SCHOOL OF MINES AND ENGINEERING

EVALUATION OF IN-PIT CRUSHING AND CONVEYING (IPCC) SYSTEMS PRODUCTIVITY IN OPEN PIT MINES

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JUNE, 2022

DECLARATION

This thesis is my original work and has not been presented for a Degree in any other University.

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ABSTRACT

Haulage of materials in Open-pit mines contributes to approximately 40%-60% of the total operational costs. Current stricter environmental conditions, an increase in depths and size of open-pit mines, an increase in labour costs, and fuel costs have made the conventional truck and shovel system extremely expensive. This predicament has motivated search for alternative material haulage options in open-pit mines. In-Pit Crushing and Conveying (IPCC) system has been regarded as the best plausible alternative for the conventional transportation approach. However, the usage of IPCC has been limited to only a few mines due to limited knowledge on the IPCC performance as a system and other technical factors of the system.

This thesis investigated and evaluated the productivity performance of the four types of IPCC systems. The study utilizes mine productivity index (MPi) as the measure of overall productivity of each IPCC type. The thesis develops a model aided by MATLAB that computes the system MPi holistically from input variables of availability, utilization, and performance. This model was applied to a quarry case study from Mombasa Cement Limited.

It was found that the FIPCC had the highest truck fleet of 55. The large truck fleet had impact on increasing the overall system availability but decreasing the system performance and utilization. In overall, the MPi for the FIPCC, SFIPCC, SMIPCC, and FMIPCC was obtained as 67.13%, 69.02%, 70.52%, and 71.52%, respectively. Apparently, the FMIPCC is the best placed IPCC for the utilized case study.

The in-depth investigation of the state of art of the IPCC systems and the evaluation of the IPCC systems based on the number of trucks, shovels, system availability, utilization, performance, and MPi provide vast knowledge on IPCC. This increases the likelihood of it being considered as better alternative haulage option in open pit mines.

DEDICATION

To my dear family: my parents (Mr. Stephen Wachira and Mrs. Sophia Wachira) and my sister (Pauline Wachira) who have always believed in me and supported my academic life and journey.

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ACRONYMS AND ABBREVIATION

IPCC	In pit crushing and conveying
FIPCC	Fixed In pit crushing and conveying
SFIPCC	Semi fixed in pit crushing and conveying
SMIPCC	Semi mobile in pit crushing and conveying
FMIPCC	Fully mobile in pit crushing and conveying
OEE	Overall equipment effectiveness
MPI	Mine productivity index

1 INTRODUCTION

1.1 Research Background

Open-pit mining technique is one of the most common surface mining approaches utilized in the extraction of minerals. This is motivated by its capability to achieve quick access to deposits, relatively low capital costs, better workplace safety, greater flexibility, and higher production rates (Rostami, 2011; Tonge & Nehring, 2017). Open-pit mining technique sequence primarily incorporates drill and blast, loading, hauling, and dumping. Notably, these steps slightly differ in various mineral extraction processes. Among these steps, the haulage category has the highest operational costs approximated to be 50% to 60% of the total operational costs (Souza et al., 2010; Tavakoli et al., 2011; Mohammadi et al., 2015; Abbaspour & Drebenstedt, 2019b). As a result, any significant changes in the haulage costs will impact the overall operational costs.

Over the years, truck and shovel haulage systems have remained the common technique chosen for open pit material transportation. The choice of the truck and shovels has been motivated by their benefits of high flexibility, easy mine planning and scheduling, lower capital costs, and reliability (Aykul et al., 2007). Recently, open-pit mines are reaching depths, which were not common in the past years (Tonge & Nehring, 2017). For instance, Bingham Canyon mine in Utah, USA, is the deepest open-pit mine in the world at approximately more than 1.2 km in depth (*Top 10 deep open-pit mines*, n. d.). The increase in depths results to increase in the fleet size necessary to meet required production, which increases overall operational costs. Additionally, governments are developing stringent environmental laws that require minimal gas emissions (Dean et al., 2015; Tonge & Nehring, 2017). With increased fleet size, it is challenging to comply with such environmental requirements. The truck-shovel is a labour extensive technique which is adversely impacted by increased labour costs globally.

The limitations evident in the conventional truck and shovel systems have motivated search for new haulage alternatives. Among the available options, the in-pit crushing and conveying method (IPCC) has been considered as the best-suited alternative (Tavakoli et al., 2011; Dzakpata et al., 2016; Abbaspour & Drebenstedt, 2019b). IPCC system is a continuous material hauling approach that incorporates a feed system, crusher system, conveyor system, and discharge system (Ritter, 2016). The method is illustrated in Figure 1.1 (Pekol, 2019).

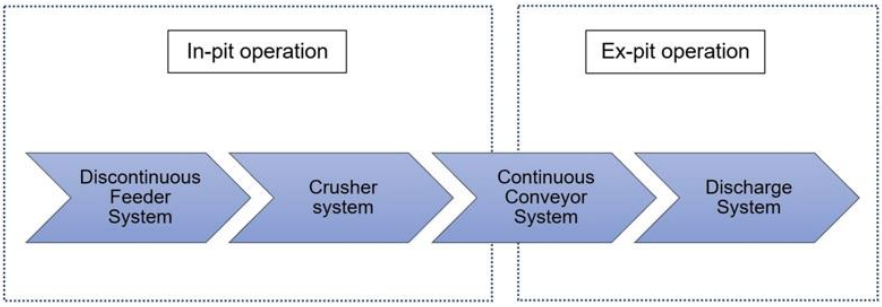


Figure 1.1: IPCC System

Consideration of IPCC system is due to its distinct advantages such as reduced dust, emissions, and noise generation, continuous ore/waster haulage, increased safety in mines, and reduced labour among others (Zimmermann & Kruse, 2006; Rostami, 2011; Tonge & Nehring, 2017; Pekol, 2019). However, its high capital expenditure requirement, high demand for electricity, and lower flexibility have majorly limited its application in open-pit mines (Abbaspour & Drebenstedt, 2019a;). IPCC system is grouped into four major categories depending on their functionality (Ritter, 2016; Tonge & Nehring, 2017, Abbaspour & Drebenstedt, 2019a, 2019b). The four major categories are:

a) Fixed In-Pit Crushing and Conveying (FIPCC) as shown in Figure 1.2 (Tavakoli et al., 2011)

Figure 1.2: FIPCC System

b) Semi Fixed In-Pit Crushing and Conveying (SFIPCC) as shown in Figure 1.3

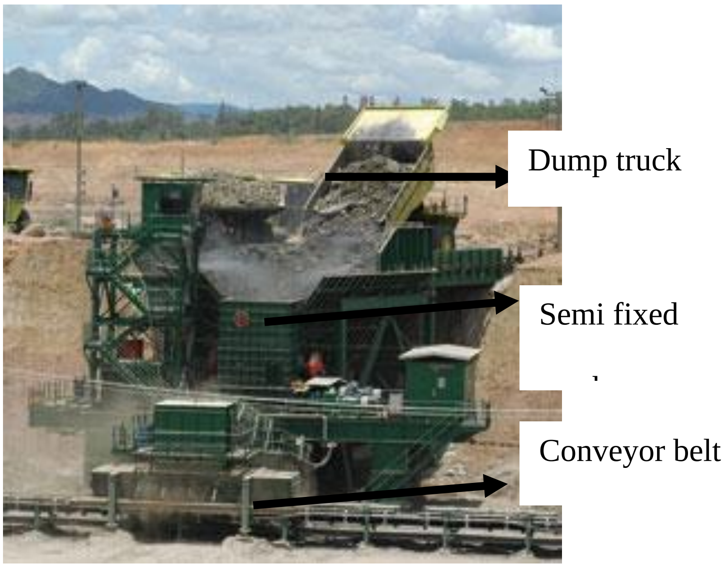


Figure 1.3 SFIPCC system

c) Semi-Mobile In-Pit Crushing and Conveying (SMIPCC) as shown in Figure 1.4 (Tavakoli et al., 2011)

Figure 1.4: Semi-Mobile IPCC system

d) Fully Mobile In-Pit Crushing and Conveying (FMIPCC) as shown in Figure 1.5 (Tavakoli et al., 2011)**.**

Figure 1.5: Fully Mobile IPCC System

The applicability of these haulage systems is dependent on various factors, such as economic, environmental, social, and technical factors, which are mostly site-specific.

1.2 Problem Statement

IPCC system has superior benefits compared to the truck and shovel handling technique. Nevertheless, since the initiation of the first IPCC system in the 1950s, its prevalence in mining operations across the globe has remained relatively low (Rahmanpour et al., 2014; Paricheh & Osanloo, 2016). One of the reasons that have led to the current situation is minimal research studies that address various elements of functionality and operations of IPCC. This is contrary to the truck and shovel system, which has extensive research studies and simulation models that accurately predict the operation of the truck-shovel system.

In the recent past, more studies are now focusing on IPCC aspects. These aspects can be broadly categorized into environmental, technical, social, safety, and economic factors of the system. Among these factors, technical considerations have been identified to be more complicated and distinctively different from the truck-shovel system. They include relocation of the crushers and conveyors, a need for different pit designs, system performance and optimum location of the in-pit crusher station. This makes the technique different from the conventional approach. In the determination of the system performance and productivity, current studies have recommended and emphasized the need for evaluating different types of IPCC systems while considering the interaction of individual components. Therefore, there is a need to investigate the IPCC systems' productivity and performance in line with the recommendations from previous studies.

1.3 Research Objectives

The main objective of the study is to evaluate the MPi of the IPCC systems. The following are the specific objectives of the study:

1. To investigate the state of art of IPCC systems and their applicability to various open-pit mines.
2. To develop and validate models for system availability, performance, utilization, and the overall productivity index for the four IPCC types.
3. To evaluate the IPCC systems using MPi generated from the results of the case studies.

1.4 Research Motivation

Mineral deposits are depleting worldwide while their demand has continued to increase. Consequently, the open-pit mines are reaching vast depths. Additionally, the strict legal conditions to reduce greenhouse gases have led to stricter environmental requirements regarding gas emissions. The labour costs, fuel costs, and the price of trucks and their spare parts are on the rise and are expected to keep this trend. These conditions are making the conventional truck and shovel system expensive and unviable economically in deep open-pit mines. Therefore, there is a need to comprehensively understand and evaluate the available alternatives for hauling materials in open-pit mines to ensure sustainability in mining operations. As IPCC system is the most plausible alternative, understanding and evaluating its productivity and performance is fundamental in the current century. A better understanding of the IPCC system will enhance its usage and implementation in open-pit mines, thus ensuring sustainability in the mining industry.

1.5 Scope

The scope of this research is limited to the evaluation of the productivity of IPCC systems utilizing the MPi. The calculations involved apply availability, utilization, and performance of individual components in generating the best MPi. This study used a limestone quarry as the case study for evaluation of various types of IPCC systems. The analysis done in this study considered the annual productivity of the systems and not the mine life productivity of the equipment.

1.6 Research Questions and Relevance of the Study

The mining industry has recently been experiencing a shift in mineral prices, labour costs, pit depths, environment laws, and fuel costs. These shifts have made the conventional truck and shovel expensive and, in some cases, uneconomically feasible. This has triggered the need for alternative material handling techniques in open-pit mines. IPCC is seen as the most plausible alternative.

Though significant strides have been made in the study of IPCC systems, there exist some gaps in fundamental areas that aid in the selection of the haulage system. The IPPC system performance is one of the key factors that need to be well understood if the method is to be fully implemented in open-pit mines. The performance dictates the overall productivity of a particular IPCC system. Further, comparing the productivity of the four types of IPCC systems is necessary.

This study considered MPi as the measure of the system productivity. Three primary variables of availability, utilization, and performance were applied in calculation of the index used as the basis of evaluation process. Given the recent trends in the industry, a model that calculates the system availability, utilization, performance, and MPi was developed.

Understanding the productivity of each of the four IPCC systems is essential in selection of the haulage technique to employ in a particular open-pit mine. The choice of the haulage approach depends on its ability to attain the required annual productivity, interact with other factors of the mine, and have the least operational costs. The developed model in this study calculates the number of shovels, trucks, and the MPi of each system. These outputs can be utilized to determine the labour costs for each system and the annual production of each method.

1.7 Thesis Overview

This research study is structured as follows:

- Chapter 1 presents an introduction of the in-pit crushing and conveying system and its justification as an alternative for the conventional truck-shovel system. It also includes scope of the study, objectives, methodology and relevance of the research to the mining industry.

- Chapter 2 gives an insight on the literature review of the IPCC system including an overview of the system, benefits, and history of this haulage approach since its first installation. Additionally, the chapter offers a discussion on performance measurement in mining and a review of the literature regarding measurement of IPCC system productivity.
- Chapter 3 investigates the state of the art of the IPCC systems including an in-depth discussion of the system overview and the subsystems. Furthermore, it illustrates the IPCC system configurations, the benefits and disadvantages of the four types of the IPCC system.
- Chapter 4 describes the proposed model for calculating the MPi. It illustrates the input parameters used in the calculations of the MPi. Additionally, it explains the step-by-step algorithm of the developed MPi model.
- Chapter 5 explains the application of the model in a case study limestone mine. This chapter focuses on data collection methods for data used in the model as well as the Monte Carlo simulation employed in the data from the case study.
- Chapter 6 explains the results and evaluates the IPCC system productivity in regard to the number of shovels, trucks, system availability, utilization, performance, and the overall MPi.
- Chapter 7 concludes by showing the outcomes of the study and provides recommendations for future research.

2 LITERATURE REVIEW

2.1 Introduction

Material movement in surface mining has the highest contribution to the operational cost of overall mining operations. The high costs in the handling of materials can be associated with labour costs, fuel costs, equipment repairs, and maintenance costs (Rostami, 2011; Tonge & Nehring, 2017). Various haulage approaches have been utilized in open-pit mines to move ore and waste material. The truck and shovel system is the most popular approach (Rostami, 2011; Rahmanpour et al., 2014). This approach employs loading equipment and trucks that are loaded from the operation face which then hauls the material to either stockpiles or dumpsite. The choice of the system is justified by its benefits which include high flexibility, low investment costs, and high productivity (Zimmermann & Kruse, 2006; Metso, 2020). On the other hand, its high operational costs are a major disadvantage of the system (Tonge & Nehring, 2017; Metso, 2020).

Conveyor system is another technique that has been used in handling of material from open-pit mines. The technique is mostly utilized in continuous mining operations. Unlike the truck-shovel system, the conveyors are not labour intensive and have few safety and environmental concerns (Nehring et al., 2018). However, the system is less flexible and requires auxiliary equipment for effective operation (Tonge & Nehring, 2017). The approach is mostly used in coal mining across the world.

Conveyors and truck-shovel systems are the conventionally utilized approaches in the mining industry (Rostami, 2011). Nevertheless, the volatile economic shifts in mining industry have made truck-shovel system more expensive and ineffective in moving the material (Scott et al., 2010; Tonge & Nehring, 2017). As a result, in-pit crushing and conveying approach has been identified as the best-suited replacement for the truck and shovel system.

2.2 Overview of In-Pit Crushing and Conveying System (IPCC)

IPCC system is a haulage method that incorporates a feed system, crusher station, conveyor, and discharge system (Dzakpata et al., 2016; Ritter, 2016; Abbaspour et al., 2019). It incorporates loading equipment, trucks, crushers, conveyor belts, spreaders, and stackers depending on the purpose of the system as illustrated in Figure 2.1.

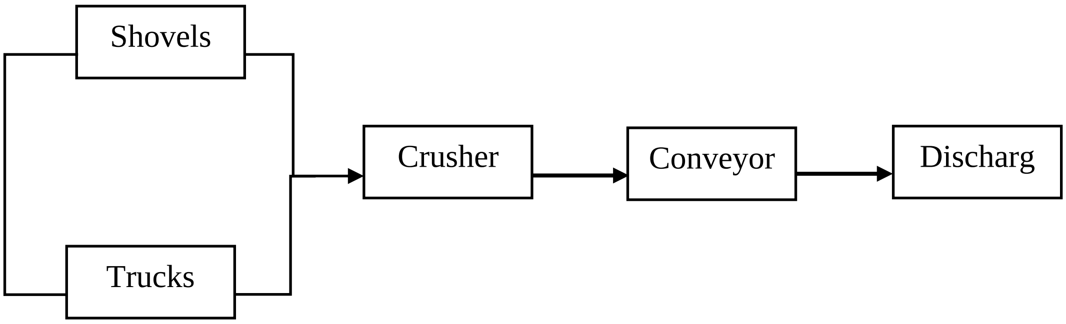


Figure 2.1: IPCC components

2.3 History and Current Trends of IPCC System

The IPCC technique was first used in 1956 in Germany as an alternative transportation system in open pit mines (Ritter, 2016; Abbaspour & Drebenstedt, 2019a). The system was introduced in limestone quarries. According to Tavakoli et al. (2011), Ritter (2016), and Tonge (2017), the innovation was justified by the increased demand for aggregates, and relatively low-cost raw materials. The fully mobile IPCC were the first common installations. The earlier installations were not driven by economic but instead to overcome problems of soft and wet grounds on which trucks could not operate (Ritter, 2016).

From the first installation, the system continued to be used in quarries until the 1980s. In this period, there was an escalation in fuel prices and copper mines opted for IPCC system as a replacement for the truck and shovel system (Ritter, 2016). The fully mobile systems were limited as the crusher could not be fixed in the operating face. As a result, the concept of semi-fixed and semi-mobile IPCC systems was developed (Oberrauner & Turnbull, 2013). From the 1990s to 2010, the demand for IPCC installations remained constant. However, there is evidence of an increased preference for semi-mobile and semi-fixed systems over other systems. The number of installations of the IPCC system from 1960 to 2010 can be summarized in Figure 2.2 (Ritter, 2016). The number of installations in the past decade has slightly decreased compared to two decades ago. This is primarily because, the new installations are replacing the conventional haulage approach while the two decades installations were for the new open pit mines and quarries.

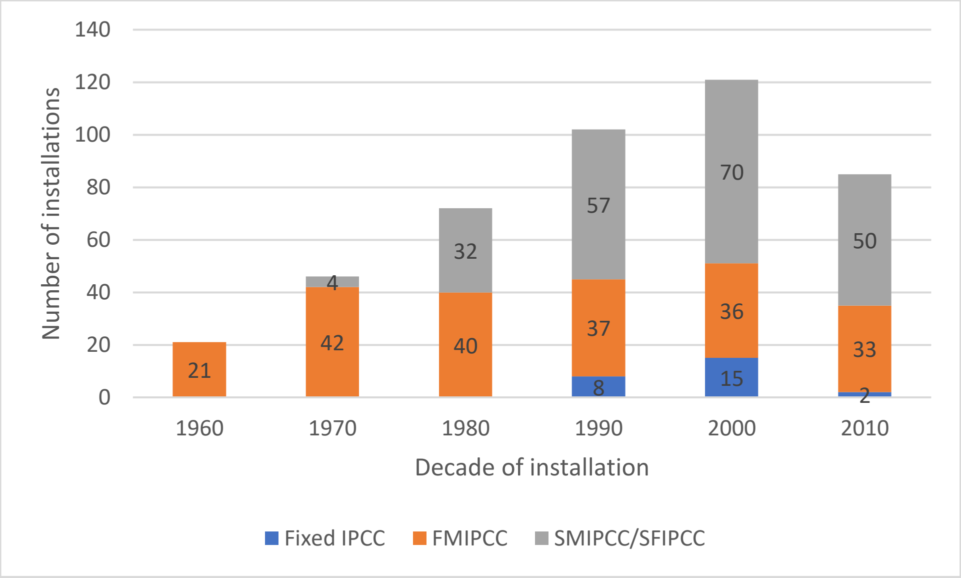


Figure 2.2: Global IPCC installations

In the last two decades, there are notable trends in the implementation and use of IPCC system. The capacity of the IPCC system has drastically increased to approximately 14000 t/h for semi-fixed IPCC and approximately 11000 t/h for FIPCC (Atchison, 2011; Tavakoli et al., 2011). Additionally, due to the increased interest towards the use of

IPCC, the companies making the systems are constantly improving the system to meet the unique clients' needs.

2.4 Justification for use of IPCC System

Several studies have been undertaken to show the benefits and limitations of IPCC compared with the conventional truck and shovel haulage method. According to Zimmermann and Kruse (2006), Sizer (2010), and Utley (2011) low operational costs, reduced labour force, improved safety, high gradeability, reduced dust, emissions, and noise generation are primary benefits that justify the use of IPCC technique. Additionally, the studies highlight low flexibility, high electricity demand, high capital cost, and complex mine planning and production scheduling as the major factors discouraging its usage in open-pit mines (Utley, 2011; Ritter, 2016; Metso, 2020).

In recent years, open-pit mines are reaching deeper depths leading to high operational costs in truck and shovel systems hence making it uneconomical to operate. Tonge and Nehring (2017) shows that the operational costs of large fleet sizes in deep open-pit mines often outweigh the benefits of the low capital cost. Additionally, strict environmental requirements increased labour, and fuel costs are negatively influencing the usage of truck and shovel systems in open-pit mines. These factors have continuously limited the use of trucks in mining operations and consequently motivating the use of IPCC approach.

2.5 Current Research on IPCC System

The majority of the studies have focused on the economic and technical aspects of the system with fewer investigations on the environmental, safety, and social aspects of IPCC (Abbaspour & Drebenstedt, 2019a). Studies agree that the IPCC system has superior economic benefits compared to the truck-shovel system due to its relatively low operational costs (Ritter, 2016). However, the IPCC system has a higher initial capital expenditure which requires a long mine life to pay back (Tavakoli et al., 2011). Turnbull and Cooper (2010) focus on the operational costs of the IPCC systems and the viability of IPCC as a replacement of the truck and shovel system. The study found that IPCC required fewer operating costs in 13 out of 15 case studies (Turnbull & Cooper, 2010). With these studies continually agreeing on the economic advantages of IPCC systems, there is a considerable increase in IPCC system utilization in open-pit mines and hence a better understanding of technical aspects of IPCC is necessary.

As aforementioned, the technical factors are fundamental in the selection criteria of the haulage approach. Atchison and Morrison (2011) discusses several factors that should be analysed and taken into account when selecting an IPCC system. Among the factors, Atchison and Morrison (2011) state that productivity of the systems, ease of relocation, interactions with drill/blast sequence, and compatibility with other mining elements are the most important factors to consider. The technical issue of relocation of the IPCC systems has been addressed by several studies. Sturgul (1987) investigates the optimum location of IPCC system in an open-pit mine by utilizing the cycling time of trucks and a simulation of truck hauling cycle. Konak et al. (2007) provides an optimum location of an IPCC that minimizes the haulage distance. Rahmanpour et al. (2014) in their research concludes that the haulage distance from the operating faces and processing plant are the underlying factors that dictate the location of the IPCC crusher station.

Morriss (2008) undertook a study on the production drivers of the IPCC system which describes productivity as a combination of system capacity and effective operating hours of the system. The study identifies availability, utilization, and service meter unit (SMU) factors as the determiners of the effective operating hours. The study provides a breakdown of these three factors and offers a summary of the four types of IPCC annual productivity. While Morriss (2008) research considers the interaction of system components in the overall IPCC system it does not incorporate the element of equipment performance in various conditions.

Dzakpata et al., (2016) offers a different viewpoint on the productivity of IPCC systems. According to their study, mine productivity is determined as a weighted product of system availability, utilization, and performance. The research examine shovels, trucks, and conveyors independently and not as one system hence having limitations on their findings (Dzakpata et al., 2016).

Recent studies have addressed the aspect of productivity in IPCC systems from varying viewpoints (Tonge & Nehring, 2017; Abbaspour et al., 2019; Hay et al., 2019;). Their studies show that the optimum location and relocation plan for the IPCC system is crucial in the overall productivity of the system. The recent studies have emphasized viewing the IPCC system as an integrated system hence determination of its performance is conducted holistically (Abbaspour et al., 2018). Abbaspour and Drebenstedt (2019b) conducted a technical evaluation of IPCC using system dynamic modelling to determine a technical index that provides a basis for the selection of the IPCC system. Abbaspour and Drebenstedt (2019b) incorporates system availability, utilization, and power consumption as the parameters used in the calculation of the technical index.

Although the IPCC systems present a viable, and safer alternative to the conventional truck haulage, inadequate methods for the long-term projection of the system productivity has resulted in high uncertainties hence discouraging their consideration (Ritter, 2016). Several researches conducted compared the four IPCC systems and found FMPCC to be the most economic system with a higher net present value (Tonge & Nehring, 2017). Regardless of these findings, SMIPCC is the most common technique being utilized in many open-pit mines (Ritter, 2016). This is motivated by technical considerations of the

IPCC systems such as productivity of the systems and interactions with other components in the mining operation.

There exist significant gaps in the current literature on the productivity of the IPCC haulage systems. As Abbaspour and Drebenstedt (2019b) highlight, the evaluation of IPCC systems through their individual components has substantial limitations and does not provide accurate depictions. Moreover, Dzakpata *et al.* (2016) argue that productivity in mining operations should incorporate availability, utilization, and the performance of the equipment. Morriss (2008) has indicated that interactions of the IPCC components, which have been ignored much in the current literature, have a key influence on the overall system availability and utilization. Therefore, this research will evaluate the productivity of the four IPCC systems utilizing a productivity index. The productivity index will be a product of system availability, utilization, and performance that will be modelled for the four IPCC systems and then validated using a case study.

2.6 Performance Measurement in Mining

The determination of the equipment performance is crucial in the selection of the equipment for a particular task. Various indices and parameters can be utilized to calculate the performance of equipment. Measurement of equipment performance was initially done from single indices of measurement (Mohammadi et al., 2015). These indices include availability, utilization, production index, cycle time, and fill factor. However, these indices have been limited as they offer a singular view to the performance of the equipment (Mohammadi et al., 2015).

In efforts to overcome the limitation of single indices, the approach of overall equipment effectiveness (OEE) was introduced by Nakajima in 1988. The OEE is commonly utilized to measure the performance of equipment in the manufacturing industry. The approach considers different major sources of production losses as illustrated in Table 2.1. While focusing on the manufacturing industry, Nakajima (1988) calculated OEE as:

$$\text{OEE} = \text{Availability} \times \text{Performance rate} \times \text{Quality rate} \tag{2.1}$$

Table 2.1 OEE Components

Six big loss categories	**OEE loss category**	**OEE factor**
Equipment failure	Downtime losses	Availability (A)
Setup and adjustment		
Idling and minor stoppages	Speed losses	Performance (P)
Reduced speed		
Reduced yield	Defect losses	Quality (Q)
Quality defects		

However, the use of OEE in mining operations has significant limitations due to the unique mining operations and working environment. Mining operations involve a serial operation of drilling, blasting, loading, hauling, and dumping. Therefore productivity of a mining equipment in each operation depends on the performance of the previous operation (Elevli & Elevli, 2010). Additionally, the huge capacity of equipment makes the effect of utilization high, while the operating environment in mining is dynamic with many unknowns that can impact the equipment utilization (Muili, 2013; Rostami, 2011).

The limitation of OEE in the mining operations has motivated the improvement of Nakajima's OEE to suit the mining environment. This lead to the invention of new approaches in performance measurement. Dzakpata *et al.,* (2016) suggested the use of MPi as the measure of the mining equipment productivity. The MPi is calculated as:

$$\mathrm{MPi} = \mathrm{Av}^{\mathrm{a}} \times \mathrm{PP}^{\mathrm{b}} \times \mathrm{U}^{\mathrm{C}} \tag{2.2}$$

Where Av is Availability, PP is Performance U is Utilization, $0 < a, b, c <= 1 \; and \; \Sigma \; a, b, c = 1$

Samanta and Banerjee (2004) investigated the productivity of the mining equipment with advancing OEE to fit the mining industry. In their study, they determined the weight of a, b, c as 0.3, 0.5, and 0.2 respectively. From combination of the studies, MPi can be calculated as (Samanta & Banerjee, 2004; Dzakpata *et al.*, 2016):

$$\mathrm{MPi} = \mathrm{Av}^{0.3} \times \mathrm{PP}^{0.5} \times \mathrm{U}^{0.2} \tag{2.3}$$

Other studies conducted agree on the application of availability and utilization as the key performance parameters of the equipment (Morriss, 2008; Sturgul, 1987; Tonge & Nehring, 2017). These parameters are determined and calculated based on time. Notably, two types of time approaches can be utilized in mining (calendar-based time and loading-based time approach) (Elevli & Elevli, 2010; Mohammadi et al., 2015; Dzakpata et al., 2016). The calendar-based time approach is preferred because the loading time approach ignores the non-scheduled time and scheduled maintenance time losses resulting in an overestimation of productivity (Elevli & Elevli, 2010; Mohammadi et al., 2015). The calendar time is categorized into total time, net available time, scheduled downtime, operating time, net operating time, and fully productive time.

2.6.1 Availability

Availability considers lost time through events that stop planned production for an appreciable length of time (Mohammadi et al., 2015). It usually happens due to equipment failures and waiting times. It is calculated as shown in Equation 2.4.

$$\mathrm{Availability} = \frac{(\mathrm{Net\ Available\ Time} - \mathrm{Downtime\ Losses})}{\mathrm{Net\ Available\ Time}} \times 100 \tag{2.4}$$

2.6.2 Utilization

Utilization includes the productive use of available hours. It is calculated as:

$$\text{Utilization} = \text{Utilized time}/\text{available time} \tag{2.5}$$

2.6.3 Performance

Performance considers the speed loss generated when the equipment is working at a slower speed than the maximum provided speed when in operation (Elevli & Elevli, 2010). The factors that can cause speed loss include the use of substandard materials, operator inefficiency and job conditions. It is calculated as:

$$\text{Performance} = (\text{Operating Time} - \text{Speed Losses})/\text{Operating Time} \times 100 \tag{2.6}$$

However, there are some inconsistencies in defining which events should be included in the determination of availability and utilization. Despite efforts made by the Global Mining Standards and Guidelines group (GMSG), there is no common standard developed for determining equipment performance (Ritter, 2016). Different mining companies have their internal standardized structure and time usage model.

2.7 Measurement of IPCC Productivity

Understanding the productivity of the mining equipment and systems is crucial when choosing the best-suited technique in material handling. Although the IPCC system is a new approach, some studies have been conducted in efforts to understand its productivity and performance. Atchison and Morrison (2011) illustrated the factors that are analysed and taken into account when selecting an IPCC system. These include productivity of the systems, ease of relocation, interactions with drill/blast sequence, and compatibility with other mining elements (Atchison & Morrison, 2011).

The technical issue of relocation of the IPCC systems has been addressed by several studies (Sturgul, 1987; Konak et al., 2007; Rahmanpour et al., 2014). These studies investigate the optimum location and relocation of the in-pit crushers in an open-pit mine by utilizing the cycling time of trucks and a simulation of the truck hauling cycle. The location of the in-pit crusher and the rate of relocation impacts the number of hours used in relocating and the number of trucks that are required in the case of semi-mobile or semi-fixed IPCC systems.

Morriss (2008) undertook a study on the production drivers of IPCC. This study describes productivity as a combination of the system capacity and effective operating hours of the system. It identifies availability, utilization, and service meter unit (SMU) factor as the determiners of the effective operating hours. It provides a breakdown of the three factors and offers a summary of the four types of IPCC system based on annual productivity. While this research considers the interaction of components in the overall IPCC system, it does not incorporate the element of equipment performance in various operational conditions.

Dzakpata *et al.* (2016) offer a different viewpoint on the productivity of IPCC systems. According to their study, mine productivity is determined as a product of system availability, utilization, and performance. Additionally, the research employs utilised time, operating time, and valuable time to calculate the IPCC system productivity (Dzakpata et al., 2016). The study examines shovels, trucks, crushers, and conveyors individually hence creating a limitation since the IPCC system is not viewed as one integrated system.

Additionally, Abbaspour and Drebenstedt (2019b) states that optimum location and relocation plan for the IPCC system is crucial in the overall productivity of the system. Unlike other studies that address IPCC components individually, Abbaspour and Drebenstedt (2019b) handles IPCC systems as one integrated system. The study conducts a technical evaluation of IPCC using systems dynamic modelling to determine a technical index that functions as a basis for the selection of the IPCC systems. It incorporates system availability, utilization, and power consumption as the input parameters in the calculation of the technical index.

The existing literature has focused on the productivity of IPCC through analysis of its equipment in the mining operations. Shovels and trucks are the two pieces of equipment that have been extensively studied and applied in most mines (Morriss, 2008). While the IPCC transportation system incorporates shovels and a few tucks, it has additional components such as crushers, conveyors, and material distributing systems (stacker and spreader). The components of the IPCC systems are interdependent therefore the performance of one piece of equipment in the system impacts the overall system. According to Abbaspour and Drebenstedt (2019b), the interaction of the systems are either serial, parallel, or hybrid dictating how the single components impact the overall system.

There exist significant gaps in the current literature on the productivity of the IPCC haulage systems. The evaluation of IPCC systems using individual components has substantial limitations and does not provide accurate depictions (Abbaspour & Drebenstedt, 2019b). Productivity in mining operations should incorporate availability, utilization, and the performance of the equipment and be evaluated using MPi (Dzakpata et al., 2016). Interactions of the IPCC components have a key influence on the overall system availability and utilization.

This research will evaluate the productivity of IPCC systems as integrated systems with several individual components. Additionally, the study will use MPi incorporating weighted availability, utilization and performance as the productivity measurement for the IPCC systems.

2.8 Summary

IPCC is an alternative haulage option utilised in open-pit mining. The system has superior advantages compared to the truck-shovel and conveying systems. However, since the initial installation, the IPCC system utilization has remained relatively low. This is plausibly due to a limited understanding of the performance of the IPCC system. However, recently studies have focused on understanding the IPCC system better. The current research dwells in the economics, technical aspects, and environmental impacts. The studies conclude that IPCC system has superior economic benefits compared to the conventional truck and shovel haulage option. Further, literature agrees that there is a need to approach IPCC system as one integrated system when calculating the overall equipment productivity. The MPi has been identified as the best-suited index to determine the productivity of the IPCC system. From this literature review, this research investigates the state of art of the system and evaluates productivity of different types of IPCC system in the next chapters.

3 STATE OF ART OF IPCC SYSTEM

3.1 System Overview

IPCC system is an integrated material handling system comprising of a feed system, crusher system, conveyor system, and discharge system. It operates in a hybrid configuration system that comprises a discontinuous (parallel configuration feed system and serial configuration of crusher, conveyor, and discharge systems as illustrated in Figure 3.1 (Ritter, 2016).

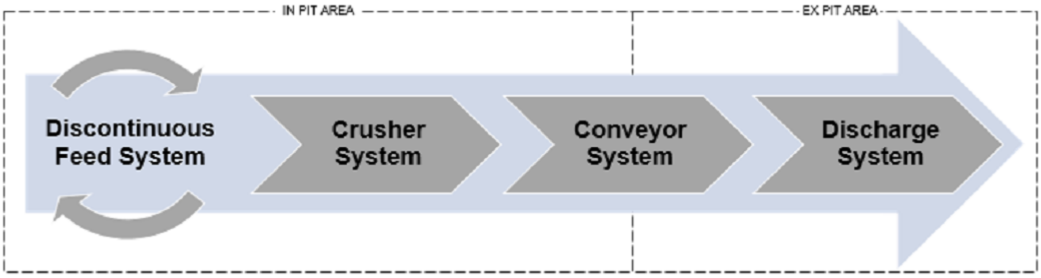


Figure 3.1: IPCC Subsystems

The general configuration slightly differs among the four categories guided by several factors depending on the type of the IPCC. The selection of the IPCC system in open-pit mines is driven by specific design parameters. These include:

- Production requirements
- Ore characteristics
- Ore-body geometry
- Mine life
- Availability of electric power and diesel
- Safety and environment
- Maintenance requirements

3.2 Feed System

The feed system is the first subsystem of the IPCC system. Its primary function is to excavate the material from the in-situ state in the operating face and then feeds the crusher. The material is either blasted from the face or excavated directly without blasting depending on the comprehensive strength of the rock.

The feed system can either be grouped as either continuous or cyclic depending on the combination of equipment used. The equipment used is dependent on the type of the IPCC in use, production requirements, ore-geometry, and the location of the crushers.

For a fully mobile IPCC, the crusher is fed directly by loaders (shovels or excavators), draglines, dozers, and front-end loaders. In semi-mobile IPCC, a combination of trucks with a front-end loader and shovels/excavators can be utilized. In some cases, draglines, dozers, and front-end loaders can be singularly utilized in SMIPCC. In fixed and semi-fixed IPCC, an indirect feed is applied to incorporate a combination of trucks with a front-end loader, shovels/excavators, and train combined with loaders. The utilization of these combinations is dependent on the distance between the operation face and the crusher station.

The determination of the loading equipment, truck capacity, and fleet size are dependent on the crusher capacity and the annual production requirement of the specific mine. The loading equipment has been regarded as the determining element in the production capacity of the overall system. Therefore, the choice of the feed system equipment is crucial.

The calculation for the loaders is as shown in Equation 3.1 (Rostami, 2011);

$$\mathrm{Q} = \mathrm{Bc} \times \mathrm{c} \times \mathrm{p} \times \mathrm{s} \times \mathrm{Bf} \tag{3.1}$$

Where:

Bc is Bucket capacity, Q is Quantity required (t/h), c is Cycles per hour, s is Swing factor, p is Production factor, and Bf is Bucket fill factor (filling factor x (loose density/bank density)

The truck fleet size is calculated as illustrated in Equation 3.2 (Rostami, 2011).

$$Q = Bc \times c \times Pe \times n \tag{3.2}$$

where:

Bc is Bucket capacity, Q is quantity required (t/h), c – cycles per hour, Pe is efficiency factors, and n is number of trucks

It is important to consider the matching of the truck and loader when calculating the loader and truck size and fleet size.

3.3 Crusher System

The crusher system is the second subsystem of the IPCC system. It receives material from the feed system and then reduces it in conveyable sizes. This material is discharged to conveyor belts to be transported to the next mining stages. The crusher system is arguably the most critical component of an IPCC system (Mohammadi et al., 2015; Dzakpata et al., 2016; Ritter, 2016). Jaw crushers, hybrid, gyratory, and roll crushers are some of the common types of crushers. As illustrated in Figure 3.2, the capacity of these crushers varies significantly (Ritter, 2016).

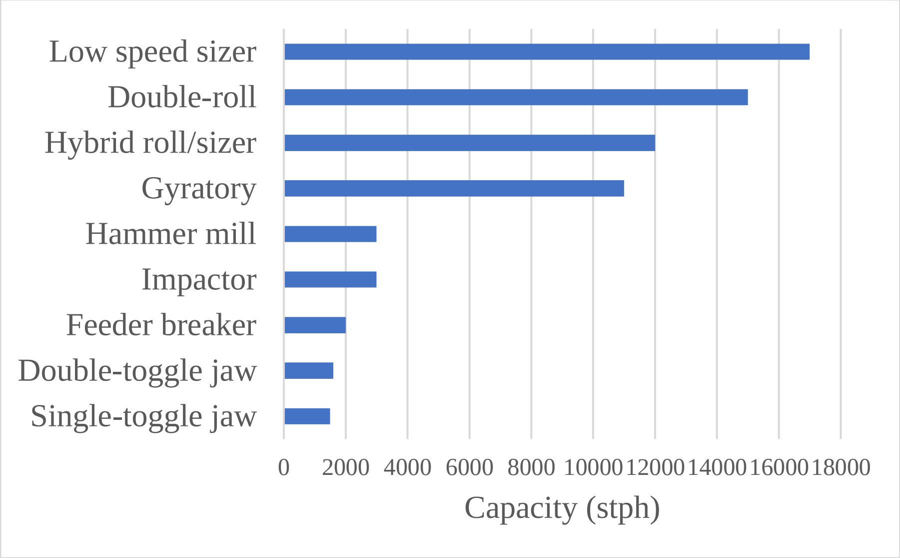


Figure 3.2: Crusher capacities per hour

In the mining industry, a gyratory crusher is the most preferred choice for IPCC systems. The crusher can reduce the size of the material ten times. It is preferred because of its easiness to start and install, high capacity per cost investment (Ritter, 2016; Michaud, 2020). Further, the power consumption of the gyratory crusher is relatively low compared to the jaw crusher and also gives finer and uniform product size (Gupta & Yan, 2006).The selection and design of a crusher depends on the following criteria;

- Type and characteristics of the material crushed.
- Required tonnage of the material hauled.
- The area, depth, and development of the open pit.
- Space availability (height and area) at the favourable crusher locations considering the mine design.
- Hauling options out of the pit.
- The type of downstream material flow in connection with the utilization of the entire crushing and conveying.

The crusher systems are broadly categorized depending on their mobility, location, and structural design. Using the selection and design criteria, the crusher system can be grouped into fully-mobile, semi-mobile, semi-fixed, and fixed crusher stations(Ritter, 2016; Wachira et al., 2021). Each of the category's unique attributes is summarized in Table 3.1 (Dzakpata et al., 2016; Ritter, 2016; Tonge & Nehring, 2017; Hay et al., 2019). The crusher station type is dependent and dictates the overall type of the IPCC.

The choice of the crusher used in the mining operation is primarily dependent on the compressive strength of the material and production capacity of the crusher. Figure 3.3 shows a summary of the common types of crushers and their applications.

Table 3.1: Summary of IPCC crusher parameters

Characteristic	**Fully Mobile**	**Semi-Mobile**	**Semi-Fixed**	**Fixed**
Relocation frequency	Frequently	Often	Infrequent	Not intended
Retention time at the site of operation	Hours	Weeks to years	Annual to perennial	Mine life
Mobilization time	Non	Hours	Days to weeks	-
Parts relocated	1	1	2-6	-
Relocation distance	Within metres	Hundreds of metres	Hundreds of metres to kilometres	-
Location	Working face	Working level	Centroid of mass	At or near pit rim
Undercarriage	Integrated	Adaptable	Adaptable	Not intended

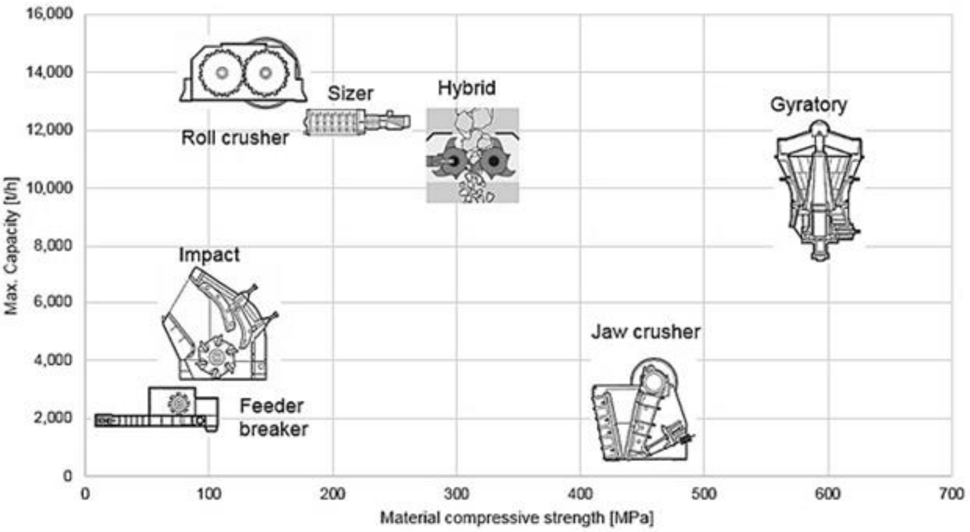


Figure 3.3: Range of application of crusher types

The crusher station comprises of other subsystems each having unique functionalities (Ritter, 2016; Abbaspour et al., 2019). These include crusher, auxiliary systems, framework, and undercarriage. The crusher design depends on the type of the crusher and the type of material being crushed. The feed hopper of the crusher is designed to hold a capacity of two to three truckloads of the trucks' capacity. The discharge chamber is located below the crusher holding a minimum of 1.25 times the capacity of the feed hopper. This provision prevents the crushed material from backing up into the crusher and damaging it.

Semi-mobile crusher stations are designed as direct dump stations incorporating high-speed conveyors capable of transporting the material at rates that exceed the crusher capacity. The initial gyratory crushers are fitted with an inclined apron feeder which facilitates the height of the station to be maintained within two bench heights hence allowing instantaneous dumping of material to the crusher. The following operational considerations must be met during the design and setting of a crusher station:

- Well ventilated space
- Optimal access to trucks or loaders

- Minimum noise and vibration
- Crusher operator visibility

The crusher reduction ratio defined as the ratio of the feed material size and the product particle size is essential in crusher design. Table 3.2 shows a summary of various crusher reduction ratios (Michaud, 2019).

Table 3.2: Crusher reduction ratios

Type	**Ratio**
Single or double toggle jaw crusher	6:1
Gyratory crusher	8:1
Standard head cone crusher	7:1
Fine head cone crusher	5:1
Hammer crusher	Up to 20:1
Impact crusher	Up to 20:1
Vertical roller mill	2-2.5:1

3.4 Conveyor Systems

A conveyor system is a combination of belt conveyors that are arranged to move the material from the crusher system to the discharge system. The selection criteria for the conveyors incorporates these factors:

- Size and weight of hauled material
- Physical characteristics
- Production requirements
- Haulage distance

Conveyor belts can be installed in an open pit mine either through a tunnel, a dedicated conveyor ramp or in an existing haul road. The conveyor belts are grouped into either fully mobile, semi-mobile, and fixed conveyors as illustrated in Figure 3.4 (Ritter, 2016).

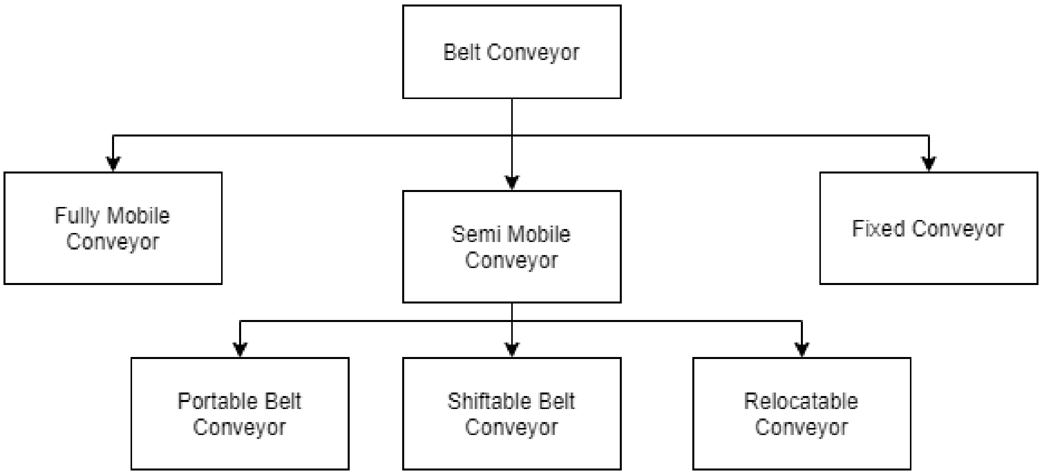


Figure 3.4: Belt conveyor categories

The fully mobile belt conveyors are utilized in fully mobile IPCC systems. They can change positions and are mostly used as an interlink between the fully mobile crusher and shiftable conveyors. The portable conveyors are inclined belt conveyors that primarily connect the crusher with the main conveyor. The portable conveyor illustrated in Figure 3.5 is mostly located at the operating face as well as in the dumping area to connect the discharge system with the main conveyor (Ritter, 2016).

Figure 3.5: Portable Belt Conveyor

The shiftable conveyors are located either in the operating or the dumping face. They are mounted on steel sleepers and moved by dozers without disassembly. The shiftable conveyors are moved periodically to follow the dump or operating face. On the other hand, relocatable conveyors are mounted on concrete sleepers and require disassembling during relocation. According to Rostami (2011), fixed conveyors also referred to as high-angle conveyors are built with no intention of relocation. These conveyors transport material of small sizes, approximately < 250 mm. The belt width of the conveyors is determined by the manufacturers and are currently ranging from 800 to 3200 mm. The choice of the conveyor is based on the reduced size of crushed material whereby the material size should be less than a third of the conveyor width.

3.5 Discharge System

This is the last component of the IPCC system. The discharge system dumps the material/ore from the conveyor to the final destination or storage points. The discharge system can be categorized as shown in Figure 3.6 depending on the material discharged and location (Ritter, 2016).

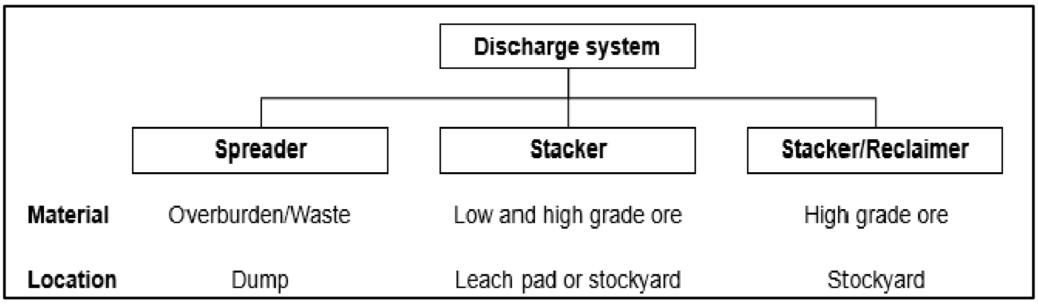


Figure 3.6: Categories of discharge system

According to Ritter (2016), the spreader is primarily made up of five elements namely:

a) A receiving boom (may have crawler track support),

b) A superstructure and substructure incorporated on crawler tracks,

c) A discharge boom and

d) A counterweight.

The spreader can be further grouped into either compact, c-frame, or cross pit depending on the design of their components. Stacker receives ore at the stockyard and stacks it stably. They are distinguished as single boom, double boom, and mobile stacking conveyors. Stacker/reclaimer operates stacks and recovers the material from the stockpile using a bucket. A discharge system should have a maximum deep cast height, low dust emission, low downtime due to dump conveyor shifting, and optimal human safety (Oberrauner & Turnbull, 201).

3.6 IPCC Components Configuration

Equipment in an IPCC system work in three main configurations: parallel, serial, and hybrid configurations. The parallel configuration is a setting in which components operate in a manner that as long as one of the components is available, the system remains functional (Hoda & Kamali, 2014). In IPCC operations, the discontinuous feed system of trucks and shovels can be categorized as a parallel configuration (Ritter, 2016; Abbaspour & Drebenstedt, 2019b). The system fails when all the individual components fail.

Serial configuration occurs when all components are required to be available for the system to operate. According to Hoda and Kamali (2014), the system availability for this configuration is derived by multiplying components of the system. In an IPCC system, the crusher, conveyors, and discharge system operate in a serial configuration. A hybrid configuration is a configuration that incorporates both parallel and serial configurations. IPCC system is regarded as a hybrid system having a combination of both serial and parallel configurations.

3.7 Summary

This chapter is summarised using Table 3.3 showing the advantages and disadvantages of the four IPCC systems (Ritter, 2016; Abbaspour and Drebenstedt, 2019a) .

Table 3.3: Advantages and disadvantages of IPCC types

System	**Advantages**	**Disadvantages**
FMIPCC	• Elimination of trucks • Reduced number of workers in the mine • Reduction of operational costs by the absence of trucks • Minimization of gaseous emissions	• Increased total capital costs • Increased maintenance associated with apron feeder • Increased costs associated with the movement of the mobile crusher station
SMIPCC	• Low bench height for dumping ore • Reduced truck delays due to low number of trucks • Reduced capital costs due to limited relocation of the crusher station • Ability to integrate a traditional plant configuration • Greater capacity and finer product size • Reduced maintenance costs due to	• The large heavy structure requires large transporters for moving • Higher overall height due to the requirement of a higher dump point bench level • There is a requirement for extensive bench-retaining walls

	the absence of an apron feeder	
SFIPCC	• Can be easily configured with traditional plants for in-pit crushers • The absence of an apron feeder reduces maintenance costs • It has a high crushing throughput • Reduced capital costs due to a minimal degree of mobility • There is increased long-term flexibility as the fewer relocations allow future changes and modifications • Greater capacity and finer product size due to the weight of the ore column	• Mounting of crusher stations involves expensive civil works • There is a requirement for extensive bench-retaining walls due to the high requirement of a higher dump point bench level
FIPCC	• Absence of apron feeder results in reduced maintenance • High crushing chamber throughput • Traditional plants with simple configurations can be configured with in-pit crushers	• It has less flexibility • Needs large fleet size as the mine operation progresses

4 DEVELOPMENT OF THE MINE PRODUCTIVITY INDEX MODEL

4.1 Chapter Overview

The methodology utilized in this thesis is summarized in Figure 4.1. Foremost, a model that calculates the MPi is developed in this chapter. Data is then obtained from the selected case study mine and prepared for application in the model. The results obtained from running the model with the case study is utilized in the evaluation of the IPCC systems as extensively discussed in the subsequent chapters.

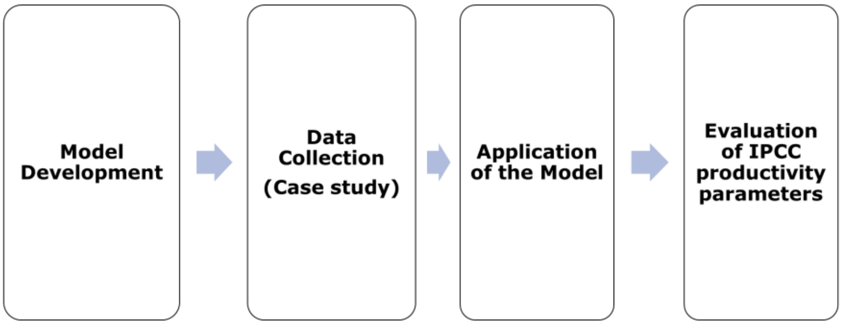


Figure 4.1: Summary of the methodology

Mathematical models have become common in solving problems in the mining industry. These models are used in simulation, prediction, prognostics, diagnostics, performance evaluation, and control system design (Abram et al., 1991). The increased popularity of models in the mining industry is justified by their ability to represent real situations and ease to use (Abram et al., 1991; Doble & Kumar, 2005). The development and application of mathematical models have increased the number of mining software that solve problems quickly and accurately. This research develops a model that measures system performance and productivity using the MPi. MATLAB platform is used in the implementation of the developed model.

4.2 Model development

The primary purpose of the model developed was to calculate MPi of the four IPCC systems. Generally, the model performed the following tasks:

- Calculated the availability, utilization, and performance of shovel, trucks, crusher, conveyor belt, and spreader,
- Calculated IPCC system's overall availability, utilization, and performance, and
- Computed the mine productivity index for each of the IPCC systems.

MATLAB software was utilized as the integrated development environment for the model development and execution. The conceptual framework for the model is as illustrated in Figure 4.2. The final index depends on three parameters: availability, utilization, and performance of the individual components.

The IPCC system comprises of five components that interact in a hybrid nature (in both series and parallel configurations). The MPi calculation is as shown in Equation 4.1 (Elevli & Elevli, 2010):

$$\mathrm{MPi} = \mathrm{Av}^{0.3} \times \mathrm{PP}^{0.5} \times \mathrm{U}^{0.2} \tag{4.1}$$

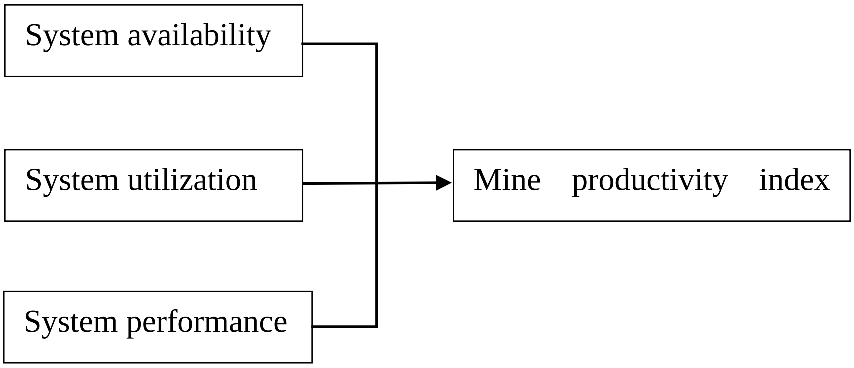


Figure 4.2: A model conceptual framework

where Av is system availability, PP is system performance, and U is system utilization. The overall Av, PP, and U are derived from the individual components as shown in Figure 4.3.

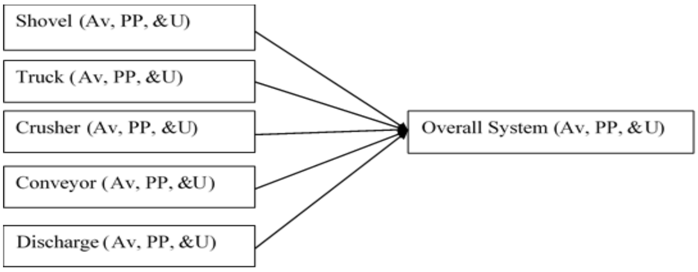


Figure 4.3: Calculation of overall system Av, PP & U

4.2.1 System Availability

IPCC system availability was calculated as the combination of the five components interacting in a hybrid nature. The number of trucks and shovels differ among the four IPCC systems. According to Abbaspour and Drebenstedt (2019b), there are four possible scenarios that an IPCC system can operate in. These scenarios have distinctive availability determination as summarized in Table 4.1.

Table 4.1: IPCC system availability

Number of shovels (NS)	**Number of trucks (NT)**	**System availability**
1	>1	$Av = A_s * [1 - (1 - A_T)^{NT}] * A_C * A_{CB} * A_{SP}$
>1	>1	$Av = [1 - (1 - A_T)^{NT}] * [1 - (1 - A_S)^{NS}] * A_C * A_{CB} * A_{SP}$
1	0	$Av = A_S * A_C * A_{CB} * A_{SP}$
>1	0	$Av = [1 - (1 - A_T)^{NS}] * A_C * A_{CB} * A_{SP}$

Where A_s is shovel availability, A_T is truck availability, A_C is crusher availability, A_{CB} is conveyor availability, and A_{SP} is spreader (discharge) availability.

4.2.2 System Utilization

The utilization of the overall system was calculated by computing the average utilization of all the components. Table 4.2 summarizes the utilization of each IPCC system. The summation of crusher, conveyor, and discharge components is represented by 3 in the equations.

Table 4.2: IPCC system utilization

IPCC Type	**Component**	**Utilization**	**System overall utilization**
FIPCC, SFIPCC, & SMIPCC	Shovels	U_S	$(N_s.\ U_S + N_T.U_T + U_C + U_{CB} + U_{SP})/\ (N_T + N_S + 3)$
	Trucks	U_T	
	Crushers	U_C	
	Conveyor belts	U_{CB}	
	Spreader	U_{SP}	
FMIPCC	Shovels	U_S	$(N_s.\ U_S) + U_C + U_{CB} + U_{SP})/\ (N_S + 3)$
	Crushers	U_C	
	Conveyor belts	U_{CB}	
	Spreader	U_{SP}	

4.2.3 System Performance

The overall performance was computed by getting the average performance of the individual components. Table 4.3 shows the performance calculation of each IPCC system. Similarly, the summation of crusher, conveyor, and discharge components is represented by 3 in the equations.

Table 4.3: IPCC system performance

IPCC Type	Component	Performance	System overall utilization
FIPCC, SFIPCC, & SMIPCC	Shovels	PP_S	$(N_s.\ PP_S + N_T.PP_T + PP_C + PP_{CB} + PP_{SP})/(NT + N_S + 3)$
	Trucks	PP_T	
	Crushers	PP_C	
	Conveyor belts	PP_{CB}	
	Spreader	PP_{SP}	
FMIPCC	Shovels	PP_S	$(N_s.\ PP_S)+PP_C + PP_{CB} + PP_{SP})/(N_S + 3)$
	Crushers	PP_C	
	Conveyor belts	PP_{CB}	
	Spreader	PP_{SP}	

4.3 Model Parameters Definition

The model calculates the MPi by combining the three parameters- availability, utilization, and performance. It considers the number of trucks and loading equipment in the system. According to Mohammadi et al. (2015), there exist inconsistencies in the definition of the three parameters and categorizing events resulting in the calculation of each parameter. For example, there are inconsistencies in grouping the scheduled maintenance as either planned shutdown time or under available time Elevli & Elevli, 2010; Mohammadi et al., 2015; Dzakpata et al., 2016). Therefore, there is a need to define the input parameters of the MPi model as illustrated in section 4.3.1 to 4.3.9.

4.3.1 Time Usage Model

According to Elevli and Elevli (2010), there are two categories of time usage models that are in use in mining operations: loading time approach and total calendar time. In the proposed model, the total calendar time approach, illustrated in Figure 4.4, is applied. The calendar-based time approach is preferred because the loading time approach ignores the non-scheduled time and scheduled maintenance time losses resulting in an overestimation of productivity (Elevli & Elevli, 2010; Mohammadi et al., 2015)

Ritter (2016a) groups the total calendar time into operating time and downtime. Operating time refers to the period in which the equipment service meter unit is running. It includes the operating time and the delays while in operation. The downtime is defined as the planned downtime and unplanned downtime.

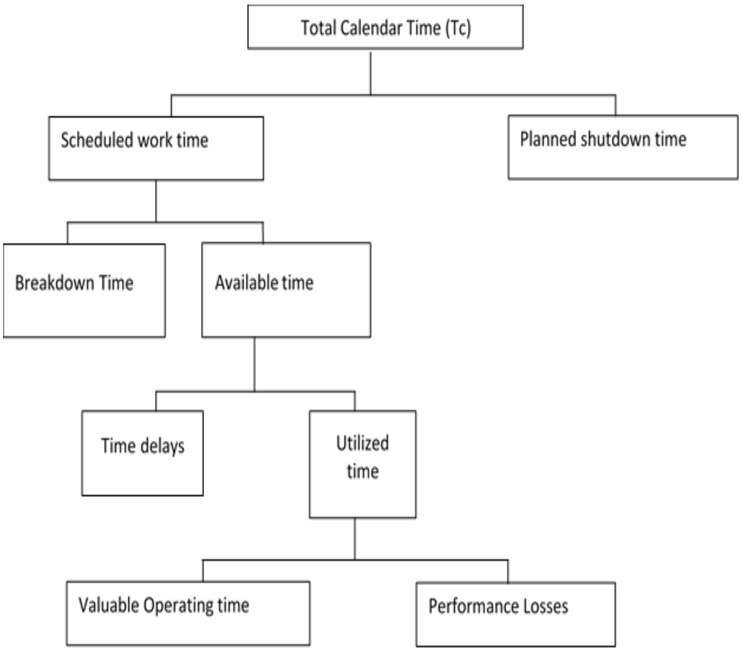


Figure 4.4: Breakdown of time usage model

Availability and utilization of equipment are determined using the breakdown of total calendar time. Mohammadi et al. (2015) state that time can be broken down into total calendar time, planned shutdown time (non-scheduled time for operation), planned operating time, breakdown time, idle time, set-up, and adjustment time, and utilization time. Elevli and Elevli (2010) categorize time into total time, scheduled downtime, net available time, operating time, net operating time, and fully productive time.

Several studies have shown that losses can be classified into downtime losses, speed losses, and defect losses (Nakajima, 1988; Rajput & Jayaswal, 2012; Elevli & Elevli, 2010; Mohammadi et al., 2015). Downtime losses are brought about by equipment failure, set up, and adjustment of equipment. Speed losses include reduced speed, idling, and minor stoppages while defect losses are caused by reduced yield and quality defects.

4.3.2 Total Calendar Time

Total time is the number of hours mining equipment is required to work in a given time, for instance, a year (Arputharaj, 2015). It is a management decision informed by various considerations such as output required, type of mineral, ore reserve, and market conditions among other factors. This can be 8 hours/Shift, 2 shifts/ day, 6 days/week, and 52 weeks/year.

4.3.3 Planned Shutdown Time (PSDT)

Planned shutdown time (PSDT) is the non-scheduled time for the operation of equipment. The events included in this category are scheduled non-work time, scheduled maintenance, industrial losses, daily service, weekly maintenance, scheduled maintenance, and crusher relocation hours (Morriss, 2008; Elevli & Elevli, 2010; Arputharaj, 2015; Mohammadi et al., 2015;).

4.3.4 Breakdown Time (BDT)

Breakdown time (BDT) includes the equipment breakdown time and the time taken to repair the equipment. It is the summation of all durations when equipment stops functioning to the time it is restarted. The mean time between failures (MTBF) and mean time to repair (MTTR) are useful in the determination of the breakdown time of equipment (Vagenas et al., 1997). Alternatively, the breakdown time can be determined as a percentage of the total scheduled working time of equipment.

4.3.5 *Availability (Av)*

Availability is the overall number of hours that equipment is available and fit for work with a specific given period. Mathematically, availability is calculated as illustrated in Equation 4.2 (Mohammadi et al., 2015).

$$\mathrm{Av} = \frac{\mathrm{AT}}{\mathrm{TT}} \tag{4.2}$$

$$\mathrm{AT} = \mathrm{TT} - (\mathrm{PSDT} + \mathrm{BDT})$$

AT is available time, TT is total time, BDT is breakdown time, and PSDT is planned shutdown time.

4.3.6 *Utilization (U)*

Utilization is described as the loss of available hours and represents the productive use of available hours.

It is calculated as:

$$\mathrm{U} = \frac{\mathrm{UT}}{\mathrm{AT}} \tag{4.3}$$

where UT is utilized time.

The events that result in the loss of hours of the available time include time lost during shift changes, attendance, and blast delays (Fourie, 2016). Manoeuvring time, meal breaks, and fuel/lubrication time are considered in the determination of the utilization of equipment (Morriss, 2008). Equipment utilization is also influenced by other specific factors such as waiting time in the case of loading equipment such as shovels.

4.3.7 *Performance (PP)*

Performance (PP) is the product of job management and equipment operating efficiencies. Job management efficiency is dictated by work conditions, environmental factors like weather, and human skills while operating efficiency is determined by the comparison of the achieved output to the rated equipment capacity (Arputharaj, 2015). Speed losses of the equipment, which is either a result of poor job management and equipment operating efficiency, have an impact on the performance of equipment (Elevli & Elevli, 2010). Performance of equipment is calculated using Equation 4.4.

$$\text{Performance } = \frac{(\text{ Operating time} - \text{Speed losses})}{\text{Operating time}} \times 100 \qquad (4.4)$$

Reduced speed losses are the difference that exists between the equipment-designed speed and the actual speed achieved.

4.3.8 Truck Cycle Time

The cycle time of a truck is generally categorized into four categories namely load, travel loaded, unload, travel empty (Rostami, 2011). Spot time and wait time are calculated in the cycle time during loading and unloading. The equation used to calculate the truck cycle time is defined as:

Truck Cycle time = (travel empty + wait time at loader + spot time + loading time + travel loaded + wait time at dumping + spot time + dumping time) (4.5)

The total travel time when loaded and empty is calculated from the speed of the vehicle and the travel distance (Dzakpata et al., 2016). The speed is dependent on the vehicle condition, road grade and condition, and traffic.

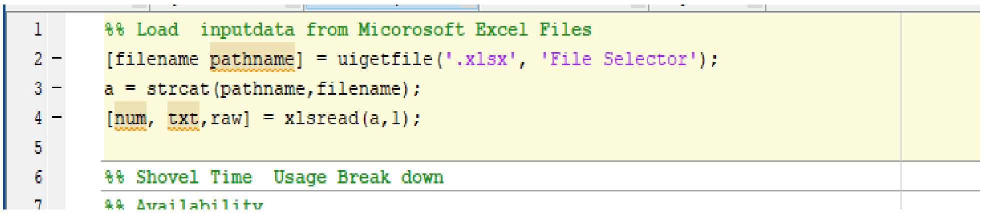
4.3.9 Loader Cycle Time

Loading cycle time is described as the time it takes loading equipment (excavator) to complete one entire excavating process (Rostami, 2011). This incorporates excavation time, the time it takes to swing to the dumping position, dumping time, and the time it takes to return to the digging position.

4.4 Development of IPCC Mine Performance Index Model Algorithm

The model algorithm used in the development of the application is summarised in a step-by-step procedure. The step-by-step procedure is outlined below.

1. Load input raw data from Microsoft Excel files that will be used in the model. This include time usage model and production parameters. The input data is imported from the excel file and assigned to different variables as illustrated in Figure 4.5.

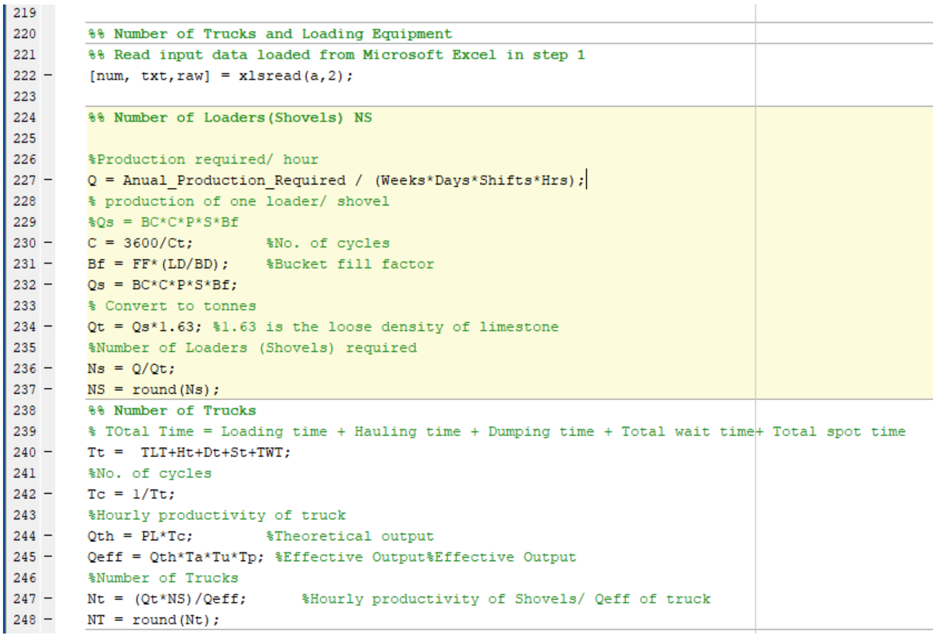


```
%% Load  inputdata from Micorosoft Excel Files
[filename pathname] = uigetfile('.xlsx', 'File Selector');
a = strcat(pathname,filename);
[num, txt,raw] = xlsread(a,1);

%% Shovel Time  Usage Break down
%% Availability
```

Figure 4.5: Loading input data to MATLAB

2. After loading the data in MATLAB, the model calculates the individual equipment availability, utilization, and performance.
3. The production parameters from the Microsoft Excel file are used to compute the number of shovels (NS) and the number of trucks (NT) as shown in Figure 4.6. The NS and NT are rounded off to the nearest whole number for subsequent calculations.



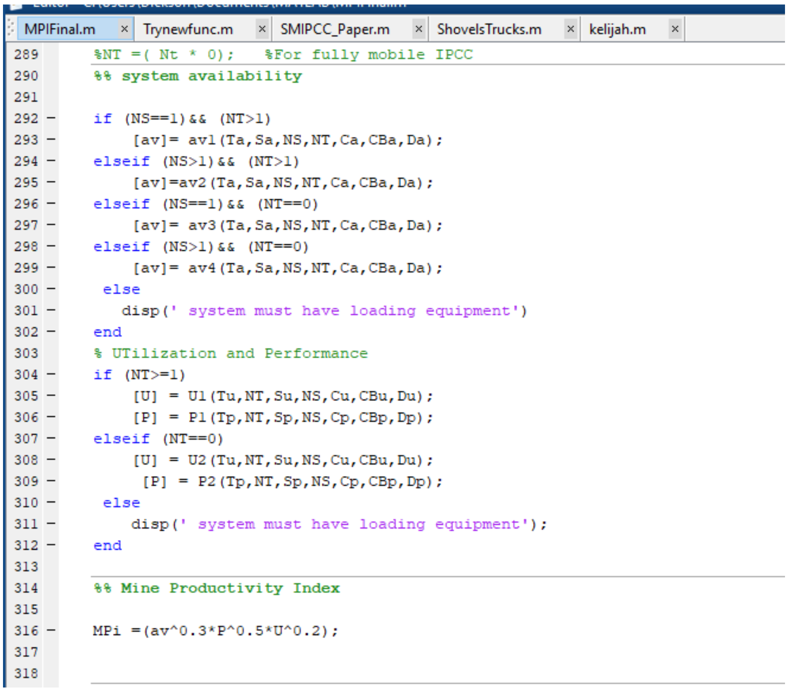
```
%% Number of Trucks and Loading Equipment
%% Read input data loaded from Microsoft Excel in step 1
[num, txt,raw] = xlsread(a,2);

%% Number of Loaders(Shovels) NS

%Production required/ hour
Q = Anual_Production_Required / (Weeks*Days*Shifts*Hrs);
% production of one loader/ shovel
%Qs = BC*C*P*S*Bf
C = 3600/Ct;        %No. of cycles
Bf = FF*(LD/BD);    %Bucket fill factor
Qs = BC*C*P*S*Bf;
% Convert to tonnes
Qt = Qs*1.63; %1.63 is the loose density of limestone
%Number of Loaders (Shovels) required
Ns = Q/Qt;
NS = round(Ns);
%% Number of Trucks
% TOtal Time = Loading time + Hauling time + Dumping time + Total wait time+ Total spot time
Tt =  TLT+Ht+Dt+St+TWT;
%No. of cycles
Tc = 1/Tt;
%Hourly productivity of truck
Qth = PL*Tc;        %Theoretical output
Qeff = Qth*Ta*Tu*Tp; %Effective Output%Effective Output
%Number of Trucks
Nt = (Qt*NS)/Qeff;      %Hourly productivity of Shovels/ Qeff of truck
NT = round(Nt);
```

Figure 4.6: Determining the number of shovels and calculations

Utilising the logical operator 'if-else' in MATLAB, the overall system availability, overall system utilization, and system performance is calculated. The 'if-else' considers the variables NT and NS for each scenario as illustrated in Figure 4.7.



```
%NT =( Nt * 0);   %For fully mobile IPCC
%% system availability

if (NS==1)&& (NT>1)
    [av]= av1(Ta,Sa,NS,NT,Ca,CBa,Da);
elseif (NS>1)&& (NT>1)
    [av]=av2(Ta,Sa,NS,NT,Ca,CBa,Da);
elseif (NS==1)&& (NT==0)
    [av]= av3(Ta,Sa,NS,NT,Ca,CBa,Da);
elseif (NS>1)&& (NT==0)
    [av]= av4(Ta,Sa,NS,NT,Ca,CBa,Da);
 else
   disp(' system must have loading equipment')
end
% UTilization and Performance
if (NT>=1)
    [U] = U1(Tu,NT,Su,NS,Cu,CBu,Du);
    [P] = P1(Tp,NT,Sp,NS,Cp,CBp,Dp);
elseif (NT==0)
    [U] = U2(Tu,NT,Su,NS,Cu,CBu,Du);
     [P] = P2(Tp,NT,Sp,NS,Cp,CBp,Dp);
 else
    disp(' system must have loading equipment');
end

%% Mine Productivity Index

MPi =(av^0.3*P^0.5*U^0.2);
```

Figure 4.7: MPi parameters calculation

Using the obtained parameters of availability, utilization, and performance, the MPi for the system is determined as shown in Figure 4.7.

Using the literature and current trends in the industry, the MPi is checked to confirm if it falls under the range of productivity and equipment performances. If not, the input variables are rechecked, and the algorithm repeated.

Various output graphs are drawn from the model calculations. These graphs include availabilities, utilization, and performance graphs.

Figure 4.8 shows a summary of the model.

4.5 Summary

The developed model described in this chapter calculates the MPi for the IPCC systems. The MPi model algorithm incorporates the determination of the trucks and shovels for each of the IPCC systems. The computer-aided application developed for this model was coded in MATLAB. Microsoft Excel 2019 spreadsheets were used for storage of raw data. The MPi model uses the system availability, utilization, and performance parameters in computation of the MPi. The model developed in this chapter is applied in a limestone quarry as the case study which is discussed in the next chapter (Chapter 5).

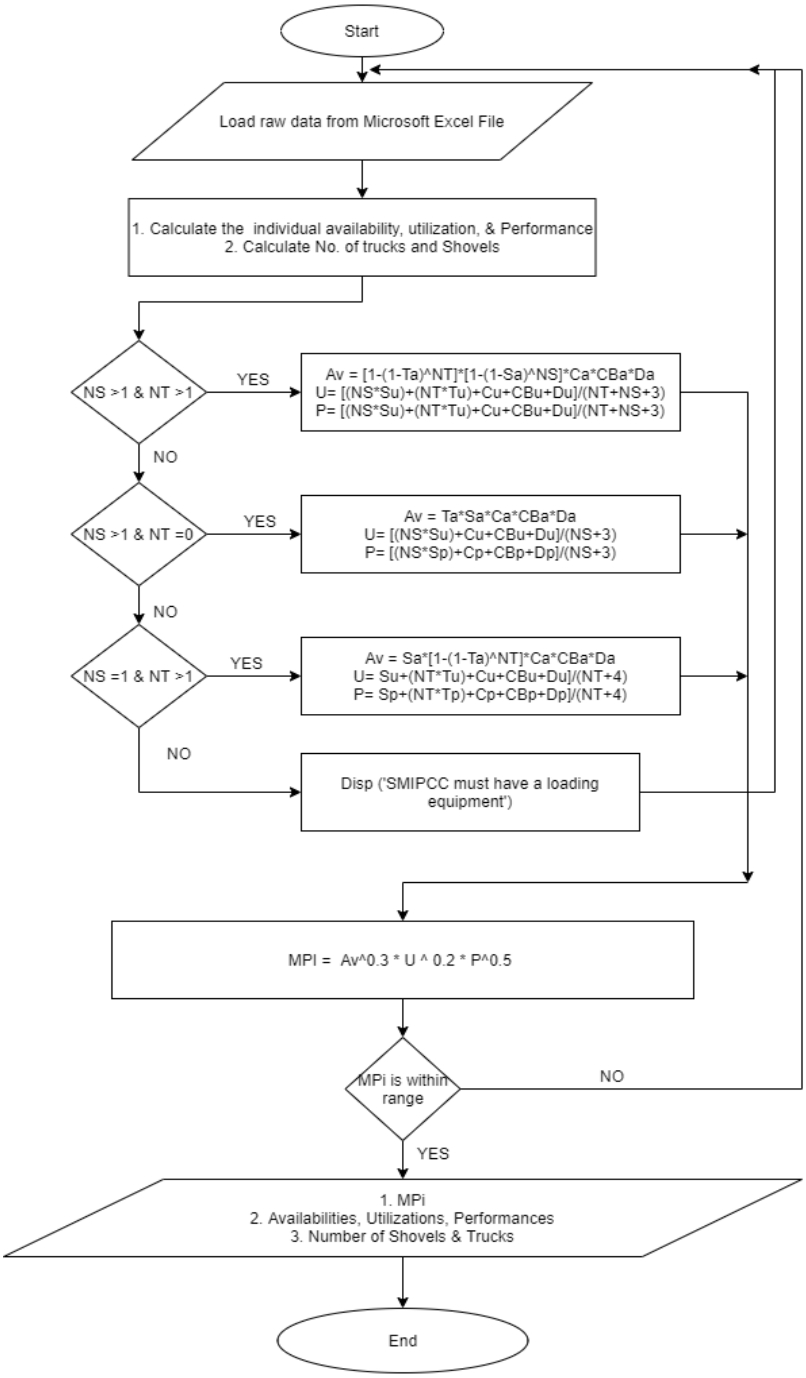


Figure 4.8: Model flow chart

5 APPLICATION OF THE MINE PRODUCTIVITY INDEX MODEL

5.1 Chapter Overview

The MPi model developed and described in the previous chapter is applied in limestone quarries operated by Mombasa Cement Limited (MCL) in the coastal part of Kenya. The cement company is located in Kilifi County, Kenya as shown in the map in Figure 5.1 (author's construct). The limestone quarry operations are similar to typical open pit mining operations that include drilling, loading, haulage, dumping of the extracted material. Therefore, the case study chosen will offer realistic results that are generalizable for open pit mines handling one material type.

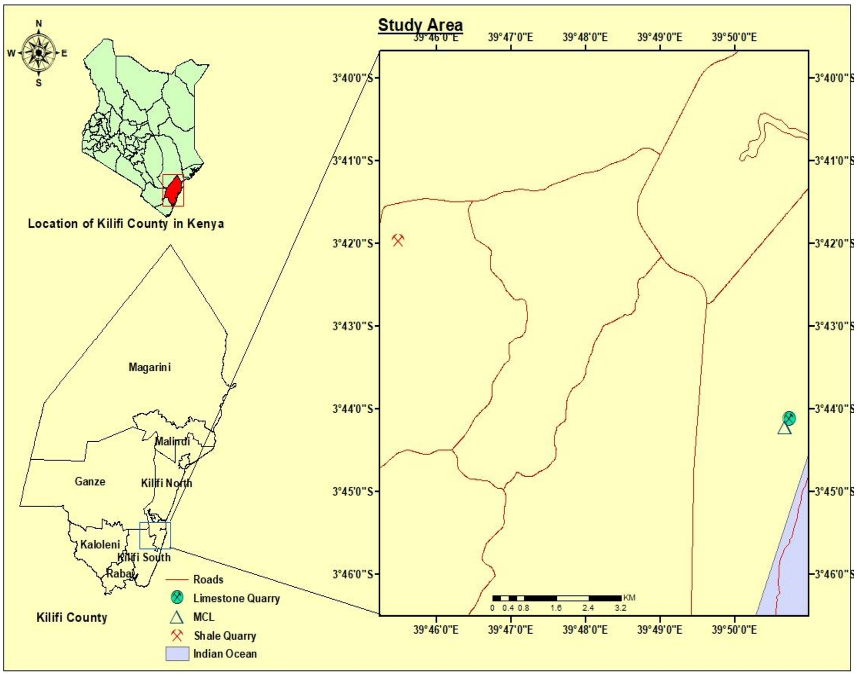


Figure 5.1: Case study area map

The data from the company was taken during the month of February 2020. It was acquired through field observations, time recording, and interviews which were recorded in log sheets. It was later simulated using Monte-Carlo simulation method to generate data that would be applied in the developed model. Monte Carlo simulation uses statistical and graphical techniques, including linear and nonlinear modelling to simulate probable distribution of the data. The detailed mathematical calculations underlying the method are not presented, as they are beyond the scope of this study. The Monte Carlo method is one of the statistical methods with a computational algorithm using randomness to solve problems that might be deterministic (Githiria, 2018).

The limestone quarry in this study employs a fixed IPCC haulage configuration with trucks, excavators, conveyor belts and a crusher. The data collected contains the following information: quarry production data, truck and excavator cycle time data and annual time usage breakdown data.

The production and cycle time data is used to calculate the number of trucks and loading equipment required for each IPCC configuration while the annual time usage breakdown data is used to calculate the equipment availability, utilization, and performance. Utilisation and performance are calculated from the shift time usage breakdown.

5.2 Input parameters used in determining the number of trucks and shovels

In determining the number of loaders and trucks required in a specific mining operation, in order to achieve the required tonnage, the cycle time is determined using Equations 5.1 and 5.2, respectively. The other parameters are collected from the quarry operation and tabulated as shown in Table 5.1.

$$\mathrm{Q} = \mathrm{Bc} \times \mathrm{c} \times \mathrm{p} \times \mathrm{s} \times \mathrm{Bf} \tag{5.1}$$

Where Bc represents bucket capacity, Q is quantity required (t/h), c is cycles per hour, s is swing factor, p is production factor, and Bf is bucket fill factor (i.e., filling factor * (loose density/bank density).

$$Q = Bc \times c \times Pe \times n \tag{5.2}$$

Where Bc represents the tray capacity, Q is quantity required (t/h), c is cycles per hour, Pe is efficiency factor, and n is the number of trucks.

Table 5.1 Quarry production data

Parameter	**Value**
Annual production required (tonnes)	2,700,000
Weeks per year	52
Days per week	6
Shifts per day	2
Hours per shift	8
Limestone loose density (kg/m^3)	1630
Limestone bank density (kg/m^3)	2608
Excavator capacity (m^3)	3.5
Truck capacity (tonnes)	27

The excavator and truck cycle times were observed and recorded in log sheets as shown in Table 5.2 and 5.3. The truck cycle time recorded data included travel empty time, waiting time at loader and dump, spot times at loader and dump, travel loaded time, loading time, and dumping time. The excavator cycle time recorded included excavation time, swing time when loaded and empty, dumping time and wait and spot time.

The loader cycle time is determined as a summation of excavation time, swing time when loaded and empty, dumping time, and wait and spot time. The repetitive cycle times recorded from the quarry operations were simulated to generate a more reliable result.

Table 5.2: Loading time for the excavators (Doosan)

Entry Number	**Excavator-SL019 (3.5 m^3)**		**Excavator-SL018 (3.5 m^3)**		**Excavator-SL065 (3.5 m^3)**	
	Time (mins)	**No. of passes**	**Time (mins)**	**No. of passes**	**Time (mins)**	**No. of passes**
1	4.30	10.00	5.13	12.00	2.43	7.00
2	4.35	10.00	5.02	12.00	2.22	7.00
3	5.03	12.00	5.31	12.00	2.29	7.00
4	4.22	10.00	3.18	7.00	2.35	7.00
5	5.10	12.00	5.34	12.00		
6	5.35	12.00	4.12	10.00		
7	2.54	6.00	3.24	7.00		
8	4.57	11.00	4.25	10.00		
9	4.20	10.00	4.41	10.00		
10	4.41	10.00	4.05	9.00		
11	3.52	8.00	5.13	12.00		

Table 5.3: Truck cycle time data (Shacman)

Entry Number	**Travel empty (mins)**	**Travel loaded (mins)**	**Dump time (sec)**	**Wait time when loading (mins)**	**Wait time when dumping (mins)**	**Spot time (secs)**
1	15.00	18.00	39.00	0.30	4.10	31.00
2	13.00	19.00	27.00	3.09	1.00	43.00
3	11.20	17.00	28.00	2.10	0.50	49.00
4	16.00	28.00	34.00	7.51	5.30	48.00
5	12.00	23.00	36.00	9.35	6.05	52.00
6	15.00	18.00	29.00			48.00
7	13.50	21.00	35.00			76.00
8	11.00	17.00	20.00			34.00
9	14.00	28.00	23.00			43.00
10	12.00	24.00	33.00			42.00

The data required to calculate the MPi in the developed model should be in an annual basis. Therefore, the recorded repetitive data in the log sheets was simulated to obtain a more reliable mean value for each event. Therefore, the cycle time data was taken through Monte Carlo simulation, which uses statistical and graphical techniques, including linear and nonlinear modelling to simulate probable distribution of the data (Paricheh & Osanloo, 2016; Githiria, 2018; Sağlam & Bettemir, 2018).

Monte Carlo simulation method was applied in this study to generate independent, random values from the probabilistic model. The simulation was undertaken using an Excel add-on, RiskAMP. It utilizes mean value and standard deviation of the data being simulated. In instances where the two input parameters were inadequate, the minimum and maximum industry values were incorporated for the simulation. The procedure undertaken in simulating the data in RiskAMP interface is attached in Appendix 2. The overall truck and loader parameters after simulation of cycle time components is summarized in Table 5.4. This data is used as an input in the MPi model to compute the number of trucks and shovels.

Table 5.4: Summary of simulation data

Item	**Value**
Loader loading time (minutes)	4.50
Passes	9.00
Truck travel empty (minutes)	13.94
Truck travel loaded (minutes)	21.97
Dumping time (seconds)	31.32
Truck wait time when dumping (minutes)	3.92
Truck spot time (seconds)	45.33
Truck wait time when loading (minutes)	5.39
Truck capacity (tonnes)	27.00
Loader waiting time (minutes)	1.16

5.3 Input Parameters used in Calculation of Av, U and P

The time usage breakdown data is used in calculation of availability, utilization, and performance of individual equipment. Time usage breakdown is the breakdown of annual hours of operation. The availability is determined from the available hours breakdown as summarized in Table 5.5. The time usage breakdown for the other IPCC system is illustrated in Tables 9.1, 9.2 and 9.3 in Appendix A.

Table 5.5 Current system operating hours (FIPCC)

Availability	**Shovel**	**Truck**	**Crusher**	**Conveyor**	**Spreader**
Calendar hours	8760	8760	8760	8760	8760
Scheduled non-work time	192	192	192	192	192
Wet weather losses	270	270	270	270	270
Crusher relocation losses	0	0	0	0	0
Industrial losses	0	0	0	0	0
Scheduled Hours	8298	8298	7962	8298	8298
Daily service	270	330	365	243	365
Weekly maintenance	365	365	365	365	365
Annual maintenance shutdown	168	168	336	0	168
Scheduled maintenance	803	863	1066	608	898
Breakdown as % scheduled	4%	4%	4%	2%	3%
Breakdowns	331.92	331.92	318.48	165.96	248.94
Available hours	7163.08	7103.08	6900.08	7524.04	7151.06

Table 5.5 shows a summary of the available operating hours in a year for the current fixed IPCC system in operation at the quarry. A unique time component for the FMIPCC, SMIPCC, and SFIPCC is the crusher relocation hours. The relocation of the crusher is undertaken after every one or two years and takes 2-3 days (Abbaspour and Drebenstedt, 2019a). Mostly, during the relocation time, the processing plant is fed from the stockpile or is scheduled to coincide with the non-scheduled working hours (Mohammadi, Rai and Gupta, 2015). The relocation time incorporates both the crusher and belt conveyors' relocation hours. The overall relocation hours and the haulage distance to the crusher are summarized in Table 5.6.

Table 5.6: Crusher relocation hours for IPCC systems

Parameter	**FIPCC**	**SFIPCC**	**SMIPCC**	**FMIPCC**
Truck Haul Distance (Km)	10	3	1.5	0
Crusher type	Any	Any	Any	Sizer, Jaw/double roll crusher
Total Relocation Hours	-	336	336	192

The relocation hours in Table 5.6 has an impact on the available hours of the crushers in FMIPCC, SMIPCC, and SFIPCC configurations. As mentioned earlier, utilization and performance are determined using shift time breakdown. Table 5.7 shows a breakdown of shift time usage for the current system in operation (FIPCC system). Other configurations shift time usage data are summarized in Tables 9.1, 9.2 and 9.3 in Appendix A.

SMIPCC and SFIPCC configurations have similar time breakdown with FIPCC. However, FMIPCC has different shift time usage breakdown since it has a higher loading equipment manoeuvre time since the shovel loads directly to the mobile crusher. Additionally, FMIPCC does not have trucks in the system.

Table 5.7: Shift time usage breakdown

FIPCC operating time (minutes)				
	Shovel	**Truck**	**Crusher**	**Spreader**
Shift duration	480	480	480	480
Shift change	10	10	10	10
Equipment inspection	10	10	10	10
Meal break	30	30	30	30
Blasting delays	0	0	0	0
Fuel/lubrication	15	25	15	0
Manoeuvre	4%	0%	0%	0%
Waiting time	30	50	0	0
Other delays	20	10	0	0
Total delays	134.2	135	65	50
Effective operating time	345.8	345	415	430
Time loss due to job conditions	11	11	11	11
Speed losses	30	50	25	25
Operator efficiency time losses	24	30	5	5
Total losses	65	91	41	41
Net operating time	280.8	254	374	389

5.4 MPi Model Results

The data obtained from Monte Carlo simulation (time usage breakdown and production data is run in the MPi model to generate system availability, utilisation and performance for each component as shown in the next section.

The overall system MPi of the four IPCC systems are presented in this section validating the applicability of the developed model in open-pit mining. The results obtained are used in the evaluation of the four IPCCs. The results are summarised into two sections since FMIPCC has a slightly different configuration with no trucks in the system.

5.4.1 FIPCC, SFIPCC, and SMIPCC Results

The individual equipment availability, utilization, and performance results are illustrated in Table 5.8, in percentage, for FIPCC, SFIPCC, and SMIPCC systems.

Table 5.8: Individual equipment parameters in percentage

FIPCC system	**Shovel**	**Truck**	**Crusher**	**Conveyor**	**Discharge**
Availability	81.77	81.09	78.77	85.89	81.63
Utilization	72.04	71.66	86.46	89.58	89.58
Performance	81.20	73.62	90.12	90.47	90.47
SFIPCC system	Shovel	Truck	Crusher	Conveyor	Discharge
Availability	81.77	81.09	75.09	85.89	81.63
Utilization	73.08	72.92	86.46	89.58	89.58
Performance	82.90	78.57	90.12	90.47	90.47
SMIPCC system	Shovel	Truck	Crusher	Conveyor	Discharge
Availability	81.77	81.09	75.09	85.89	81,63
Utilization	75.17	75.00	86.46	89.58	89.58
Performance	83.37	80.28	91.33	91.63	91.63

Table 5.9 represents a summary of overall system parameters for FIPCC, SFIPCC, and SMIPCC obtained after running the model.

Table 5.9: Overall system MPi parameters

Parameter	**FIPCC**	**SFIPCC**	**SMIPCC**
No. of Shovels	2	2	2
No. trucks	55	19	11
System Availability	53.39 %	50.90 %	50.90 %
System Utilization	72.65 %	74.73 %	77.41 %
System Performance	74.63%	80.26 %	82.63 %
MPi	67.13 %	69.02 %	70.52 %

5.4.2 FMIPCC Results

The FMIPCC system has no trucks, instead, the shovel loads directly to the crusher. As a result, the utilization and performance of the shovel drastically reduces due to increased manoeuvring time and other reduced speed delays. Using a 3.5m^3 shovel with the FMIPCC data in the developed model, the overall results are generated as illustrated in Table 5.10.

A system operating with 5 shovels is not feasible for the quarry. Most crusher stations are designed to accommodate two equipment dumping at one time. Therefore, using 5 shovels will lead to substantial delays failing to achieve the required annual productivity.

For the FMIPCC to achieve the desired annual production, the bucket size needs to be adjusted to 7.5m^3. The change of bucket size has an implication on the cycle time and overall performance. Table 5.11 and Table 5.12 shows the summary of the results obtained after adjustment.

Table 5.10: FMIPCC system MPi parameters (3.5 m^3 shovel)

Parameter	**Value**
Number of shovels	5
Number of trucks	0
System availability	53.66 %
System utilization	73.65 %
System performance	80.85 %
MPi	70.17 %

Table 5.11: FMIPCC individual equipment parameters (7.5 m^3 shovel)

FMIPCC	**Shovel**	**Crusher**	**Conveyor**	**Discharge**
Availability	81.77 %	76.66 %	88.05 %	79.51 %
Utilization	65.92 %	81.42 %	89.08 %	89.08 %
Performance	76.30 %	85.67 %	89.24 %	90.41 %

Table 5.12: FMIPCC overall system MPi Parameters (7.5 m^3 shovel)

Parameter	**Value**
No. of Shovels	2
No. trucks	0
System Availability	51.89%
System Utilization	78.28%
System Performance	83.58 %
MPi	71.52%

5.5 Model Validation

Model validation is the process of confirming that the developed model achieves its intended purpose and the results obtained are reliable. The discussion on this section focuses on highlighting the quality of the results that are obtained from the MPi model. According to Ritter (2016), the FIPCC have the highest number of trucks due to the distance between the operation face and the dumping place. Similarly, the model developed in this study achieves the same results with FIPCC recording the highest number of trucks.

Abbaspour & Drebenstedt (2019b) developed a technical index model utilizing dynamic modelling. The model incorporated determination the determination of system availability and utilization. The results obtained from these calculations are in the same range as those obtained from the MPi model with a difference of approximately 5%. Additionally, the results of the developed model is within the theoretical arguments made by other researchers as cited in subsequent sections of this study.

5.6 Summary

The developed model (MPi model) is applied and implemented on the limestone quarry to compute the number of trucks and shovels, system availability, utilization, and performance for the different IPCCs. In this chapter, the data used in the model is illustrated as shown in the Tables 5.2 to 5.7. Monte Carlo simulation is used to simulate the raw cycle time recorded at the quarry to obtain more reliable data for use in the model computations.

Among the four IPCC configurations, the FMIPCC has a distinctive difference among the systems due to the lack of trucks in the system. This makes its computation unique. For instance, initial results for FMIPCC system indicated that the system needs five loading equipment to achieve the annual throughput. As explained in section 5.4.2, there is a need to adjust the number of shovels by increasing the bucket size. As a result, other parameters are readjusted accordingly. Using the results obtained in this chapter, the next chapter (Chapter 6) offers an in-depth discussion in the evaluation of the IPCC systems.

6 RESULTS AND DISCUSSION

6.1 Chapter Overview

This chapter discusses the results obtained from the MPi model for the four IPCC systems. The evaluation is done based on the number of trucks and shovels, system availability, utilization, and performance. The overall MPi for the four IPCC configurations is also evaluated.

6.2 Number of Trucks

The number of trucks significantly differs among the four systems as shown in Figure 6.1. The FIPCC has the highest number (55) while FMIPCC has the least with no trucks in the system. The SMIPCC records 11 trucks while SFIPCC 19. The number of trucks has implications on the overall operational costs of the systems, specifically, the labour costs, fuel costs, and maintenance costs. The changes in the number are caused by the changes in distance to the dumping crusher station.

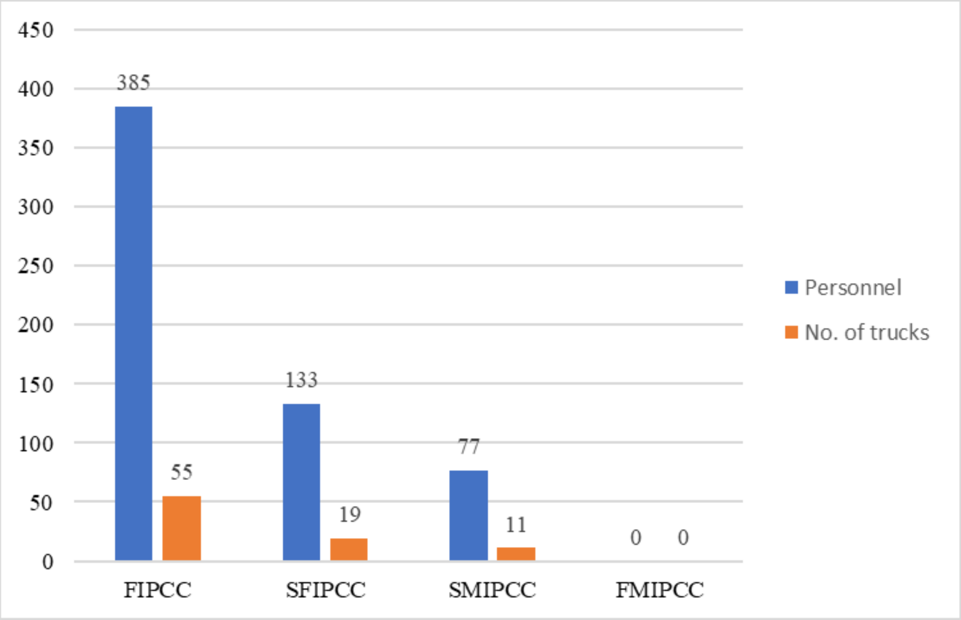


Figure 6.1: Number of trucks and personnel

A high truck fleet size for the FIPCC implies a higher number of personnel needed for operating the trucks and maintenance. According to Nehring *et al.* (2018) and Dean *et al.* (2015), it is estimated that one truck requires approximately seven people to operate. These include approximately 4 operators and 3 maintenance workers for a 12 hour-shift per day. From this approximation, the number of staff required for the four IPCC systems for truck operations is summarized in Figure 6.1. The FIPCC will require approximately 385, SFIPCC 133, SMIPCC 77, and FMIPCC zero people to operate.

The FIPCC requires twice the personnel compared to SFIPCC and SMIPCC while FMIPCC has no personnel due to the lack of trucks in operation. In current global costing trends, labour costs have risen with many countries raising their minimum wage (Dansereau, 2006). It is the expensive aspect of labour costs that encourages the search for alternatives in material handling systems. Other technical and economic impacts that are related to selection of fleet size include the truck maintenance costs, fuel consumption, road maintenance, gaseous emissions, and safety in mines. Due to these factors, the best choice of material handling system is the one with minimal trucks. However, zero trucks in the system limits system flexibility and applicability in open-pit mines with irregular shaped orebodies.

6.3 Number of Shovels

The number of the shovels is maintained at two for the four IPCC systems as shown in Figure 6.2. However, the FMIPCC which has no trucks theoretically requires 5 shovels to achieve the required production. Operating 5 shovels in a limestone quarry is not feasible hence an adjustment of size from 3.5 to 7.5 m^3.

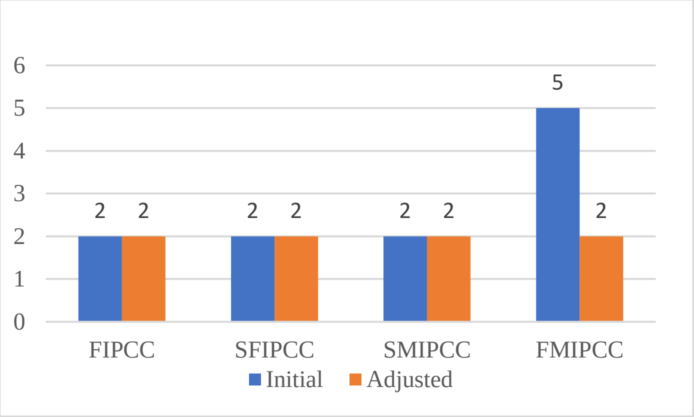


Figure 6.2: A graph of loaders and trucks of IPCC systems

Klanfar, Korman and Kujundžić (2016) showed that fuel consumption is influenced by the equipment size. The cost analysis done regarding the loading equipment shows that FMIPCC will have higher operational costs compared to the other IPCC configurations that operates with two shovels. The change of the shovel parameters has impacts on the overall operational costs of the mining.

6.4 System Availability

A system is regarded as available when it meets three primary qualifications- functioning equipment, functioning under normal conditions, and functioning when needed. Accordingly, a system is only available when all its components and sub-systems meet the mentioned criteria. It is therefore expected that the overall system availability will be lower than the individual components as illustrated in Figure 6.3. This is because a system in the hybrid configuration as IPCC will only be regarded as available when all of its subsystems are available.

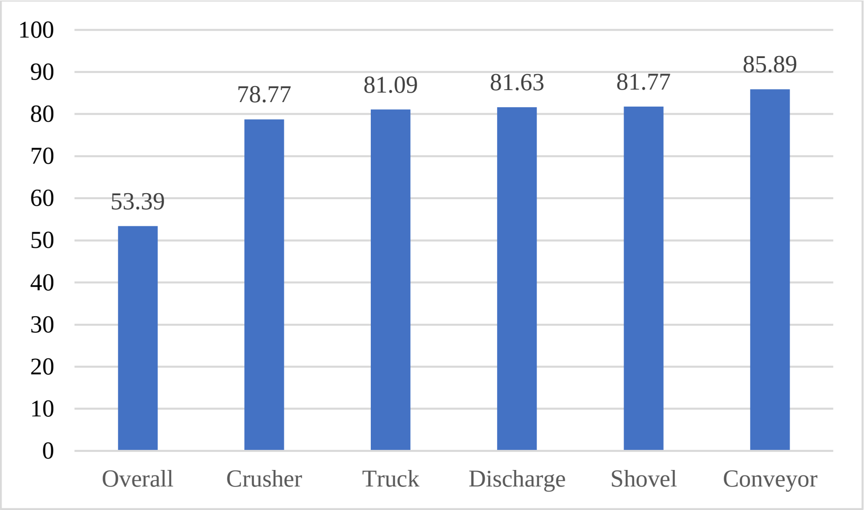


Figure 6.3: FIPCC individual component availability

As shown in Figure 6.4, FIPCC records the highest availability (53.39%) justified by the large fleet size. Many trucks in the system imply a low probability of total failure in event of the unavailability of several trucks. The system can continue running even without the availability of one or two trucks (Abbaspour and Drebenstedt, 2019b). FMIPCC has slightly higher availability compared to the SFIPCC and SMIPCC.

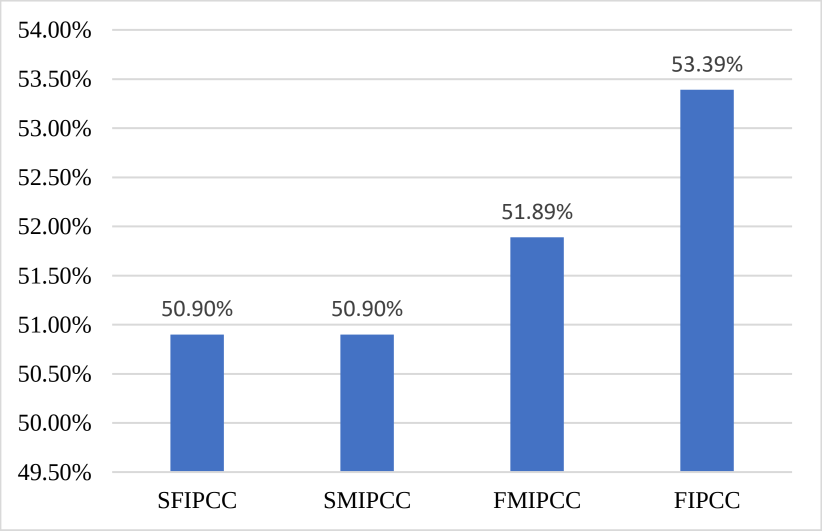


Figure 6.4: IPCC system availability

6.5 System utilization

Overall system utilization is the average of individual equipment utilization in the system. As illustrated in Figure 6.5, the conveyors, discharge system, and crushers have the highest utilization while trucks and shovels have the lowest utilization. The low truck and shovel utilization is associated with improper fleet control and management.

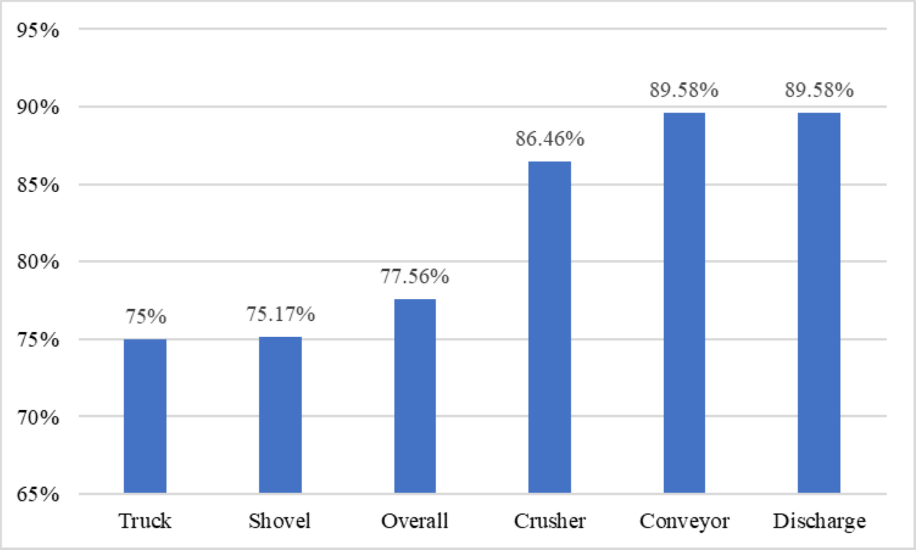


Figure 6.5: FIPCC equipment utilization

System utilization is highest in FMIPCC (78.28%) and lowest in FIPCC (72. 65%) as illustrated in Figure 6.6. Utilization decreases with an increase in number of trucks since a higher number of trucks in the system implies more stoppages and delays in the operations.

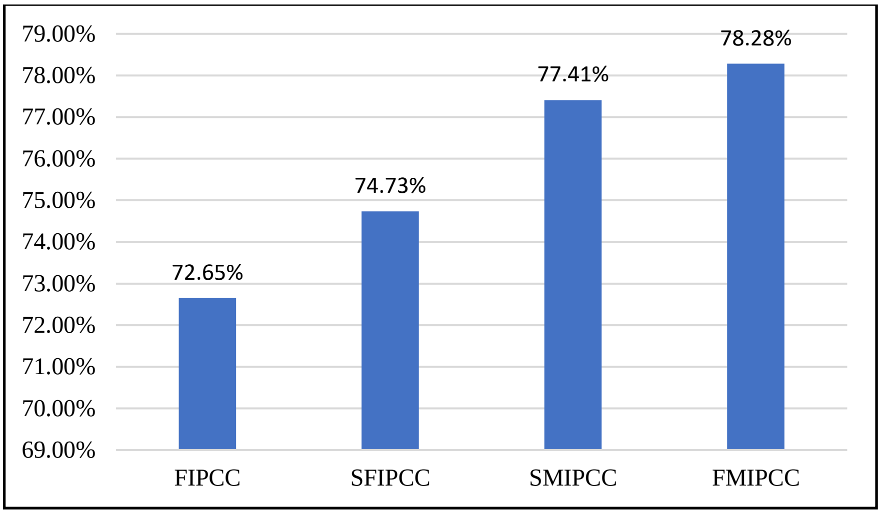


Figure 6.6: IPCC system utilization

Utilization is also influenced by factors impacted by the personnel such as lunch breaks and shift changes. A higher number of personnel results in increased time delays during the shift change and breaks hence generating low system utilization. Consequently, FMIPCC is better utilized compared to other systems and this has an impact on the cost per tonne produced in the system.

6.6 System Performance

The performance of the crusher, conveyors, and discharge system records the highest performance while the truck and shovel components have lower performance as shown in Figure 6.7. This is justified by high-speed losses, low operator efficiency and job conditions in trucks and shovels compared to other components.

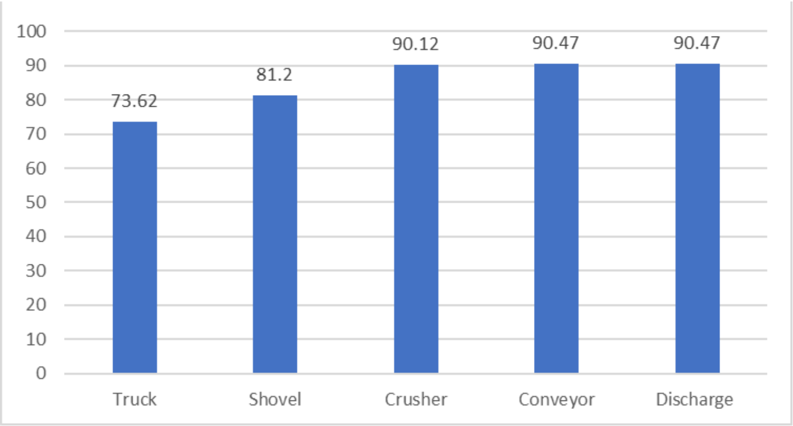


Figure 6.7: FIPCC equipment performance

As illustrated in Figure 6.8, FMIPCC records the highest system performance of 83.58% while the FIPCC has the lowest performance of 74. 63%.

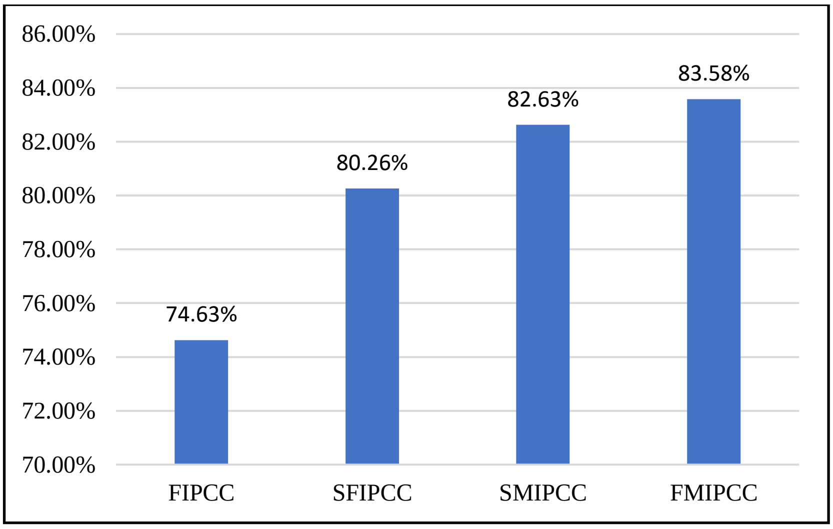


Figure 6.8: IPCC system performance

6.7 Mine productivity index (MPi)

The MPi which is the primary objective of this study is summarized in Figure 6.9. FIPCC system has the lowest productivity index (67.13%) while the FMIPCC has the highest MPi (71.50%). From these results, it is apparent that high number of trucks results in higher system availability but leads to low overall productivity. This is because productivity is more impacted by the valuable operating time of all equipment. According to Dzakpata *et al.* (2016), 45% of shovel operating time is spent spotting trucks hence reduced productivity for systems with truck-shovel interaction. Therefore, productivity increases with reduction of the number of trucks.

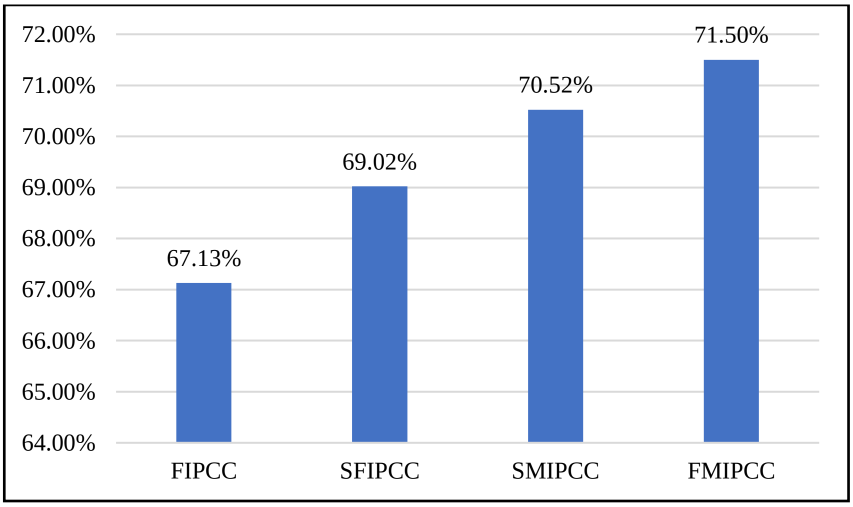


Figure 6.9: IPCC overall MPi

The MPi generated for all the IPCC systems is above 60%, which is above the standard in the industry. However, it is less than 85%, the industrial 'world class' benchmark (Anon, n. d). Therefore, the current system parameters affecting operation of the four IPCC systems can be optimized.

6.8 Summary

The chapter provides an evaluation of the four systems based on number of trucks and shovels, system availability, utilization, performance, and MPi. The number of trucks significantly differs among the four IPCC systems as a result of the distance between the loading and dumping location. FMIPCC has no trucks in the system, instead, the loading equipment loads directly to the mobile crusher.

Theoretically, 5 shovels of 3.5 m^3 was required to meet the annual throughput in FMIPCC system. However, operating five shovels in the quarry would have major operational challenges, therefore the shovels are readjusted to 2 shovels by increasing the bucket size to 7.5 m^3. This modification has cost implications to the FMIPCC system.

Evaluation of the four IPCC systems is done based on the number of trucks and shovels, availability, utilization, performance, and MPi. These parameters are evaluated to determine the implications of the system operation to the cost, throughput, and operating efficiency of the systems. The results generated for the case study show that the FMIPCC has a superior MPi compared to its counterparts. The next chapter (chapter 7) presents conclusions and recommendations based on the findings made from the developed model.

7 CONCLUSION AND RECOMMENDATIONS

This chapter is subdivided into two subsections: conclusions and recommendations. The first section summarises the work described in this thesis showing how it has met its objectives by evaluating the four IPCC systems used in open-pit mines. It also outlines the main contributions of the thesis to the industry. The second section lays down some recommendations for future work arising from results of this thesis.

7.1 Conclusion

In mining operations, haulage costs accounts for the highest percentage of the operational costs with values between 50-60%. The conventional truck and shovel transportation approach has continually become more expensive hence the need for an alternative haulage approach. Research done on the plausible alternatives has shown IPCC as the best option, however, there is limited knowledge on the technical aspect of IPCC system which has limited its consideration. This thesis has discussed and analysed the aspect of the productivity index for the IPCC.

An algorithm is developed in this research thesis to determine the productivity index of the IPCC systems. The developed model utilizes individual equipment availability, utilization, and performance to compute the overall MPi. The system number of trucks and loading equipment is also crucial in the determination of the index. The developed model is applied in a limestone quarry as the case study and the results are used in evaluation of the four IPCC systems. The model is validated as its results are in compliance with the scientific facts and previous studies done on IPCC systems. Evaluation of the IPCC systems is done based on the number of trucks, the number of shovels, system availability, system utilization, system performance, and MPi.

This thesis determines the IPCC productivity by utilizing the mine productivity index. The index uses three variables: availability, performance, and utilization. Overall, the FMIPCC has a superior MPi of 71.5% compared to its activities. In the case study, the fixed IPCC configuration is similar to the conventional truck-shovel and records the least MPi (67.13%). Additionally, the evaluation of the IPCC from other parameters indicates a significant difference in the operational costs through a difference in personnel, fuel costs, and maintenance. While MPi offers a basis for choice among the four IPCC systems, cost analysis of the systems is critical for better-informed decision making. Therefore, further research on the cost analysis of all the IPCC systems as a haulage option needs to be undertaken for a more holistic evaluation and comparison.

The number of trucks in a system has a significant on the overall productivity index. Primarily, fleet size has higher impact on the overall availability and minimal effect to system utilization and performance. From the results, a high number of trucks leads to higher system availability but lower performance and utilization.

In calculation of MPi, availability has the lowest weight hence low influence on the overall productivity. Accordingly, the IPCC systems with higher trucks have higher availability and lower MPi while the system with no trucks have the highest MPi. FMIPCC recorded the highest MPi of 71.5% while FIPCC had the lowest value of 67.13%. This implies that FMIPCC has a better productivity compared to the other three IPCC types. However, it is worthy to note that the shovel size used in the computation for the FIMPCC was increased to 7.5m^3 to meet the required productivity.

While the MPi is crucial in the choice of the IPCC system, there are other technical aspects that play a major role in determining the most suitable IPCC system in an open pit mine. The location and ease of relocation of the IPCC components is a fundamental factor in the selection of the IPCC. The individual MPi input variables are important factors in mining operations and can solely be used as a basis for comparison with other haulage options.

The evaluation of the productivity index of IPCC offers a better understanding of the IPCC systems' productivity. This knowledge will increase the likelihood of IPCC system being considered as an alternative for the conventional haulage methods.

7.2 Recommendations

The work undertaken in this thesis fulfilled the research objective to evaluate the four IPCC systems using MPi. The research has made significant contribution to the study of IPCC systems by development of an algorithm which determined the productivity of IPCC system. The research found that the FMPCC has superior productivity compared to other categories. Therefore, the Mombasa Cement Limited should consider utilizing the FMIPCC system as a replacement of the current system. Further, other local Kenya cement companies that are predominantly operating limestone quarries should also consider a FMIPCC system. The system, have low operational costs that can be leveraged for better profits.

The proposed algorithm can further be improved to optimise its results by considering the dynamic nature of mining operations. This modification will incorporate stochastic approach in calculating MPi hence generating more realistic results of the productivity by showing the changes along the entire life of the mine.

The research is limited when considering the impacts of relocating crusher stations in different IPCC systems. Additionally, the parameters of the individual equipment change as the equipment wear over time (depreciation of the equipment). Consideration of capital and operational expenditure in relation to the productivity of each IPCC system would offer a better basis for comparison. An algorithm that models an entire mine life will put such factors into consideration.

REFERENCES

Abbaspour, H., Drebenstedt, C., & Dindarloo, S. R. (2018). Evaluation of safety and social indexes in the selection of transportation system alternatives (Truck-Shovel and IPCCs) in open pit mines. *Safety Science*, *108*, 1–12. https://doi.org/10.1016/j.ssci.2018.04.020

Abbaspour, H., & Drebenstedt, C. (2019a). *IPCC systems as a bulk material handling method in mines : A review regarding the technical , economic , environmental , Safety, and Social Factors*. *June*.

Abbaspour, H., & Drebenstedt, C. (2019b). *Truck-Shovel vs IPCC systems : a technical evaluation in open pit mines by system dynamics modeling . System dynamics modelling for defining technical index*. 1–14.

Abbaspour, H., Drebenstedt, C., Paricheh, M., & Ritter, R. (2019). Optimum location and relocation plan of semi-mobile in-pit crushing and conveying systems in open-pit mines by transportation problem. *International Journal of Mining, Reclamation and Environment*, *33*(5), 297–317. https://doi.org/10.1080/17480930.2018.1435968

Abram, J., Edwards, D., & Hamson, M. (1991). Guide to Mathematical Modelling. *The Mathematical Gazette*, *75*(472), 243. https://doi.org/10.2307/3620299

Arputharaj, M. E. M. (2015). Studies on Availability and Utilisation of Mining Equipmente - An Overview. *International Journal of Advanced Research in Engineering and Technology*, *6*(3), 14–21.

Atchison, T. (2011). In-pit crushing and conveying bench operations. *Coal International*, *259*(5), 35–40.

Atchison, T., & Morrison, D. (2011). In-pit crushing and conveying bench operations. *IRON ORE 2011, Proceedings*, *July*, 157–163.

Aykul, H., Yalcin, E., Ediz, I. G., Dixon-Hardy, D. W., & Akcakoca, H. (2007). Equipment selection for high selective excavation surface coal mining. *Journal of the Southern African Institute of Mining and Metallurgy*, *107*(3), 195–210.

Dansereau, S. (2006). Globalization and mining labour: Wages, skills and mobility. *Minerals and Energy - Raw Materials Report*, *21*(2), 8–22. https://doi.org/10.1080/14041040600977845

Dean, M., Knights, P., Kizil, M. S., & Nehring, M. (2015). Selection and planning of fully mobile in-pit crusher and conveyor systems for deep open pit metalliferous applications. *Future Mining, AusIMM, The University of New South Wales, Australia*, *146*, 219–225.

Doble, M., & Kumar, A. (2005). Mathematical Models. In *Biotreatment of Industrial Effluents* (pp. 39–53). Elsevier. https://doi.org/10.1016/B978-075067838-4/50005-1

Dzakpata, I., Knights, P., Kizil, M. S., Nehring, M., Aminossadati, S. M., & Kizil, S. (2016). *Truck and Shovel Versus In-Pit Conveyor Systems: a Comparison Of The Valuable Operating Time*. *February*, 463. www.oilsandstoday.ca

Elevli, S., & Elevli, B. (2010). Performance measurement of mining equipments by utilizing OEE. *Acta Montanistica Slovaca*, *15*(2), 95–101.

Fourie, H. (2016). Improvement in the overall efficiency of mining equipment: A case study. *Journal of the Southern African Institute of Mining and Metallurgy*, *116*(3), 275–281. https://doi.org/10.17159/2411-9717/2016/v116n3a9

Githiria, J. M. (2018) ‘A stochastic cut-off grade optimisation algorithm’, PhD Thesis, University of the Witwatersrand, Johannesburg. https://hdl.handle.net/10539/26474

Gupta, A., & Yan, D. S. (2006). Mineral processing design and operations: An introduction. In *Amsterdam, Elsevier B.V.,*.

Gyratory Crusher - an overview | ScienceDirect Topics. (n.d.). Retrieved May 1, 2020, from.https://www.sciencedirect.com/topics/engineering/gyratory-crusher

Hay, E., Nehring, M., Knights, P., & Kizil, M. S. (2019). Ultimate pit limit determination for semi mobile in-pit crushing and conveying system: a case study. *International Journal of Mining, Reclamation and Environment*, *34*(7), 498-518

Hoda, R., & Kamali, R. A. (2014). Calculating total system availability. *Universiteit van Amsterdam*, 27. https://staff.science.uva.nl/c.t.a.m.delaat/rp/2013-2014/p17/report.pdf

Jide Muili, A. (2013). Optimization of the Overall Equipment Efficiency (OEE) of Loaders and Rigid Frame Trucks in NAMDEB Southern Coastal Mine Stripping Fleet, Namibia. *Earth Sciences*, *2*(6), 158. https://doi.org/10.11648/j.earth.20130206.17

Konak, G., Onur, A. H., & Karakus, D. (2007). Selection of the optimum in-pit crusher location for an aggregate producer. *Journal of the Southern African Institute of Mining and Metallurgy*, *107*(3), 161–166.

Metso. (2020). *In-pit crushing and conveying saves more than just fuel - Metso*. https://www.metso.com/showroom/mining/in-pit-crushing-and-conveying-saves-more-than-just-fuel/

Michaud, L. (2019). *Crusher Reduction Ratio*. Mineral Processing & Metallurgy. Retrieved 5 December 2020, from https://www.911metallurgist.com/blog/crusher-reduction-ratio.

Michaud, L. (2020). *Gyratory VS Jaw Crushers: Advantages & Disadvantages*. Mineral Processing & Metallurgy. Retrieved 5 December 2020, from https://www.911metallurgist.com/blog/advantages-disadvantages-gyratory-jaw-crushers.

Mohammadi, M., Rai, P., & Gupta, S. (2015). Performance Measurement of Mining Equipment. *International Journal of Emerging Technology and Advanced Engineering*, *5*(7), 240–248.

Morriss, P. (2008). Key Production Drivers in in-Pit Crushing and Conveying (Ipcc) Studies. *The Southern African Institute of Mining and Metallurgy, Surface Mining 2008*, 33.

Nakajima, S. (1988). *Introduction to TPM: total productive maintenance*. Productivity Press.

Nehring, M., Knights, P. F., Kizil, M. S., & Hay, E. (2018). A comparison of strategic mine planning approaches for in-pit crushing and conveying, and truck/shovel systems. *International Journal of Mining Science and Technology*, *28*(2), 205–214. https://doi.org/10.1016/j.ijmst.2017.12.026

Oberrauner, A., & Turnbull, D. (2013). Essentials on in-pit crushing and conveying (IPCC). In *Beltcon 17. International Materials Handling Conference*.

Paricheh M, & Osanloo M. (2016). Determination of the Optimum In-Pit Crusher Location in Open_Pit Mining Under Production and Operating Cost Uncertainties. *16th International Conference on Computer Applications in the Mineral Industries, October*, 5–7.

Pekol, A. (2019). Evaluation and Risk Analysis of Open-Pit Mining Operations. *BHM Berg- Und Hüttenmännische Monatshefte*, *164*(6), 232–236. https://doi.org/10.1007/s00501-019-0854-9

Rahmanpour, M., Osanloo, M., Adibee, N., & Akbarpourshirazi, M. (2014). An

Approach to Locate an In Pit Crusher in Open Pit Mines. *International Journal of Engineering*, *27*(9 (C)), 1475–1484. https://doi.org/10.5829/idosi.ije.2014.27.09c.18

Rajput, H. S., & Jayaswal, P. (2012). *Literature for OEE TPM-to-Improve-OEE*. *2*(6), 4383–4386.

Ritter, R. (2016). *Contribution to the capacity determination of semi-mobile in-pit crushing and conveying systems* (Doctoral dissertation, Technische Universität Bergakademie Freiberg).

Rostami, J. (2011). *SME Mining Engineering Handbook, Third Edition* (P. Darling (Ed.)). Society for Mining, Metallurgy, and Exploration,Inc_. https://books.google.ru/books?id=5uq-kdfHLWUC

Samanta, B., & Banerjee, J. (2004). Improving productivity of mining machinery through total productive maintenance. *theammj. com/262pdf/tpmforproductivity. pdf*.

Scott, B., Ranjith, P. G., Choi, S. K., & Khandelwal, M. (2010). A review on existing opencast coal mining methods within Australia. *Journal of Mining Science*, *46*(3), 280–297. https://doi.org/10.1007/s10913-010-0036-3

Souza, M. J. F., Coelho, I. M., Ribas, S., Santos, H. G., & Merschmann, L. H. C. (2010). A hybrid heuristic algorithm for the open-pit-mining operational planning problem. *European Journal of Operational Research*, *207*(2), 1041–1051. https://doi.org/10.1016/j.ejor.2010.05.031

Sturgul, J. R. (1987). How to determine the optimum location of in-pit movable crushers. *International Journal of Mining and Geological Engineering*, *5*(2), 143–148. https://doi.org/10.1007/BF01560872

Tavakoli, M., Hashemi, A., & Moosakazemi, F. (2011). Review of the in-pit crushing and conveying (IPCC) system and its case Study in copper industry. *The First World Copper Congress*, *October*.

Tonge, J., & Nehring, M. (2017). *The Implications of Improved Conveyor Technology on In-Pit Crusher Conveyor Systems*. doi: https://doi.org/10.14264/uql.2018.296

Top 10 deep open-pit mines. (n.d.). Retrieved April 22, 2020, from https://www.mining-technology.com/features/feature-top-ten-deepest-open-pit-mines-world/

Topf, A. (2017). In-Pit Crushing and Conveying Systems Changing the way Ore is Moved. *Mining.Com*. http://www.mining.com/in-pit-crushing-systems-changing-the-way-ore-is-moved/

Turnbull, D., & Cooper, A. (2010). In-pit crushing and conveying (IPCC) - A tried and tested alternative to trucks: Part 2. *AusIMM Bulletin*, *6*, 76–77.

Utley, R. W. (2011). In-pit crushing. *SME Mining Engineering Handbook*, 941-956.

Vagenas, N., Runciman, N., & R.clément, S. (1997). A methodology for maintenance analysis of mining equipment. *International Journal of Surface Mining, Reclamation and Environment*, *11*(1), 33–40. https://doi.org/10.1080/09208119708944053

Wachira, D., Githiria, J., Onifade, M., & Mauti, D. (2021). Determination of semi-mobile in-pit crushing and conveying (SMIPCC) system performance. *Arabian Journal of Geosciences*, *14*(4), 297. https://doi.org/10.1007/s12517-021-06550-4

Zimmermann, E., & Kruse, W. (2006, September). Mobile crushing and conveying in quarries-a chance for better and cheaper production!. In *RWTH Aachen-Institut für Bergbaukunde III, 8th International Symposium Continuous Surface Mining* (pp. 481-487).

APPENDICES

Appendix A: Data Collected

This section summarizes the data obtained for use in the application of the MPi Model. Tables 9.1, 9.2, and 9.3 provides a summary of the time usage breakdown for SMIPCC, SFIPCC, and FMIPCC configurations respectively. The tables show both the annual breakdown and shift breakdown for all the equipment in each configuration. The data was used in the MPi model for the computation of availability, utilization, and performance.

Table 9.1: Raw Data for Individual SMIPCC time usage breakdown

	Availability of SMIPCC Components					
Availability	**units**	**Shovel**	**Truck**	**Crusher**	**Conveyor**	**Spreader**
calendar Hours	hours	8760	8760	8760	8760	8760
Scheduled non-work time	hours	192	192	192	192	192
Wet weather losses	hours	270	270	270	270	270
Crusher Relocation losses	hours	0	0	300	0	0
Industrial losses	hours	0	0	0	0	0
Scheduled hours	hours	8298	8298	7962	8298	8298
Daily service	hours	270	330	365	243	365
Weekly Maintenance	hours	365	365	365	365	365
Annual maintenance shutdown	hours	168	168	336	0	168
Scheduled maintenance	hours	803	863	1066	608	898
Breakdown as % Scheduled	%	4%	4%	4%	2%	3%
Breakdowns	hours	331.9	331.92	318.48	165.96	248.94

		2				
Available Hours	hours	7163.1	7103.08	6577.52	7524.04	7151.06
	Utilization for IPCC components (shift)					
IPCC operating hours						
Shift duration	hours	8	8	8	8	8
Shift duration	mins	480	480	480	480	480
No. of shifts/day		2	2	2	2	2
Shift change	minutes	10	10	10	10	10
Equipment inspection	minutes	10	10	10	10	10
Meal break	minutes	30	25	30	30	30
Blasting delays	minutes	0	0	0	0	0
Fuel/lubrication	minutes	15	25	15	0	0
Manoeuvre	% of shift	4%	0%	0%	0%	0%
Manoeuvre	minutes	19.2	0	0	0	0
Waiting time	minutes	15	40	0	0	0
Other delays	minutes	20	10	0	0	0
Total delays	minutes	119.2	120	65	50	50
Effective operation/shift		360.8	360	415	430	430
	Performance for IPCC components (shift)					
Time loss due to Job conditions	minutes	11	11	11	11	11
Speed losses	minutes	25	36	25	25	25

Operator efficiency time losses	minutes	24	24	0	0	0
Total losses	minutes	60	71	36	36	36
Net operating time	minutes	300.8	289	379	394	394

Table 9.2: Raw data for individual SFIPCC time usage breakdown

	Availability for SFIPCC Components (annual)					
Availability		**Shovel**	**Truck**	**Crusher**	**Conveyor**	**Spreader**
calendar Hours	hours	8760	8760	8760	8760	8760
Scheduled non-work time	hours	192	192	192	192	192
Wet weather losses	hours	270	270	270	270	270
Crusher relocation losses	hours	0	0	336	0	0
Industrial losses	hours	0	0	0	0	0
Scheduled hours	hours	8298	8298	7962	8298	8298
Daily service	hours	270	330	365	243	365
Weekly maintenance	hours	365	365	365	365	365
Annual Maintenance shutdown	hours	168	168	336	0	168
Scheduled maintenance	hours	803	863	1066	608	898
Breakdown as % scheduled	%	4%	4%	4%	2%	3%
Breakdowns	hours	331.92	331.92	318.48	165.96	248.94
Available hours	hours	7163.	7103.0	6577.5	7524.04	7151.06

		1	8	2		
	Utilization for IPCC components (shift)					
IPCC Operating Hours						
Shift duration	hours	8	8	8	8	8
Shift duration	mins	480	480	480	480	480
No. of Shifts/day		2	2	2	2	2
Shift change	minutes	10	10	10	10	10
Equipment Inspection	minutes	10	10	10	10	10
Meal break	minutes	30	30	30	30	30
Blasting delays	minutes	0	0	0	0	0
Fuel/lubrication	minutes	15	25	15	0	0
Manoeuvre	% of shift	4%	0%	0%	0%	0%
Manoeuvre	minutes	19.2	0	0	0	0
Waiting time	minutes	25	45	0	0	0
Other delays	minutes	20	10	0	0	0
Total delays	minutes	129.2	130	65	50	50
Effective operation/shift		350.8	350	415	430	430
	Performance for IPCC components (shift)					
Time loss due to job conditions		11	11	11	11	11
Speed losses		25	40	25	25	25
Operator efficiency time losses		24	24	5	5	5

Total losses		60	75	41	41	41
Net operating time		290.8	275	374	389	389

Table 9.3: Raw Data for individual FMIPCC time usage breakdown

	Availability for FMIPCC Components				
Availability		**Shovel**	**Crusher**	**Conveyor**	**Spreader**
calendar hours	hours	8760	8760	8760	8760
Scheduled non-work time	hours	192	192	192	192
Wet weather losses	hours	270	270	0	270
Crusher relocation losses	hours	0	192	192	192
Industrial losses	hours	0	0	0	0
Scheduled hours	hours	8298	8106	8376	8106
Daily service	hours	270	365	183	365
Weekly maintenance	hours	365	365	312	365
Annual maintenance Shutdown	hours	168	336	0	168
Scheduled maintenance	hours	803	1066	495	898
Breakdown as % scheduled		4%	4%	2%	3%
Breakdowns		331.92	324.24	167.52	243.18
Available hours		7163.1	6715.76	7713.48	6964.82
	Utilization for IPCC components (shift)				
IPCC operating hours					
Shift duration	mins	480	480	480	480
No. of shifts/day		2	2	2	2
Shift change	minutes	10	10	10	10
Equipment inspection	minutes	15	15	10	10

Meal break	minutes	30	30	30	30
Blasting delays	minutes	0	0	0	0
Fuel/lubrication	minutes	25	15	0	0
Manoeuvre	% of shift	7%	4%	1%	1%
Manoeuvre	minutes	33.6	19.2	2.4	2.4
Waiting time	minutes	30	0	0	0
Other delays	minutes	20	0	0	0
Total delays	minutes	163.6	89.2	52.4	52.4
Effective operation/Shift		316.4	390.8	427.6	427.6
	Performance for IPCC components (shift)				
Time loss due to job Conditions		11	11	11	11
Speed losses		40	35	25	25
Operator efficiency time losses		24	10	10	5
Total losses		75	56	46	41
Net operating time		241.4	334.8	381.6	386.6

Appendix B: Monte Carlo simulation

The Monte Carlo simulation was undertaken in an Excel Add-in (RiskAMP). The simulation requires the mean value, standard deviation, or range of the data as the inputs. The data collected in the MCL quarries was prepared in an Excel and used in the simulation process as summarized in the following steps.

a) Open the Monte Carlo Add-in in excel as illustrated in Figure 9.1

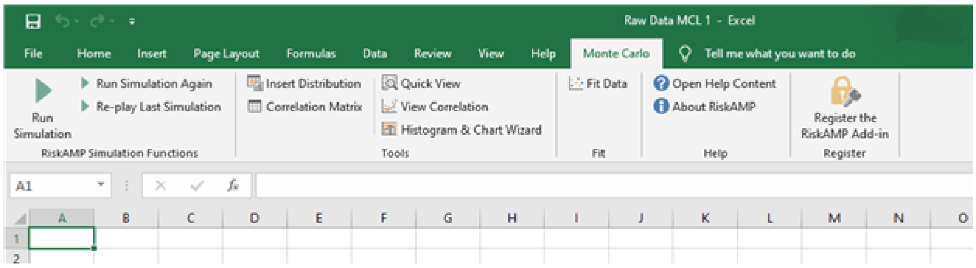
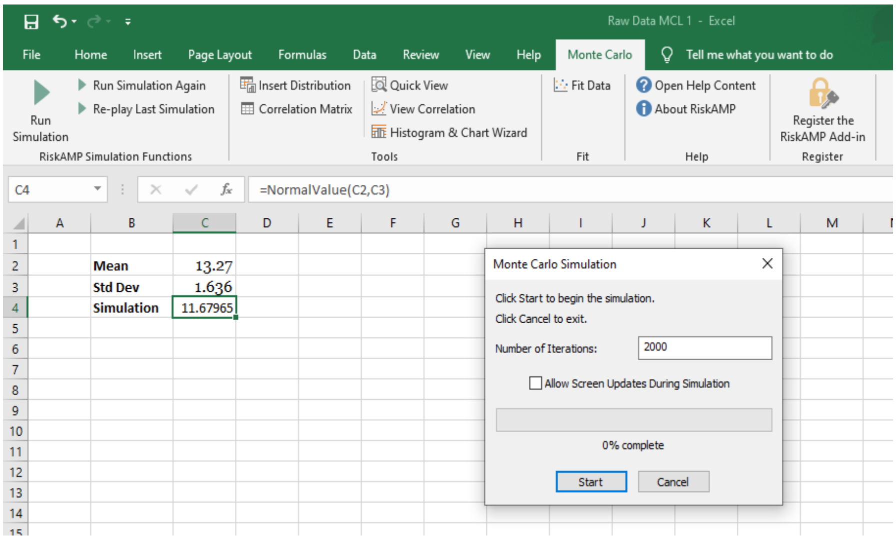


Figure 9.1: Monte Carlo simulation Add-in

b) Using the Insert Distribution button, the distribution is specified to Normal distribution.

c) The mean and standard values are inserted in the cells as illustrated in Figure 9.2. The normal value is inserted as =NormalValue (Mean, Std Dev).



C4 =NormalValue(C2,C3)

	B	C
2	**Mean**	13.27
3	**Std Dev**	1.636
4	**Simulation**	11.67965

Monte Carlo Simulation

Click Start to begin the simulation.
Click Cancel to exit.

Number of Iterations: 2000

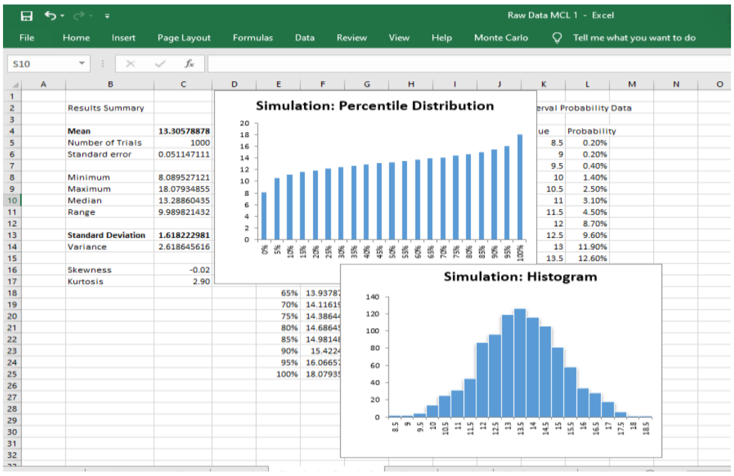
☐ Allow Screen Updates During Simulation

0% complete

Figure 9.2: Running a simulation

d) The 'run simulation' button is then pressed and the number of iterations is specified (in this case number of iterations was chosen to be 2000). Once the iterations are set, the simulation starts.

e) Eventually, a summary of the results of the simulation is available under the histogram and chart as shown in Figure 9.3



Results Summary

Mean	**13.30578878**
Number of Trials	1000
Standard error	0.051147111
Minimum	8.089527121
Maximum	18.07934855
Median	13.28860435
Range	9.989821432
Standard Deviation	**1.618222981**
Variance	2.618645616
Skewness	-0.02
Kurtosis	2.90

65%	13.93787
70%	14.11619
75%	14.38644
80%	14.68645
85%	14.98148
90%	15.4224
95%	16.06657
100%	18.07935

erval Probability Data

ue	Probability
8.5	0.20%
9	0.20%
9.5	0.40%
10	1.40%
10.5	2.50%
11	3.10%
11.5	4.50%
12	8.70%
12.5	9.60%
13	11.90%
13.5	12.60%

Figure 9.3: Monte Carlo simulation results

f) The steps a) to e) were repeated for other data collected.

The data obtained from the Monte Carlo simulation was prepared in an Excel sheet for use in the further steps in the calculation of the number of trucks and loading equipment. An example of Monte Carlo simulation is shown Table 9.4.

Table 9.4: Data Simulation results

Summary	**1**	**2**		**4**	**5**	**Mean**
Loader loading time (mins)	4.582518	4.468418	5.047996	4.231899	4.265534	**4.52**
Passes	11.40602	9.805077	7.49606	10.99667	5.695512	**9.08**
truck travel empty (mins)	13.78643	15.98397	14.3918	15.35778	16.00966	**15.11**
Truck travel loaded (mins)	30.26503	20.48389	23.1716	21.31792	18.22338	**22.69**
Dumping time (secs)	30.29871	29.17679	24.50284	29.68339	26.17379	**27.97**
truck wait time @Dumping (mins)	3.973284	1.920033	3.725478	8.100066	6.109823	**4.77**
truck Spot time (secs)	49.62859	35.74623	59.7977	44.3753	34.82614	**44.87**
truck wait time @loading (mins)	6.995314	5.496487	2.970301	2.820086	8.134591	**5.28**
Truck capacity (tonnes)	29.39872	26.21055	27.36357	24.96968	29.21293	**27.43**
Loader wait time (mins)	1.155368	0.95417	1.134805	1.138104	1.189964	**1.11**

Appendix C: MPi Model Code

```
[num, txt, raw] = xlsread('ipcc');
%% Shovel Time Break down

PSDT = (SNWT+SM+RH);        % Planned_Shutdown_Time (PSDT)
% Break down time (BDT)
%% Number of trucks and shovels
[num, txt, raw] = xlsread('Trucks&Shovels');
%Volume Handled annually
Vol = APR + (SR*APR);
%Production required/ hour
Q = Vol / (Days*Shifts*Hrs);
% production of one loader/ shovel
%Qs = BC*C*P*S*Bf
C = 3600/Ct;        %No. of cycles
Bf = FF*(LD/BD);    %Bucket fill factor
Qs = BC*C*P*S*Bf;
%Number of Loaders (Shovels) required
Ns = Q/Qs;
NS = round(Ns);
%% Number of Trucks
% TOtal Time = Loading time + Hauling time + Dumping time + Total spot time
Nt = (Qs*NS)/Qeff;      %Hourly productivity of Shovels/ Qeff of truck
NT = round(Nt);
%% system availability
if (NS==1)&& (NT>1)
[av]= av1(Ta,NS,NT,Ca,CBa,Da);
elseif (NS>1)&& (NT>1)
    [av]=av2(Ta,Sa,NS,NT,Ca,CBa,Da);
elseif (NS==1)&& (NT==0)
    [av]= av3(Ta,Sa,NS,NT,Ca,CBa,Da);
elseif (NS>1)&& (NT==0)
    [av]= av4(Ta,Sa,NS,NT,Ca,CBa,Da);
else
    disp(' system must have loading equipment')
end
if (NT>=1)
    [U] = U1(Tu,NT,Su,NS,Cu,CBu,Du);
```

```
     [P] = P1(Tp,NT,Sp,NS,Cp,CBp,Dp);
elseif (NT==0)
    [U] = U2(Tu,NT,Su,NS,Cu,CBu,Du);
    [P] = P2(Tp,NT,Sp,NS,Cp,CBp,Dp);
  else
    disp(' system must have loading equipment');
end
 System Utilization
 [num,txt,raw] =xlsread('availability',3);
[num,txt,raw] =xlsread('availability',2);
% NT = num(1,:); %number of trucks
% NS = num(2,:); %number of shovels
% if (NT>=1)
% if (NT>=1)
%     [P] = P1(Tp,NT,Sp,NS,Cp,CBp,Dp);
elseif (NT==0)
%[P] = P2(Tp,NT,Sp,NS,Cp,CBp,Dp);
%  else
%     disp(' system must have loading equipment');
% end
%% Mine Productivity Index
MPi =(av^0.3*P^0.5*U^0.2);
 %% Bar Graphs
 x = 1:1:3;
 y = [Ta Sa Ca CBa Da av; Tu Su Cu CBu Du U; Tp Sp Cp CBp Dp P];
 figure(1);
%  x = bar(y)
 x = bar(y,'grouped')
figure (2);
x = [av U P MPi];
bar(x)
```

Appendix D: Publication

Appendix E: Turnitin Report