crusher was installed in a limestone quarry in Hover, West Germany (Darling, 2011). The crusher enabled the quarry operator to take advantage of continuous belt conveyor haulage and eliminated a problem of high-cost road construction and maintenance in wet soft ground, with resultant cost savings. Since that time, the number of mobile in-pit crushing and conveying operations has increased to over 1000.

The network of conveyors, spreaders (for waste) or stackers (for ore), crushers and excavators, and sometimes trucks in IPCC are scheduled primarily to optimize productivity and allow for a continuous supply of ore from the mine. Although a few IPCC systems were initially introduced earlier, the last few years have seen an unprecedented level of renewed interest, pushing for greater productivity and continuous mining. Before a mine chooses IPCC as its main haulage system, thorough planning is required. Due to the lack of flexibility compared to load and haul, medium to long-term production planning should be well thought-out and optimized before installation of an IPCC system. The consequences of improper planning are very costly. Despite some of its challenges, there is renewed interest in high capacity production IPCC in base metals.

In comparison to truck haulage system, the operating expenditure of IPCC is significantly less. The capital cost of IPCC installation however, is higher and trade-off studies can be done when factors such as truck tire replacement cost, labor cost, number of trucks required and truck maintenance cost are considered. All these additional cost for the truck haulage system causes a higher operating cost compared to the IPCC system (Dean et al., 2015). Jeric and Hreber (1977) discussed the advantages, disadvantages and operating techniques of the components of the IPCC infrastructure in their study. Koehler (2003) stated that, for a large mining operation with long mine life and long haulage distances, a continuous haulage system such as IPCC are most cost efficient. De Werk et al. (2016) investigated an economic comparison between truck and shovel haulage system and semi-mobile IPCC system for an iron ore deposit. They compared the two systems in terms of material haulage costs and concluded that IPCC systems are more cost effective than truck and shovel system for a mine with long life.

In addition, it is important to note that to transport material via a conveyor system, the largest material to be transported on the conveyor should not exceed approximately one-third of the belt width. Because of this limitation, a crusher is required to reduce mined material into suitable sizes and then conveyed out to the dump or mill. In an IPCC system, both ore and waste material can be crushed and conveyed or only ore material is crushed and conveyed while waste material is hauled using trucks. Dilhuydy et al. (2017) showed with a hypothetical case study that, waste crushing is a feasible less costly alternative for a mine with extended mine life and long haulage distance. In this paper, a cost analysis of a semi-mobile IPCC system for a bauxite ore deposit is evaluated. Based on the results from Dilhuydy et al. (2017), ore and waste material will be crushed and conveyed to their allocated destinations.

1.2. Objectives of the Study

Technological advances in recent years have helped to improve and raise awareness of IPCC systems, but the fact remains that there is a lack of industry interest when it comes to IPCC systems and the tendency is to favor truck and shovel methods of operation for open pit mines. There are many benefits from implementing an IPCC haulage system including cost savings, safety and a significant reduction in the environmental footprint. In order to use an IPCC system, the pit design must be optimized for a conveyor system with straight and elongated walls as large amount of time is needed to set-up and dismantle the system to relocate the conveyors to the next bench. Commonly, the cost of electricity is lesser than the cost of diesel fuel. Since IPCC are electrically powered, they reduced (in the case of fixed and semi-mobile) or completely eliminate (in the case of fully mobile) the use of diesel fuel. This reduction in diesel use reduces the carbon dioxide emissions and the overall carbon footprint of the mine.

In this research, life of mine mining costs is evaluated in terms of selecting truck and shovel or semi-mobile IPCC as the primary material handling system. Capital, replacement and operational costs of each system are evaluated and an economic comparison is conducted to highlights the advantage of the semi-mobile IPCC system over the truck and shovel system. Whittle software (GEOVIA Whittle, 2013) is used to generate the optimum pit shell and production schedule, while GEMS software (GEOVIA Gems, 2016) is used to design the optimum pit shell to meet the required design aspects for implementing the IPCC system.

2. Conceptual Mine Plan

A block model and a topography file were provided to analyze the viability of application of a semi-mobile IPCC system versus load and haul in extracting a Bauxite deposit. A pit optimization was completed and pit designs generated for life-of-mine planning. The pit designs include multiple phases, which allow ore to be extracted selectively throughout the life-of-mine. The three pit phases are designed to fit the use of an IPCC system as an alternative material handling method. An optimum production schedule was generated using Whittle Milawa NPV (GEOVIAWhittle, 2013) algorithm to determine the NPV of the operation and life-of-mine at 10% discount rate. This section discusses the main steps and technical specifications used to complete the pit optimization, pit designs and production schedule.

2.1. Pit Optimization and Design

The pit optimization parameters in Table 1 were extracted from Minkah (2014). The designed pit shell contains 1,566 Mt of ore material with an average grade of 51% Al_2O_3 and 5% SiO_2, and 1,437 Mt of waste material.

Table 1: Pit optimization and design parameters

Parameter	Value
Reference mining cost	\$3.16/tonne
Reference processing cost	\$9.6/tonne
Selling price	\$0.76/%mass
Processing (beneficiation) recovery	80%
Bench height	25m
Bench face angle	75°
Berm width	12m
Overall pit slope	53°

The Whittle shell does not include access, and therefore must be designed to include appropriate ramps. The final pit design is within 8.6% deviation from the Whittle optimized pit shell, which is less than the standard 10% deviation accepted in the industry. Table 2 shows the quantity of material available in the Whittle pit shell and the designed pit limit as well as the segregation of material by pushbacks. From the final pit design, the development of the pit is split into multiple phases in order to suite the semi-mobile IPCC system. Divided into three, the construction of each phase allows for a more controlled independent construction phase, and subsequently a better cash flow and efficient reclamation planning. The three pushbacks are shown in Figure 1. The pushbacks are chosen by splitting the optimum designed pit shell into three areas of similar size. Each pushback has its own ramp access from the North West side of the pit. The pits are mined sequentially to facilitate in-pit waste and tailings dumping, and continuous reclamation.

Table 2: Summary of material tonnages in Whittle pit shell and designed pit phases

Description	Total tonnage (Mt)	Ore tonnage (Mt)
Whittle optimum pit shell	2763	1610
Designed pit shell	3003	1566
Pushback 1	822	402
Pushback 2	1260	587
Pushback 3	921	577

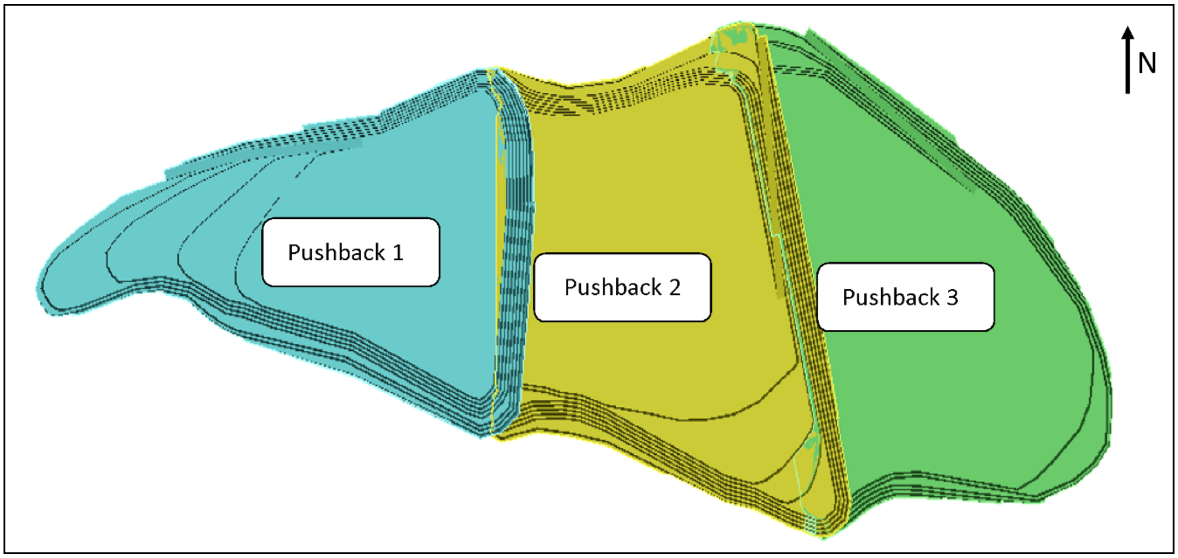

Figure 1: Pushback designs

2.2. Mine Layout

All roads and ramps were designed 40 m wide. All haul roads throughout the mine are two way and allows for clearance for all equipment. Haul road ramps are designed at a constant grade of 10% and will be mainly used for auxiliary equipment as well as haul trucks for the load and haul system.

Waste dumps are essential for open pit operations as waste material must be stripped to expose the ore. The waste material can be used for construction of roads or other facilities. However, a large amount of the waste will not be required and needs to be placed in a waste dump. Dump designs are based on material properties including the angle of repose and particle size distribution related to blasting and ripping. Figure 2 shows the conceptual layout of the mine area including locations for the processing plant, stockpile/reclaimer, waste dump, haul roads and exit points of the ramp system for each pushback.

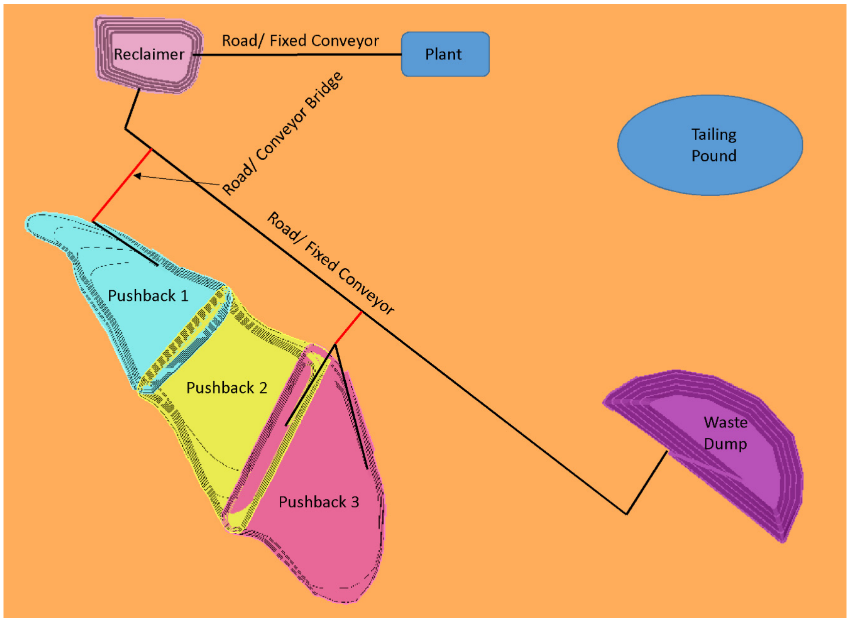

Figure 2: Conceptual layout of the mine area

In the case of using trucks and shovel as the primary haulage system, ore and waste will be hauled out of each pushback to their destinations using trucks while in the case of semi-mobile IPCC, trucks will only be used to transfer ore and waste to the crusher located in the pushback. Conveyors will then be used to transfer the crushed ore and waste to their respective destinations.

Using the phase mining strategy enables each pushback to be mined out completely before moving to the next. An initial ex-pit tailings pond is considered during mining of the first pushback. When pushback one is exhausted, the area could be used as an in-pit tailings pond or waste dump while mining continues in pushback two.

2.3. Production Schedule

Using a stockpile reclaimer system, processing plant capacity was met throughout the mine life. It is envisaged that the stockpile material will be accumulated on a platform and fed with an apron feeder onto an underground conveyor system which transfers the material back into the main processing plant system. The targeted mining capacity was also fully utilized throughout the life of mine. Figure 3 illustrates the mining activity in each pushback including stockpiling. Figure 4 and Figure 5 show the processing plant material tonnage and grade schedule respectively. In each year according to the processing plant capacity and ore availability in the pushback, some amount of ore is reclaimed from the stockpile to the plant. Due to the material reclaiming strategy proposed, the stockpile management is controlled using the First-In First-Out (FIFO) technique.

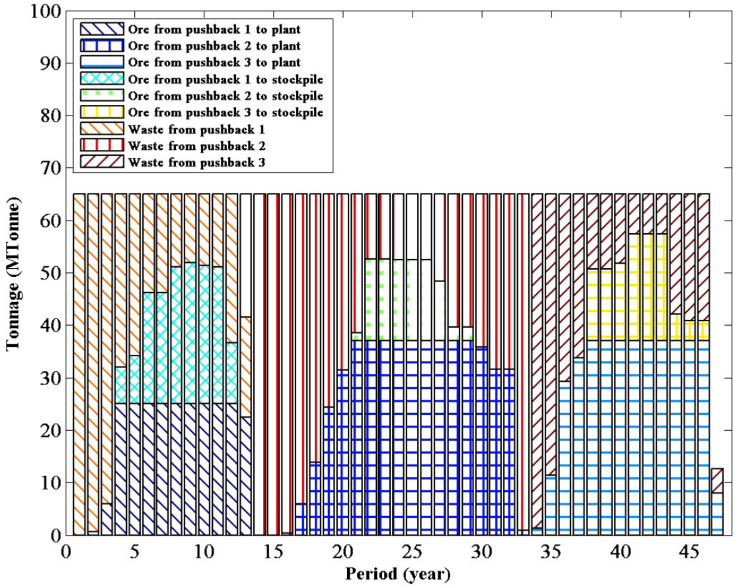

Figure 3: Mining activity in each pushback

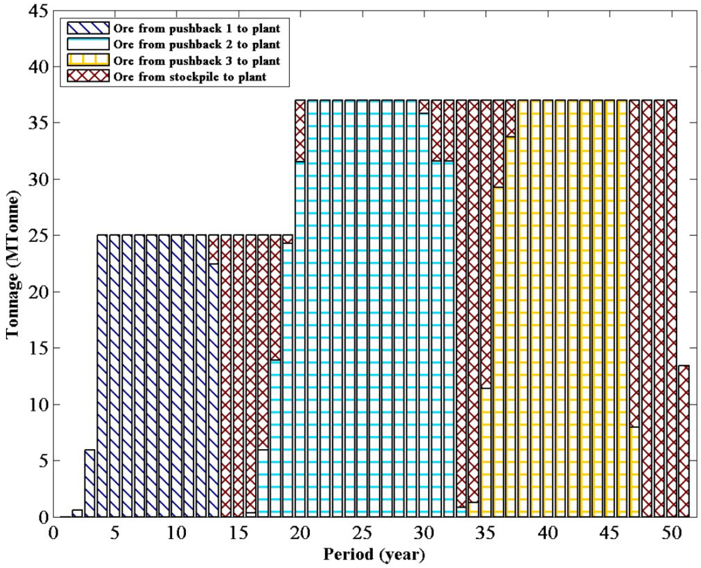

Figure 4: Processing plant material tonnage schedule

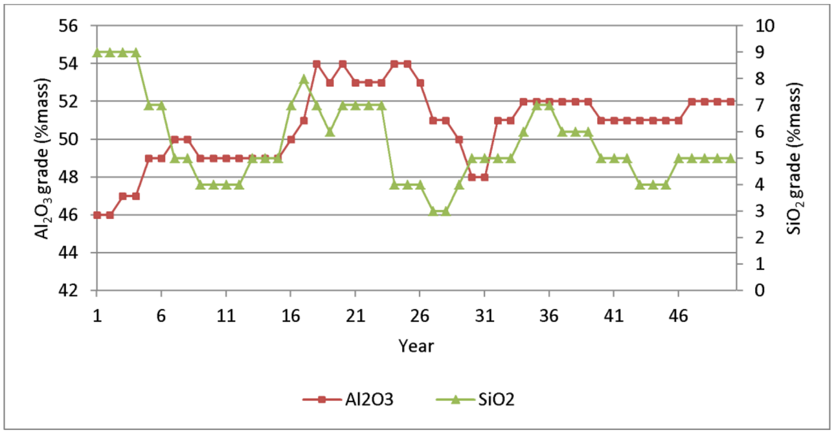

Figure 5: Processing plant grade schedule

3. Primary Haulage System

In order to determine the primary haulage system for the case study, two haulage systems were considered: shovel and truck and semi-mobile IPCC. To evaluate the economic viability of each system; the capital costs, replacement costs and operational costs were compared to determine the best haulage system. In the comparison, some costs such as drilling and blasting are assumed to be the same for both systems and hence are not considered.

3.1. Shovel and Truck

Based on the life-of-mine production targets and shovel-truck matching requirements, CAT 6060 FS hydraulic shovel and CAT 793 D truck fleet were selected as part of the primary haulage system. To determine the required hourly production rate, assumptions were made for different mining activities. Table 3 shows the assumptions and calculations for effective working hours for trucks and shovels. Based on the effective working time, the shovel productivity was calculated. Table 4 presents the details for estimating the shovel net production capacity.

Table 3: Effective working hours

Category	Truck	Shovel
Days/Year	360	360
Shift/Day	2	2
Hours/Shift	12	12
Scheduled time per shift (min)	720	720
Total available hours per year	8,640	8,640
Average equipment availability (%)	85	85
Gross machine operating hours per year (GOH)	7,344	7,344
Average equipment GOH per shift	10.2	10.2
Worker usability factor (%)	90	90
Net operating hours per year	6,610	6,610
Coffee break (min)	30	30
Lunch (min)	30	30
Net scheduled (min)	60	60
Shift change (min)	18	18
Inspection and fueling (min)	6	-
Net scheduled productive time (min)	636	642
Job efficiency factor* (post scheduled breaks) (%)	86	86
Time lost to job efficiency (min)	89	90
Net productive operating time/Shift (min)	547	552
Net productive operating hours (NPOH)/Shift	9.1	9.2
Total available productive hours per year	6,552	6,624

Table 4: Shovel and truck capacity estimates

Description	Value
Shovel bucket size	34 (m^3)
Truck capacity	129 (m^3)
Shovel fill factor	90%
In-situ density	2.80 (t/m^3)
Swell factor	30%
Loose density	2.15 (t/m^3)
Tonnes per bucket	65.9 (tonnes)
Time/Pass	0.67 (min)
Passes/Truck	3.31
Rounded	3.00
Loading time (full pass #)	2.00 (min)
Truck leaving time	0.25 (min)
Truck spot time	0.83 (min)
Total time at shovel/Truck	3.08 (min/truck)
Shovel NPOH/Shift	9.1 (hrs.)
Shovel – Truck loads/Shift	177 (loads/shift)
Tonnes per trip	197.7 (tonnes /trip)
Operating shift production capacity	35,075 (tonnes /shift)
Mechanical availability	83%
Utilization	90%
Net shift production capacity	26,201 (tonnes /shift)
Net daily production capacity	52,401 (tonnes /day)
Net yearly production capacity	18,864,511 (tonnes /year)
Shovel life hours	60000 (hrs.)
Truck life hours	55000 (hrs.)

To calculate the total number of trucks required to achieve the mine plan, truck cycle times were determined based on haulage distances and CAT's rimpull charts including 3% rolling resistance. Table 5 shows the estimates for truck speeds and Table 6 presents cycle time calculations for different destinations. The cycle times for CAT 793 D were estimated based on the truck speeds and the calculated distances from pushbacks to dump, and pushbacks to processing plant.

Table 5: Truck speeds (CAT 793 D)

Description	Truck Speeds (m/min)
Flat in-pit (loaded)	333
Flat in-pit (empty)	417
Ramp 10% ascending (loaded)	212
Ramp 10% descending (empty)	333
Topography 2% (loaded)	589
Topography 2% (empty)	667

Table 6: Truck cycle times

Description	Total haulage time (min)
Pushback 1 to plant	17.7
Pushback 2 to plant	27.6
Pushback 3 to plant	28.5
Average travel time to plant	24.6
Pushback 1 to dump	32.2
Pushback 2 to dump	30.8
Pushback 3 to dump	41.5
Average travel time to dumps	34.8
Truck dumping time	1

Based on the average truck cycle time and shovel cycle time, the number of trucks required to meet mine production requirements are calculated. Four shovels and 44 trucks are required to meet the production capacity with operational flexibility. Shovel costs is excluded from the comparison since both systems need the same number of shovels to meet the production requirements. Truck fleet will be replaced approximately every 8 years over the 47 years mine life. The truck operational cost per hour includes tire, lube, diesel and maintenance cost for part and labor. In order to get the yearly operational cost, the total available productive hours per year in Table 4 is used. Table 7 shows the capital, replacement and operational costs for the truck haulage system. Equipment costs were estimated based on CostMine (2016). The US$ to CAD$ exchange rate of 1.2 was considered for the equipment cost.

Table 7: Truck fleet costs (44 CAT 793 D trucks)

Description	Cost (M CAD$)
Capital cost	218
Replacement cost	1,090
Operational cost	5,375
Total cost	6,683

3.2. Semi-Mobile IPCC

In the case of implementing a semi-mobile IPCC system, the shovels are used to extract ore and waste, and the trucks transport these materials to the crusher. Location of the crusher changes during the mine life to reduce haulage distance for the trucks. In this study, an assumption is made that the crusher is initially located at the ramp exit point of the pushback and will be moved downward every two benches equivalent to approximately 3 years. This will keep the average haulage distance for the trucks to a minimum throughout the mine life. Table 8 presents estimated cycle times for each pushback to calculate the number of trucks required to meet the production capacity; 16 trucks are required.

Table 8: Truck cycle times

Description	Average haulage time (min)
Pushback 1 to crusher	6.9
Pushback 2 to crusher	8.8
Pushback 3 to crusher	9.8
Average haulage time to crusher	8.5
Truck dumping time	1

Due to the high mechanization requirement for the semi-mobile IPCC system, the cost of equipment takes up a huge chunk of the capital cost. In the case of the crusher, the cost is a sum of a gyratory crusher and a crawler to give an estimate of the cost of a mobile crusher. Table 9 shows a list of the major semi-mobile IPCC equipment required and their unit capital cost. Table 10 presents the capital, replacement and operational costs of the semi-mobile IPCC system. Equipment costs and their operational costs in Tables 9 and 10 were estimated based on CostMine (2016).

Table 9: Semi-mobile IPCC equipment unit capital cost

Equipment	Quantity	Unit cost (M CAD$)
Crusher	1	23.4
In-pit conveyors	1,500 (m)	9.2
Overland conveyor	7000 (m)	31.8
Spreader (waste)	1	24.3
Stacker/Reclaimer (ore)	2	27.4
CAT 793 D trucks	19	4.9

Table 10: Semi-mobile IPCC costs

Description	Cost (M$)
Capital Cost	237
Replacement Cost	470
Operational Cost	1,954
Total Cost	2,661

3.3. Discussion of Results

As IPCC system is capital intensive, the payback period is usually longer. Thus, the system requires a longer mine life to fully take advantage of it implementation. With 47 years mine life, IPCC will be very beneficial. In this case study, due to long haulage distance, more trucks are required to meet the production capacity. In addition, because of long mine life the replacement cost for large truck fleet is very high. Also, due to the high cost of truck maintenance, the operational cost of IPCC is only 36% of the truck haulage system. Electricity costs are a major factor as the IPPC system reduces drastically the diesel fuel usage which costs relatively higher. Figure 6 shows the comparison between truck and shovel haulage system and semi-mobile IPCC system. From Figure 6, except the capital cost, the IPCC system's costs are lower than that of shovel and truck. By implementing a semi-mobile IPCC system, the overall mining cost can be reduced by $1.33 per tonne compared to the traditional load and haul system.

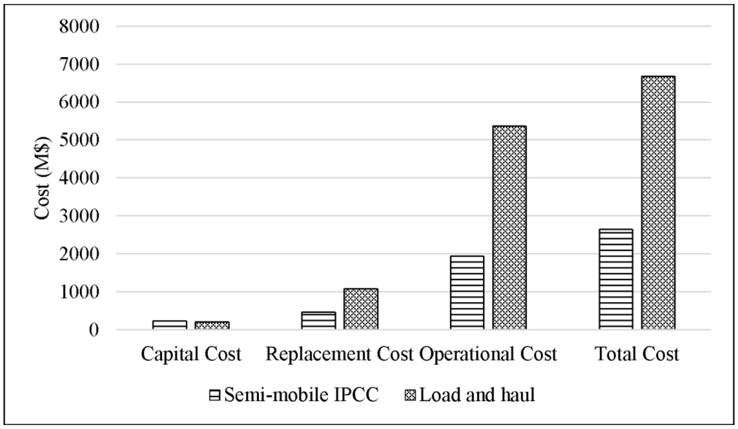

Figure 5: Cost comparison between semi-mobile IPCC and load and haul

4. Conclusion

Technological advances have helped to improve and raise awareness of IPCC systems but the fact remains that there is a lack of industry interest when it comes to IPCC systems and the tendency is to favor truck and shovel methods of operation for open pit mines. There are many benefits from implementing an IPCC haulage system including cost savings, safety and a significant reduction in the environmental footprint. Depending on individual parameters, IPCC can achieve full or partial replacement of trucks for material transport within and out of a mine.

In general, IPCC systems are increasingly cost effective for mining operations that have high capacity with extended mine life, deeper pits, longer haulage distances, high fuel cost and high labor cost. Conveyors in the pit are believed to be the way forward for reduced operational costs in deeper pits with lower grades. Modern conveyor drive techniques like gearless drives can additionally enhance the economic value of IPCC. IPCC should be considered as a main haulage system for open pit mines given appropriate geological and technical parameters. The most important aspect in designing the system is proper and detailed planning as it is less forgiving if the mine planning is poorly done. The more customized the IPCC system implementation is, the less number of trucks are required.

In this study, a semi-mobile IPCC system was evaluated and compared to the traditional load and haul system. Considering only the cost associated with each of the haulage systems, though operational flexibility is limited with the semi-mobile IPCC system, it can potentially reduce the haulage cost of the operation by about 60%. This has significant effect on the economic aspect and environmental footprint of the operation.

5. References

[1] CostMine. (2016). Mining Equipment Costs.

[2] Darling, P. (2011). In-pit crushing. in *SME Mining Engineering Hand Book*, 3rd ed, pp. 941-974.

[3] de Werk, M., Ozdemir, B., Ragoub, B., Dunbrack, T., and Kumral, M. (2016). Cost analysis of material handling systems in open pit mining: Case study on an iron ore pre-feasibility study. *The Engineering Economist. http://dx.doi.org/10.1080/0013791x.2016.1253810*.

[4] Dean, M., Knights, P., Kizil, M. S., and Nehring, M. (2015). *Selection and Planning of Fully Mobile IPCC Systems for Deep Open-Pit Metalliferous Applications*. in Proceedings of AusIMM 2015 3rd International Future Mining Conference, Sydney, Australia.

[5] Dilhuydy, E., Ozdemir, B., and Kumral, M. (2017). Economic analysis of waste crushing in semi-mobile in-pit crushing and conveying systems. *Canadian Institute of Mining, Metallurgy and Petroleum*, *8* (2).

[6] GEOVIA GEMS (2015). Strategic mine planning software. Ver. 6.7.1, Vancouver.

[7] GEOVIA Whittle (2013). Strategic mine planning software. Ver. 4.5.4, Vancouver.

[8] Jeric, S. A. and Hrebar, M. J. (1977). An update on in-pit crushing-conveying-stacking systems in surface metal mines. *Presentation at the SME Annual Meeting Denver, Colorado*, 24-27.

[9] Koehler, F. (2003). *In-pit crushing system the future mining option*. in Proceedings of Twelfth International Symposium on Mine Planning and Equipment Selection, pp. 176-371.

[10] Lerchs, H. and Grossmann, I. F. (1965). Optimum design of open-pit mines. *Transactions of the Canadian Mining and Metallurgical Bulletin*, *68* 17-24.

[11] Minkah, E. A. (2014). Determination of optimized Inchiniso pit, Ghana Bauxite Company Limited, MSc Thesis, University of Mines and Technology, Tarkwa, Pages 86.