# Contribution to the Capacity Determination of Semi-Mobile In-Pit Crushing and Conveying Systems

To the Faculty of Geosciences, Geoengineering and Mining
of the Technische Universität Bergakademie Freiberg
approved

## THESIS

to attain the academic degree of

Doktor-Ingenieur

(Dr.-Ing.)

submitted

by Dipl. Wi.-Ing. Robert Ritter

born on the 20.12.1984 in Görlitz

Reviewers: Prof. Dr. Carsten Drebenstedt, Germany

Prof. Dr. Dietrich Stoyan, Germany

Prof. Dr. Peter Knights, Australia

Date of the award 01.11.2016

## Acknowledgment

The accomplishment of this thesis has been possible thanks to the support, mentoring, guidance and motivation of several professionals, organizations and close friends ever present, both near and far, during my university life.

I would like to sincerely express my warmest gratitude to Prof. Dr. Carsten Drebenstedt, who has been an unconditional support both in academia and my professional career development, to accomplish this thesis at the Freiberg University of Mining and Technology. I profoundly thank him for his kind supervision, valuable advice, guidance, for reviewing this thesis, and his support throughout my studies.

I would also like to genuinely thank Prof. Dr. Dietrich Stoyan, for resiliently patronising and guiding this research. He contributed the wisest of ideas to narrow and focus this investigation and to achieve my main research aim in an intelligent, professional and organised manner.

In addition, I would like to thank Professor Peter Knights from the University of Queensland for his time to review this thesis and his valuable recommendations.

I gratefully acknowledge the opportunity granted to me by Sandvik Mining Systems to undertake this research and the support of my former colleagues. In particular, I would like to sincerely thank Mr. Doug Turnbull who constantly encouraged me throughout my time with Sandvik and made me into the professional mining engineer I am today.

The fulfilment of this research has also been possible thanks to the support of several reputable organisations within the mining industry including Teck Resources, Shell Canada, MIBRAG, Vattenfall, Rio Tinto, Antofagasta Minerals, Jiangxi Copper, Huaneng Yimin Coal, Pingshuo Coal, Shougang Jingtang united iron & steel. Their provided data has established the foundation of this thesis.

Lastly, I would like to thank my parents for their unwavering support and encouragement throughout my entire academic career. Likewise, I thank my own little family for their support and for tolerating the weekends and nights that I spent working on my thesis.

## Abstract

As ore grades decline, waste rock to ore ratios increase and mines become progressively deeper mining operations face challenges in more complex scenarios. Today´s predominant means of material transport in hard-rock surface mines are conventional mining trucks however despite rationalisation efforts material transportation cost increased significantly over the last decades and currently reach up to 60% of overall mining. Thus, considerations and efforts to reduce overall mining costs, promise highest success when focusing on the development of more economic material transport methods.

Semi-mobile in-pit crusher and conveyor (SMIPCC) systems represent a viable, safer and less fossil fuel dependent alternative however its viability is still highly argued as inadequate methods for the long term projection of system capacity leads to high uncertainty and consequently higher risk.

Therefore, the objective of this thesis is to develop a structured method for the determination of In-pit crusher and conveyor SMIPCC system that incorporates the random behaviour of system elements and their interaction. The method is based on a structured time usage model specific to SMIPCC system supported by a stochastic simulation.

The developed method is used in a case study based on a hypothetical mine environment to analyse the system behaviour with regards to time usage model component, system capacity, and cost as a function of truck quantity and stockpile capacity. Furthermore, a comparison between a conventional truck & shovel system and SMIPCC system is provided.

Results show that the capacity of a SMIPCC system reaches an optimum in terms of cost per tonne, which is 24% (22 cents per tonne) lower than a truck and shovel system. In addition, the developed method is found to be effective in providing a significantly higher level of information, which can be used in the mining industry to accurately project the economic viability of implementing a SMIPCC system.

## Declaration

I hereby declare that I completed this work without any improper help from a third party and without using any aids other than those cited. All ideas derived directly or indirectly from other sources are identified as such.

In the selection and in the use of materials and in the writing of the manuscript I received support from the following persons:

Prof. Dr. Carsten Drebenstedt

Prof. Dr. Dietrich Stoyan

Dr. Felix Ballani

Persons other than those above did not contribute to the writing of this thesis. I did not seek the help of a professional doctorate-consultant. Only persons identified as having done so received any financial payment from me for any work done for me.

This thesis has not previously been submitted to another examination authority in the same or similar form in Germany or abroad.

---

Date, Signature

# Table of Contents

## List of Figures

## List of Tables

## List of Abbreviations

| | |
|---|---|
| CAT | Caterpillar Incorporation |
| CECE | Committee of European Construction Equipment |
| CPU | Central Processing Unit |
| CV | Coefficient of Variatio*n* |
| DIN | Deutsche Industrie Norm |
| e.g | exempli gratia / for example |
| EKG | Russian Rope Shovel Type |
| ESUM | Extended Summation Method |
| FAM | Förderanlagen Magdeburg |
| FMIPCC | Fully-Mobile In-Pit Crushing and Conveying |
| GDR | German democratic republic |
| HAC | High Angle Conveyor |
| IGD | Inverse Gaussian Distribution |
| IPCC | In-Pit Crushing and Conveying |
| MMD | Mining Machinery Developments |
| MSC | Mobile Stacking Conveyor |
| n.a | not available |
| O&K | Orenstein & Koppel |
| OPEX | Operational Expenditures |
| PVC | Polyvinylchlorid |
| SAE | Society of Automotive Engineers |
| SMIPCC | Semi-Mobile In-Pit Crushing and Conveying |
| SMU | Service Meter Unit |
| SPMT | Self-Propelled Modular Transporter |
| ST | Steel (conveyor breaking strenght) |
| TAKRAF | Tagebau-Ausrüstungen, Krane, und Förderanlagen |
| TGL | Technische Normen, Gütevorschriften und Lieferbedingungen |
| TNT | Terra Nova Technologies |
| TPMS | Truck Payload Management System |
| TU | Technische Universität |
| UB | Universalbagger |
| USA | United States of America |
| VBA | Visual Basic for Application |
| VIMS | Vital Information Management System |

# List of Symbols

| Symbol | Notation | Unit |
|---|---|---|
| $a$ | Shape parameter gamma function | |
| $C_{L_{th}}$ | Theoretical hourly capacity of discontinuous loaders | t/h |
| $C_L$ | Hourly capacity of discontinuous loaders | t/h |
| $C_S$ | Annual system capacity | t/a |
| $C_T$ | Hourly truck capacity | t/h |
| $c_{T_{max}}$ | Maximum acceptable truck payload | t |
| $c_L$ | Bucket payload | t |
| $c_T$ | Truck payload | t |
| $c_T$ | Truck payload | t |
| $c_v$ | Coefficient of variation | |
| $f_{c_T}$ | Maximum overload factor | |
| $f_f$ | Bucket fill factor | |
| $f_s$ | Material swell factor | |
| $F(x)$ | Function value of $x$ | |
| $g$ | Probability density function of gamma distribution | |
| $n_T$ | Number of Trucks | |
| $N$ | Number of bucket cycles | |
| $P(x)$ | Probability of $x$ | |
| $s$ | Scale parameter gamma function | |
| $\bar{t}_R$ | Mean of repair time | min |
| $\bar{t}_W$ | Mean work time | min |
| $t_{O_d}$ | Operating delay | h |
| $t_{O_e}$ | Effective operating time | h/a |
| $t_{T_L}$ | Truck travel time loaded | s |
| $t_{T_U}$ | Truck travel time unloaded | s |
| $t_1$ | Empty bucket swing time | s |

| Symbol | Notation | Unit |
|---|---|---|
| $t_2$ | Bucket fill time | s |
| $t_3$ | Loaded bucket swing time | s |
| $t_4$ | Bucket dump time | s |
| $t_B$ | Blasting time | h |
| $t_C$ | Calendar time | h |
| $t_{CT}$ | Truck cycle time | s |
| $t_D$ | Manoeuvre and dump time at crusher | s |
| $t_D$ | Downtime | h |
| $t_{Dp}^{(1)}$ | Non-scheduled production | h |
| $t_{Dp}^{(2)}$ | External disturbances | h |
| $t_{Dp}^{(3)}$ | Preventative maintenance | h |
| $t_{Dp}^{(4)}$ | Planned shift delays | h |
| $t_{Dp}^{(5)}$ | Technological downtime | h |
| $t_{Dp}^{(5)\prime}$ | Technological downtime proportional to effective operating time | h |
| $t_{Dp}^{(5)\prime\prime}$ | Technological downtime not proportional to effective operating time | h |
| $t_{Du}$ | Unplanned downtime | h |
| $t_L$ | Bucket cycle time | s |
| $t_{Lo}$ | Truck loading time | s |
| $t_{Lo}$ | Truck loading time from the loader perspective | s |
| $t_{Lo}^T$ | Truck loading time from the truck perspective | s |
| $t_O$ | Operating time | h |
| $t_{Od}^E$ | Self-induced operating delays | h |
| $t_{Od}^S$ | System-induced operating delays | h |
| $t_S$ | Manoeuvre and spot time at the loader | s |
| $t_{Sh}$ | Conveyor trackshifting time | h |
| $t_T$ | Truck travel time | s |

| Symbol | Notation | Unit |
|---|---|---|
| $t_W$ | Loader inherent wait time | s |
| $V$ | Rated bucket volume | $m^3$ |
| $V_B$ | blast volume | $m^3$ |
| $V_D$ | Maximum dump block volume | $m^3$ |
| $\bar{X}$ | Expected value | |
| $X$ | Random variable | |
| $\mu_{c_L}$ | Mean bucket payload | t |
| $\mu_{t_L}$ | Mean bucket cycle time | s |
| $\sigma^2_{c_L}$ | Variance of bucket payload | $t^2$ |
| $\sigma^2_{t_L}$ | Variance of bucket cycle time | $s^2$ |
| $\sigma^2_{t_T}$ | Variance of truck travel time | $s^2$ |
| $\sigma^2$ | Variance | |
| $\varrho_i$ | Material insitu density | $t/m^3$ |
| $\Gamma(x)$ | Gamma function | |
| $\varkappa$ | Repair ratio | |
| $\mu$ | Mean value | |
| $\tau$ | Technological downtime ratio | |
| $\Phi$ | Distribution function of standard normal distribution | |
| $\zeta$ | system delay ratio | |
| $\nu$ | Operating delay ratio | |
| $\pi$ | Pi | |
| $\varphi$ | Probability density function of standard normal distribution | |

# CHAPTER 1:
# INTRODUCTION

*This chapter presents the framework of the thesis. The main objectives and background are provided, which set the focus of the thesis.*

## 1.1 BACKGROUND

Material transport in hard-rock surface mines, as one of the primary technological processes, is comprised of all tasks necessary to transfer excavated material from the working face to the dump area, the processing plant or to subsequent treatment areas. This task is accomplished by employing appropriate technical means which are able to receive, transport and discharge excavated material according to operational requirements [1].

Today´s predominant means of material transport in hard-rock surface mines are conventional mining trucks. The reasons for this development are based on inherent advantages of conventional mining trucks which are able to carry out the majority of the technological processes, i.e. intake of material at loading point inside pit, transport and discharge to the final destination out of pit. They are furthermore well established, provide high reliability, excellent flexibility with regards to pit geometry and production rate, and sufficiently satisfy the needs for material blending. Conventional mining trucks also provide the mine owner with the choice of either owning and operating the mining fleet, or engaging a contactor to supply and manage the fleet. Lastly, conventional mining trucks allow flexible production assignments by simple up or down scaling of the truck fleet.

However, when analysing today´s situation in hard-rock surface mines under techno-economic aspects in comparison to the situation during 1970 and 2010, it must be noted that material transportation cost as part of the overall mining cost could not be reduced, despite rationalizing efforts mainly through introduction of more productive mining trucks. During 1970 and 2008 the average payload of mining trucks used in surface mines doubled from 90 t to just over 180 t [2] while the current maximum payloads reach 450 t [3]. On the contrary, material transportation cost increased significantly while facing a simultaneous and substantial increase of the overall mining cost. Some authors [4], [5] estimate transport cost shares between 40 to 50% while others even suggest costs up to 60% of overall mining cost [6], [7].

The primary reasons for these developments are:

- Constant declining head grades of ore. During the last decades, the average grade of the main hard-rock commodities has declined substantially. Figure 1-1 indicates the general trend for various hard-rock commodities over the last century.

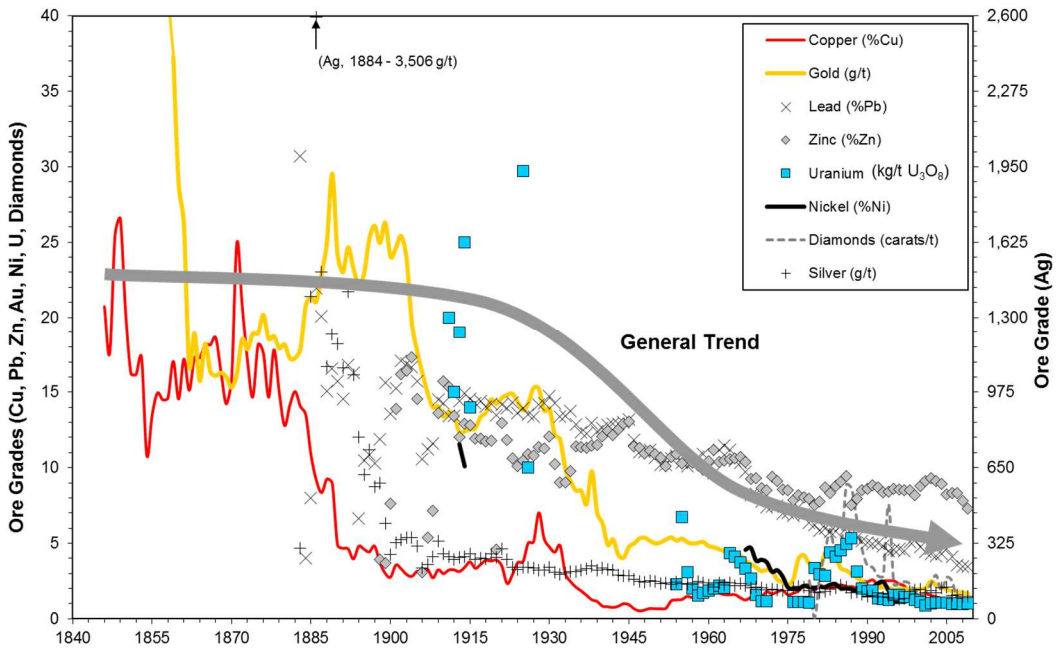



*Figure 1-1 Decreasing head grades of various metals* [8]

- Declining ore grades directly translates into an increase of material movements. Figure 1-2 indicates the development of stripping ratios of the main hard-rock commodities over the last decades. Particularly in the last 20 years the stripping ratios have doubled or even tripled.

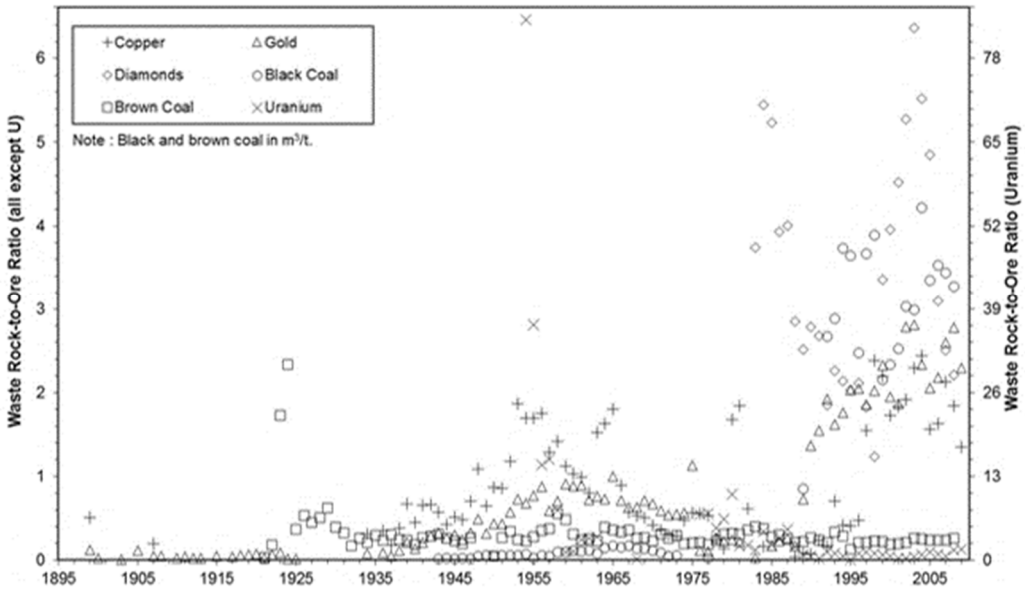



*Figure 1-2 Increasing waste rock to ore ratio* [8]

- And furthermore, increasing depth of mineral deposits which directly translates into rising horizontal and especially vertical transport distances. Figure 1-3 indicates the development of mineralization depth of copper deposits over the last decades. For example, by 2000 the average depth of mineral discovery reached 295 m in Australia, Canada and USA.

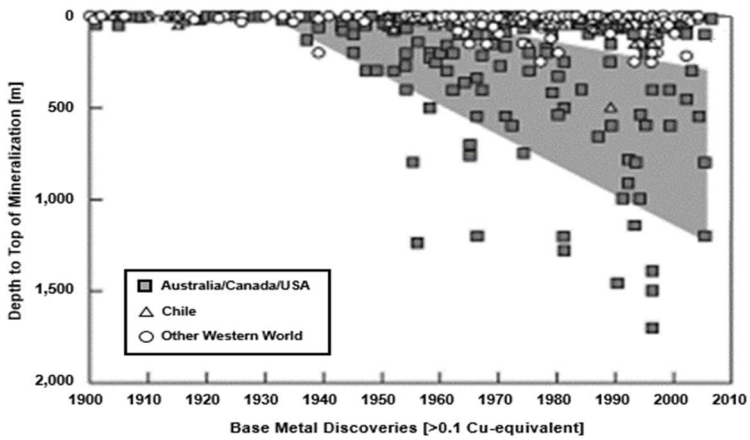



*Figure 1-3 Average depth of newly discovered ore deposits* [2]

- And lastly, the mining industry´s reluctance and risk adhesiveness to adopt new technology.

In the light of these statements, it can be concluded that:

- In terms of costs, the technological processes drilling, blasting and loading increasingly lose importance on account of material transportation.
- Should conventional mining trucks, in their current development stage, continue to be utilised for the majority of material transport in hard-rock mines, then it is to be expected that overall mining cost will continue to face a significant increase.
- Material transportation represents one of the biggest operational cost in mining and with the drive towards higher productivity, lower capital and operational expenditures it also represents an area where the greatest impact can be made.

Thus, considerations and efforts to reduce overall mining costs, promises highest success when focusing on the development, testing and utilization of more economic material transport methods. Developments which enable hard-rock surface mines to transport material more environmentally sensibly, more safely and at lower cost should therefore be seen as a main task for the future in the mining sector.

Conveyor haulage, as a well-known continuous transportation method in soft-rock mines, represents a viable, safer and less fossil fuel dependent alternative [9]. Around 40% of the total energy used in hard rock surface mines is related to diesel consumption, and truck haulage is responsible for the majority of this diesel consumption, which is the primary source of $CO_2$ emissions.

The essential criterion for the application of conveyor haulage in hard rock surface mines is the availability of a conveyable bulk mass. At the moment, crushing represents the only safe and applicable process for this criterion and can be seen as an intermediate process between the main technological processes excavation and transportation. This material transportation method is known as an in-pit crushing and conveying system (IPCC).

## 1.2 PROBLEM STATEMENT AND OBJECTIVES

The material transport by IPCC systems in hard rock surface mines is not a new technology. Already in 1956 the first self-propelled crusher connected to conveyors was installed in the limestone quarry Höver, Germany [10], [11]. The use of these early installations was not driven by economic reasons but rather to overcome major problems regarding wet and soft ground conditions which did not allow the use of trucks [12].

In the last decade, the mining industry has developed particular interest in IPCC systems for the transportation of waste material. The growing interest is mainly driven by inherent system advantages regarding operating cost, environmental health & safety as well as operational & planning considerations [13]. However, one of the mentioned drawbacks of IPCC systems is the inability to project reliable long term system capacity [14]–[17].

As the interest for IPCC systems increases so does the demand for investigative studies. Increasingly a standard procedure of mining companies to compare productivity and the profitability of conventional truck haulage and IPCC transportation methods in the early stages of a new mining project [18]. Sandvik Mining a business unit within the Sandvik Group, faces this demand and provides technical mining studies with comparisons in desktop, scoping and engineering design level.

Additionally, the interest in this material transport method is also reflected by the increasing amount of scientific studies [19]–[22]. Many of them have proven the economic advantageousness of IPCC systems compared to conventional truck and shovel operation. The emphasis of their examination lies in the area of operating cost and capital expenditure.

The groundwork for such investigative studies as well as for economic comparisons is the knowledge of achievable effective operating hours of these systems and their corresponding annual capacity to meet assigned production schedules. Historically, deterministic calculations based on empirical data adopting mean values as inputs, tempered with intuition and refined with engineering judgment provided merely satisfactory estimates of effective operating hours and corresponding annual capacity. However, disturbances and variations such as delays and hold-ups are inevitable in any earthmoving, quarrying and mining operation no matter how well the operation may be planned or managed [23], [24]. Thus, all too often such traditional calculation methods have proven to be unattainable in practice and outcomes have not met expectancy. Furthermore, all previously mentioned authors assumed a fixed annual IPCC system capacity based on deterministic methods and engineering judgment for their comparisons which has four notable shortcomings; they

1. underestimate the influence of the random behaviour of system components and their interactions,
2. are time consuming when alteration is necessary to suit individual project requirements,
3. lack in terms of standardization throughout the industry, and
4. systematically carry hazards of human error and under or overestimate the achievable IPCC system capacities.

Therefore, the objective of this thesis is to develop a structured method which allows the estimation of the annual capacity of IPCC systems under consideration of the random behaviour of system elements and their interactions with one another. Hence a research project was initiated by Sandvik Mining in cooperation with the Institute of Mining of the Freiberg University of Mining and Technology in this area, which is the subject of the work presented in this thesis.

## 1.3 THESIS OUTLINE

Following the introduction, chapter 2 discusses the current state of the art of IPCC system. The chapter provides a general definition of IPCC systems, describes the technical function of all sub-systems of an IPCC systems and analyses the current trends. This chapter further defines the scope of work.

Chapter 3 provides a literature review of previous studies and methods related to IPCC system capacity determination. It focuses on those studies and methods which emphasise semi-mobile IPCC (SMIPCC) systems. The purpose of this task is to reveal the current available methods and their disadvantages for capacity determination of SMIPCC systems.

Chapter 4 provides a comprehensive statistical analysis of the random behaviour of the SMIPCC system elements to quantify capacity and disturbance variation. The analysis is based on operational data from various mine sites obtained by the author.

Chapter 5 describes the proposed method for the estimation of the annual capacity of IPCC systems. Furthermore, chapter 5 describes the stochastic simulation model to determine the system delay ratio.

In chapter 6 the method is used in a case study to analysis the system behaviour based on a hypothetical mine with regards to time usage model component, system capacity, and cost as a function of truck quantity and stockpile capacity. Furthermore, a comparison between a conventional truck & shovel system and SMIPCC system is provided.

Lastly chapter 7 summarizes the main findings of this research and provides suggestions and ideas for further research.

# CHAPTER 2:
# STATE OF THE ART OF IPCC

*This chapter provides a general definition of the term IPCC system by dividing it into sub-systems. Each sub-system is then described in detail and general capacity limitations are provided. The chapter concludes with an analysis of the currently installed IPCC systems and presents the general development and trends.*

## 2.1 DEFINITION OF IPCC SYSTEM

In a narrow sense, IPCC systems can be defined as continuous haulage systems for surface mines, which are comprised of a crusher system (one or multiple crusher stations), located inside the pit, combined with a conveyor system for the purpose of transporting material out of the pit. In a broader sense an IPCC system can be defined as an integrated bulk material handling systems that consists of

- a feed system,
- a crusher system,
- a conveyor system, and
- a discharge system which

represents a combination of discontinuous excavation & loading as well as continuous transport & discharge[1]. Figure 2-1 illustrates the process flow of an IPCC system.

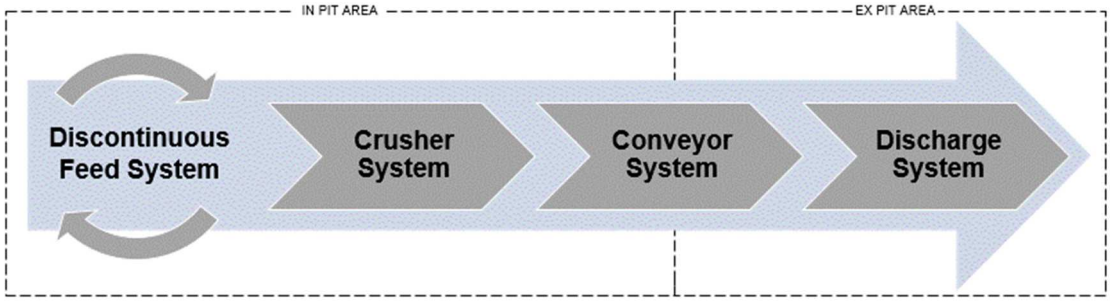



*Figure 2-1 IPCC system process flow*

Atkinson (1992) differentiates in [25] IPCC systems based on the mobility of the crushing station into mobile, semi-mobile, movable, modular, semi-fixed and fixed. Today, the mining industry simplifies the differentiation into fixed, semi-mobile and fully-mobile IPCC system [14], [26]. In this thesis, the common industry terminology is adapted and further substantiated by semi-fixed systems to better distinguish the range of mobility among IPCC systems.

A survey conducted by the author, on in-pit crusher station population according to the aforementioned definition revealed that 447 in-pit crusher stations have been installed, are currently in erection/manufacturing process or on order since 1956. Reference data provided by the leading IPCC equipment manufacturers including (in alphabetical order) Förderanlagen Magdeburg (FAM), FLSmidth, Hazemag, JoyGlobal, Metso, Mining Machinery Developments (MMD), Sandvik, Tenova TAKRAF and ThyssenKrupp[2] served as a basis of the survey. A detailed list of all IPCC references can be found in Appendix I. Figure 2-2 shows the distribution of in-pit crusher stations by region. The pie charts indicate the distribution of crusher station type and the total

[1] Hereinafter IPCC refers to the entire material handling system from winning to discharge operation.
[2] including Weserhütte, O&K and PHB Fördertechnik

number of crusher stations since 1956. The black marks point out the area of in-pit crusher stations utilised for large mining operations since 1970.

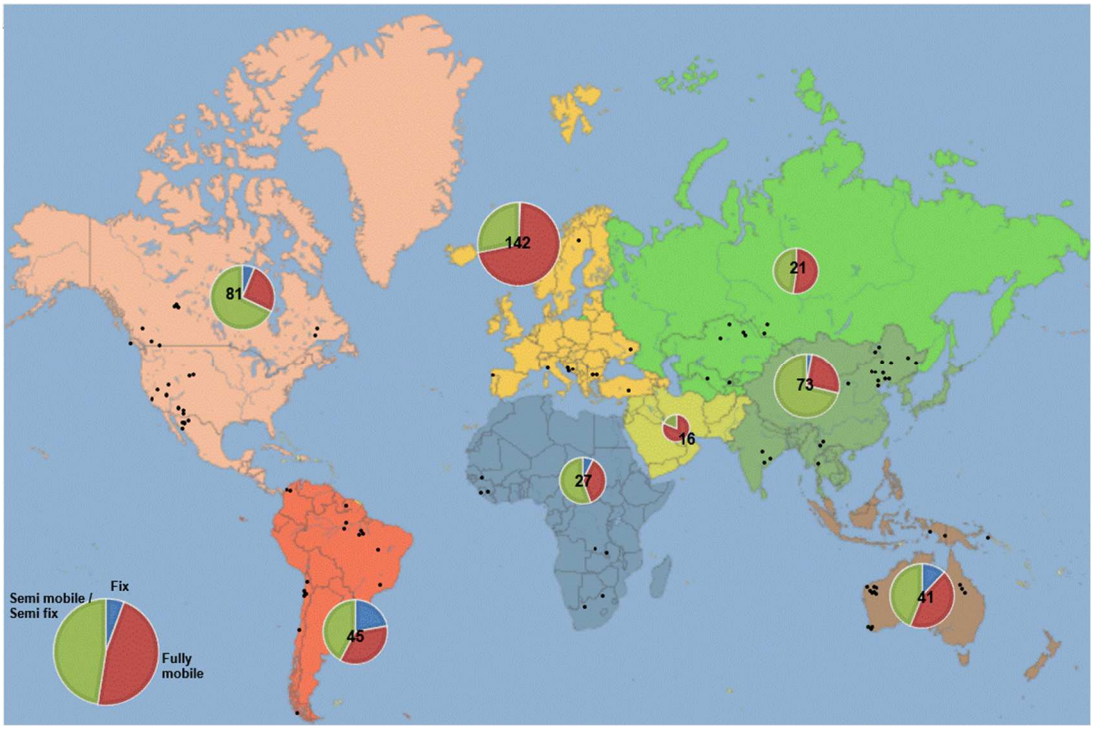



*Figure 2-2 In-pit crusher station distribution by region and type*

The majority of IPCC systems were installed in Europe, mainly during the 1960s throughout the 1990s. The systems were predominantly fully-mobile and installed in limestone quarries. However, due to stagnating mining activities in the following decades Europe became less active with regards to IPCC system installations. Increasing IPCC operations of semi-mobile and semi-fixed type started in the 1980s throughout 2000 in North America in copper and gold deposits. In recent years, Central Asia (including China, India and Thailand) and South America have become key regions for IPCC installations, due to major green field and expansion projects for iron ore in South America and for coal projects in Central Asia.

## 2.2 FEED SYSTEM

The feed systems function is to excavate the material from the operating face and feed the crusher system. It can be divided into cyclic excavation and cyclic intermittent haulage. Depending on the type of in-pit crusher the feed system may consist of a single piece of equipment or a combination of multiple.

In an IPCC system, typical equipment for the excavation process are rope shovels, hydraulic excavators and front end loader. In some cases, dozers and draglines are used to excavate material and directly load the crusher station[1]. Possible equipment combinations with respect to in-pit crusher type are shown in Figure 2-3.

[1] E.g. Gravel pit in Milford, Iowa; Oliver Iron Mining Company in Hibbing, Minnesota

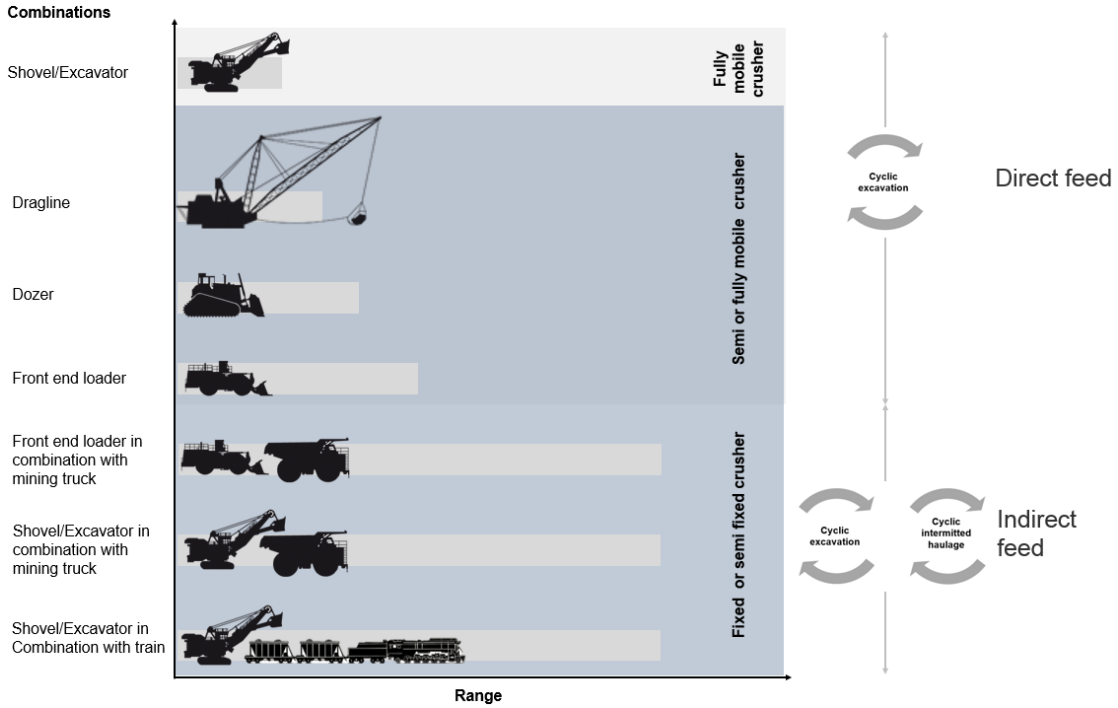



*Figure 2-3 Feed system combinations*

Fully-mobile crusher stations are commonly fed directly by cyclic unit loaders such as electric rope shovels or hydraulic excavators. Combinations of front end loaders (in load and carry operation), dozers (in dozer push operation), draglines and fully-mobile crusher stations are possible but are more common with semi-mobile crusher stations[1] [27], [28]. The feed system of fixed and semi-fixed crusher stations is typically indirect and consists of electric rope shovels, hydraulic excavators or front-end loaders in combination with mining trucks. In some cases, trains are also used for intermittent haulage[2].

## 2.3 CRUSHER SYSTEM

The crusher systems function, regardless of the type, is to receive material from feed system, comminute the material to a conveyable size and discharge it onto the conveyor system.

### 2.3.1 Crusher Station Types

The following definitions were established to categorize in-pit crusher stations by the degree of mobility, structural design and location of operation into:

- fully-mobile
- semi-mobile
- semi-fixed (modular and non-modular), and

[1] E.g. Drummonds coal Ceasar mine, Columbia – Dozer push operation
[2] E.g. ArcelorMittal´s Iron ore mine at Krivoy Rog, Ukraine

- fixed.

**Fully-Mobile In-Pit Crusher Station**

Fully-mobile crusher stations (Figure 2-4) have, analogous to the term, the ability to change position (follow the operating face) by system integrated transport mechanisms. They are directly fed by a single loading machine and move in unison along the operating face. Loading by multiple machines is possible but has been proven to be impractical [29]. Although most crusher stations with crawler track support are labelled as “fully-mobile”, only a few are actually able to follow the movements of the loader continuously. Most fully-mobile crusher station designs require the hopper of the crusher station to empty before a movement can commence. This in turn leads to significant operating delays of the loading unit.

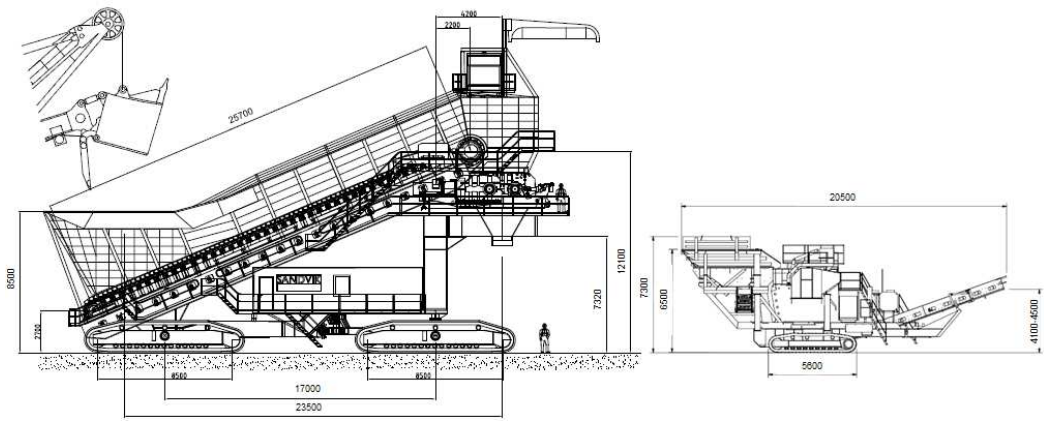



*Figure 2-4 Fully-mobile crusher stations for mining operation (left) for quarry operation (right)* [30]

**Semi-Mobile In-Pit Crusher Station**

Semi-mobile crusher stations (Figure 2-5) are machines without system integrated transport mechanisms which are commonly located at operating level and allow multiple loading machines (commonly front end loaders) to feed the material from various loading points. Relocation is realized within several hours by transport crawlers or dozers without disassembly and planning efforts whenever the distance reaches the economic limit.


*Figure 2-5 Semi-mobile in-pit crusher station a) with transport crawler for relocation* [31]*; b) skid mounted loaded by front end loader in coal mine* [32]

### Semi-Fixed In-Pit Crushing Station

Semi-fixed crusher stations are machines without system integrated transport mechanisms, which are commonly located at strategic junction points within the pit and fed by mining trucks from multiple operating levels and loading points. They are further differentiated into modular and non-modular crusher stations. The design criterion of modular in-pit crusher stations is to relocate to new locations quickly without major disassembly and erection costs whenever multiple relocations are intended. Both types can be designed as direct dump (Figure 2-7) or indirect dump stations (Figure 2-6) depending on the existence of an integrated feed system (e.g. apron feeder). Relocation requires disassembly of the entire crusher station into several parts or into multiple (2 to 6) modules and is realized by transport crawlers or self-propelled modular transporters. The relocation process takes several days for modularised semi-fixed crusher stations and several weeks up to one month for stations that are not modularised depending on the type of civil works required for ground and wall preparation.

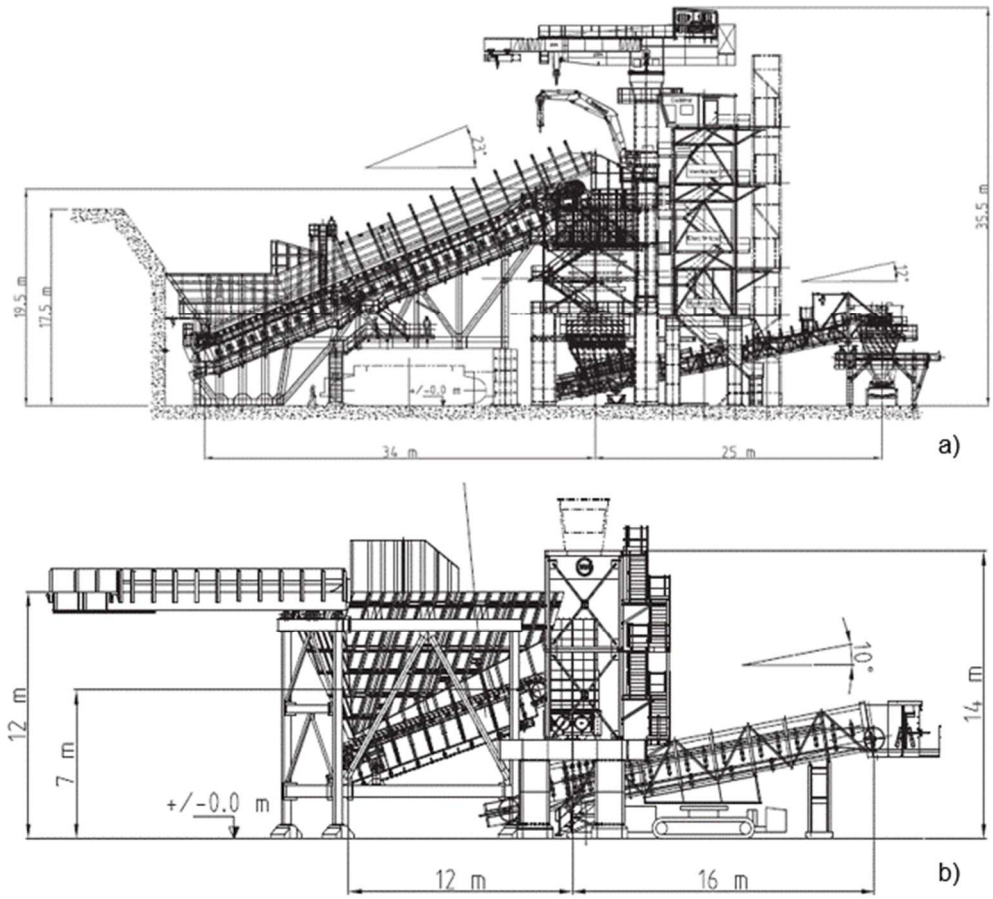



*Figure 2-6 Semi-fixed modular indirect dump in-pit crusher station a); with gyratory crusher b) with double roll crusher (both Sandvik)*

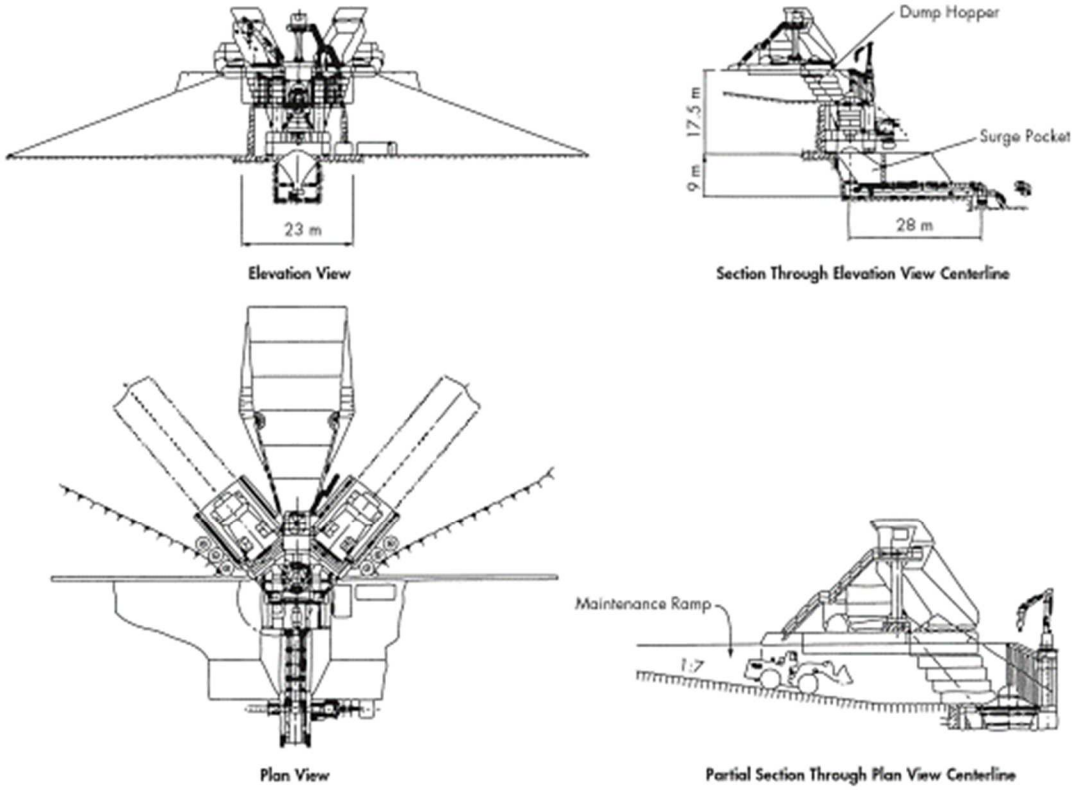



*Figure 2-7 Semi-fixed non-modular direct dump crusher station with gyratory crusher* [33]

**Fixed In-Pit Crusher Station**

Fixed crusher stations (Figure 2-8) are commonly located near the pit rim or at a position inside the pit that is not affected by mining activities. They are typically designed to operate at one place for the entire life of mine and are not intended to relocate. The two common designs are either in-ground (e.g. Dexing copper mine,) China) or rim mounted (e.g. Cananea copper mine, Mexico). In both designs, the crusher is installed in a concrete structure with some steel portions.

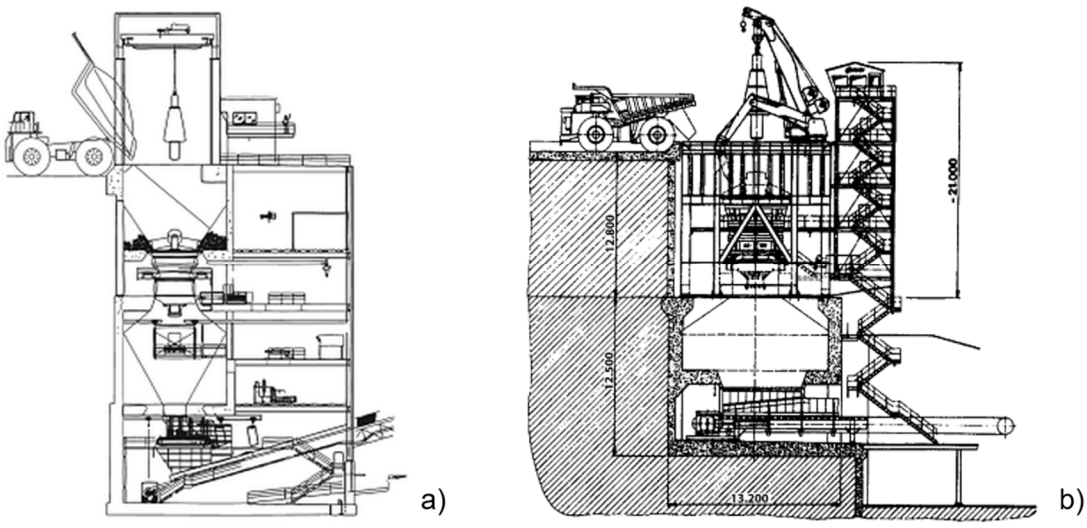



*Figure 2-8 Fixed in-pit crusher station a) concrete structure* [33]*; b) steel structure* [34]

### 2.3.2 Crusher Station Configuration

In-pit crusher stations are composed of multiple subsystems including:

- material charge,
- integrated material feed system,
- crusher,
- integrated material discharge system,
- auxiliary systems,
- framework, and
- substructure/undercarriage.

**Subsystem – Material Charge**

The subsystem material charge has, depending on the loading process and the successive subsystems, the following functions:

- to balance and buffer the inevitable fluctuation of material flow by the discontinuous loading process,
- to protect the feeding system from impact and wear damage, and
- to shorten the loading cycle time though simplified discharge procedure of the loading machine.

In current designs material charge is commonly realised by a hopper without an additional discharge mechanism. Charging troughs are less common and only applied to small capacity crusher station. The material charge system capacity is subject to the unit capacity of the loading/feeding device. Plattner [35] and Kirk [36] suggest a minimum factor of 1.5 (unit capacity to hopper capacity). More contemporary information advise a factor of 2 - 3 [37].

**Subsystem – Material Feed System**

The function of the material feed system is to evenly withdraw material from the material charge and to control the rate the material enters the crusher. Today, crusher station designs commonly use rigid apron feeders as their material feed system. They are built with a series of linked steel plates connected to electric motor driven steel chains. Apron feeders have demonstrated reliable performance when handling large sized blocks and material with high deviation in feed size distribution and moisture content. Other feed systems include chain feeder, belt feeder, vibrating feeder, and grizzly feeder. Apron feeders can be built with an inclination of up to 30° as in contrary to belt feeders with a maximum inclination of 18°. This reduces the length at equal lifting height by 60%. However, apron feeders have a high service weight, are capital intensive and require frequent maintenance.

The selection of the material feed system depends on the material properties, the fragmentation size, crusher type and capacity requirements. In-pit crusher station without material feed systems are referred to as direct dumping stations.

**Subsystem – Crusher**

The crusher subsystem is, based on its primary function which is to reduce the material to a conveyable size, a central component of an in-pit crushing station. The following crusher types are used in IPCC systems:

- Feeder breaker
- Gyratory crusher
- Hybrid crusher
- Impact crusher
- Jaw crusher
- Roll crusher
- Sizer

Principles and experiences that are valid for the selection of crushers in conventional crusher stations can also be applied for in-pit crushing stations. However, attention is required for the selection of crushers with regards to the overall concept of in-pit crushers. Service weight, design dimensions, and resulting dynamic stresses need to be accounted for. The following criteria need to be considered for the crusher selection:

- Material properties (density, moisture, hardness, stickiness, abrasiveness).
- Application requirements (feed size, product size, product size distribution, content of fines, capacity).

Figure 2-9 and Table 2-1 show the main parameters of the aforementioned crushers used for in-pit crusher stations. All parameters are based on data from [38]–[47].

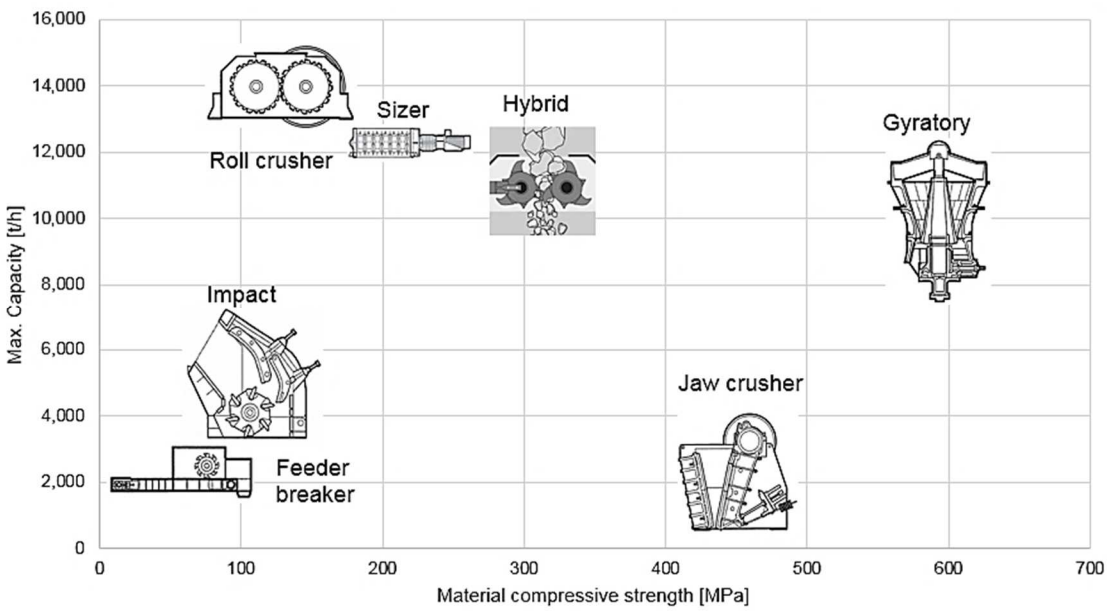
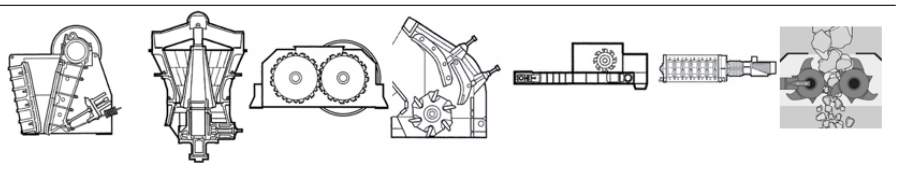



*Figure 2-9 Range of application for crusher types by material compressive strength and capacity*

The graph indicates the maximum values for capacity and compressive strength of material. It must be noted that the crusher throughput is also a function of the reduction ratio between material feed size and required final product size.

*Table 2-1 Main parameter of primary crushers*

| Crusher | | Jaw | Gyratory | Roll Crusher | Impact | Feeder Breaker | Sizer | Hybrid |
|---|---|---|---|---|---|---|---|---|
| Year introduced | | 1858 | 1883 | 1910 | 1920 | 1960 | 1979 | 2005 |
| Mechanical reduction method | | compression | compression | compression, impact & shear (for single roll) | impact, attrition, shear | compression, impact, shear | shear, compression | compression |
| Moisture content [%] | | <5 | <5 | >20 | <10 | >20 | <20 | >20 |
| Application for high clay materials | | poor - fair | poor | good | poor | fair | excellent | very good |
| Abrasiveness | | high | high | low | not applicable | low | low - medium | low - medium |
| Fine generation | | low-medium | low-medium | low | high | low-medium | low | low |
| Max. capacity [t/h] | | 1250 | 10940 | 14000 | 4500 | 6000 | 12500 | 12000 |
| Material compressive strength [MPa] | | 450 | 600 | 150 | 115 | 50 | 200 | 300 |
| Max. feed size [mm] | | 1500 | 1830 | 1600 | 3000 | 1500 | 2000 | 2500 |
| Reduction ratio | | 1:4 - 1:9 | 1:3 - 1:8 | 1:5 - 1:10 | 1:10 - 1:50 | 1:2 - 1:4 | 1:2 - 1:4 | 1:4 - 1:6 |
| Design variations | | single/double toggle | Gyratory, Jaw-type gyratory | Single/double roll | Horizontal/vertical and single/double shaft | | single/double roll, side/centre | |
| Max. Dimensions [mm] | height | 5400 | 10800 | 3500 | 8100 | 2000 | 1800 | 2000 |
| | length | 5200 | 6450 | 9700 | 5500 | 6500 | 10100 | 9300 |
| | width | 4200 | 6250 | 8200 | 5700 | 4500 | 4050 | 7000 |
| Max. Weight [t] | | 115 | 530 | 230 | 190 | 50 | 190 | 102 |
| Max. Installed power [kW] | | 400 | 1200 | 2000 | 2800 | 300 | 1200 | 2500 |
| Schematic | |  | | | | | | |

The main selection parameters including achievable capacity, maximum feed size, achievable reduction ratio and material compressive strength of primary crushers are illustrated in Figure 2-10 to Figure 2-13.

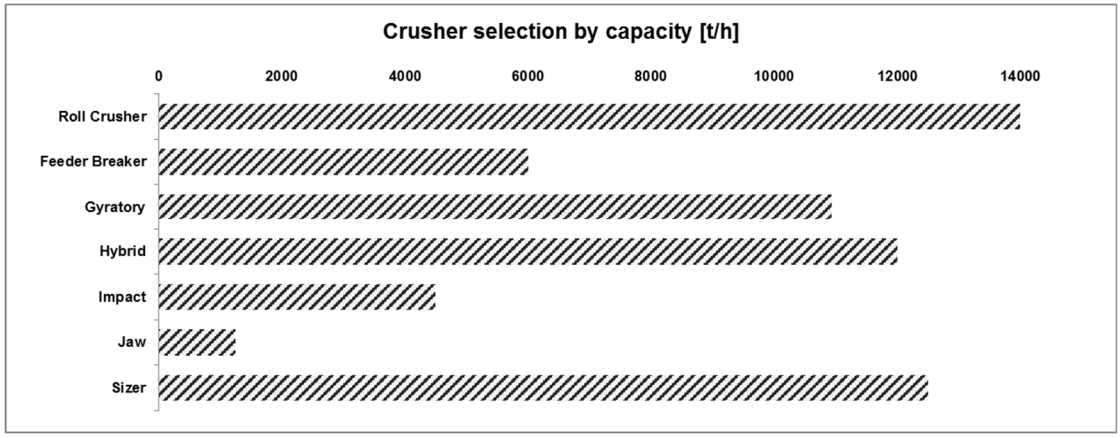



*Figure 2-10 Crusher selection by capacity*

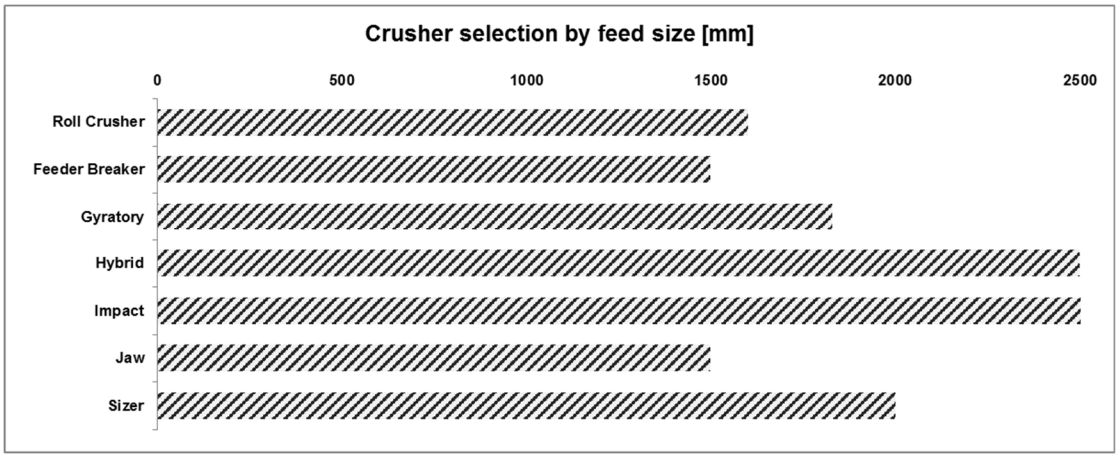



*Figure 2-11 Crusher selection by feed size*

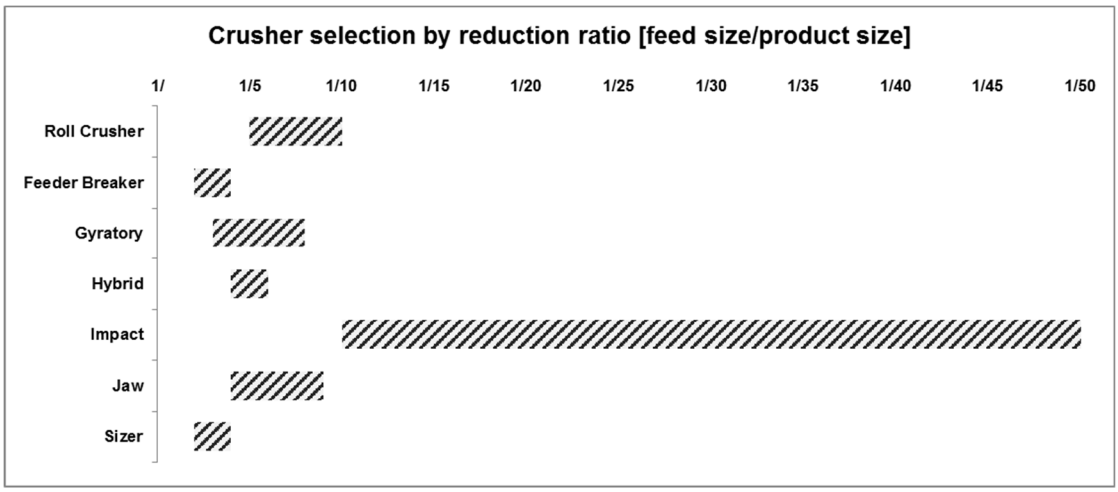



*Figure 2-12 Crusher selection by reduction ratio*

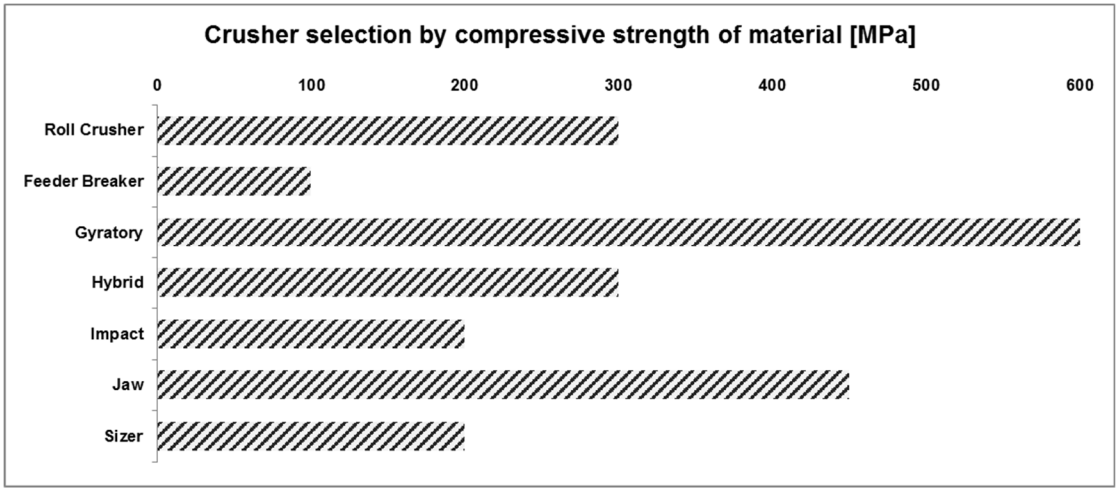



*Figure 2-13 Crusher selection by compressive strength of material*

An analysis of utilisation of the different crusher types since 1960 is illustrated in Figure 2-14.

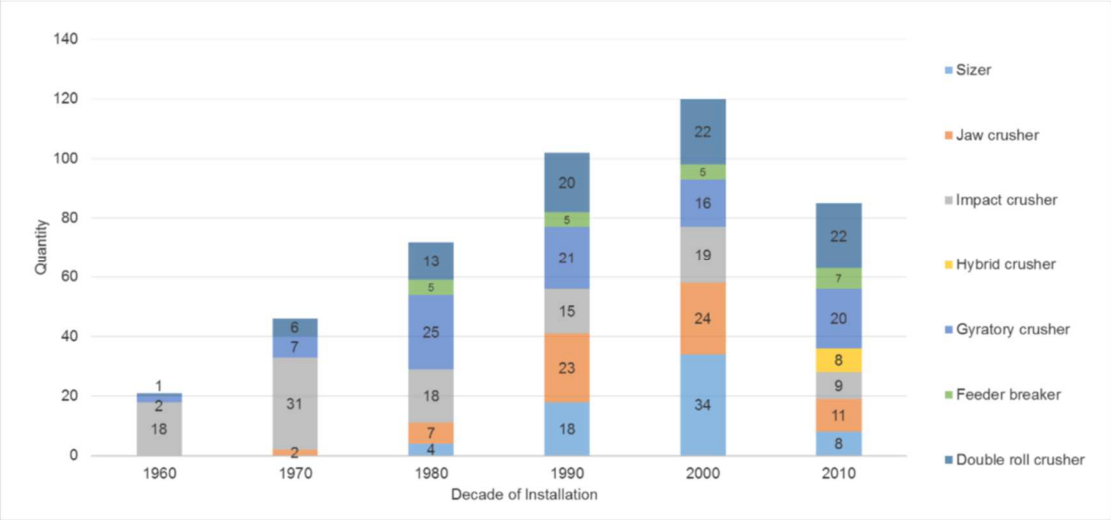



*Figure 2-14 Type of crusher by decade*

For industrial or mass commodities including limestone, dolomite, diorite, granite, marble, and basalt the impact crusher represents the most widely used crusher type (50%). This might be justified by the fact that in this industry the crusher serves an additional function which is to produce a product size and shape that can be directly fed to the processing plant (maximum reduction ratio of 1:50 and above can be achieved). Additionally, impact crushers are capable of crushing rock with a moisture content up to 10%. In recent years, jaw crushers with pre-screens and sizers have been increasingly used.

In copper and gold deposits the gyratory crusher is the main crusher type (86%). This dominance may be explained by the crusher's ability to process material with high compressive strength in high capacities.

The main crusher types for coal and oil sand deposits are double roll crusher and sizer with a share of 54 and 26%, respectively. They are able to process wet and sticky material at high capacity rates.

Iron ore deposits employ mainly gyratory crushers (39%) for the same reason as for copper and gold deposits. Recently, jaw (24%) and hybrid crushers have been frequently utilised especially in combination with fully-mobile crusher stations. Hybrid crusher feature a compact design (>40% size reduction compared to double roll crusher), generate a minimum of undesirable fines and are able to process material up to 300 MPa.

**Subsystem – Material Discharge**

The purpose of the material discharge system is to release and guide the crushed material to the subsequent element. Fixed and semi-fixed crusher stations use overlapping flight apron feeders, vibrating feeder, belt conveyor or outlet chutes as their

discharge system. Fully-mobile stations may have a slewable and/or luffable belt conveyor directly attached, or have outlet chutes.

**Subsystem – Auxiliary Systems**

Auxiliary systems include all systems that are required if additional tasks are necessary. For instance, pre-screening devices (located in the material feed systems) which allow smaller material to bypass the crusher, therefore minimising the amount of material to be crushed and increasing the overall throughput. Other auxiliary systems include service cranes, rock breakers, control room, spillage chute, truck-bridge, and magnetic separators.

**Subsystem – Framework**

The framework has the function of connecting all subsystems. Fixed crusher stations (in-ground or rim mounted) commonly have a concrete structure with some portion of fabricated steel. Semi-fixed, semi-mobile and fully-mobile crusher stations are mounted on a steel structure.

**Subsystem – Substructure**

The substructure is the lower-most part of the crusher station which supports and evenly transmits static and dynamic loads occurring in the station to the bearing ground surface. A fixed crusher station's substructure is made of concrete, whereas semi-fixed and semi-mobile crusher stations are commonly supported by steel footers. In most cases, simply a bed of compacted gravel is required to ensure an appropriate foundation for steel footers.

The substructure, or in this case undercarriage, of fully-mobile crushing stations serves an additional function which is to realize required movements during the course of the face advancement. Varying fields of application require different mobility of the fully-mobile crusher stations. The type of transport mechanism chosen depends on the frequency of relocation, the service weight, the prevailing operation and ground conditions and the installation costs. Possible integrated transportation mechanisms are:

- tires,
- hydraulic walking pads, and
- crawler tracks.

The first tire mounted fully-mobile crusher stations were introduced during the 1970s and increased the mobility compared to crawler tracks and particularly hydraulic walking pads. The main disadvantage is the specific ground pressure which results from comparatively small contact surface. Tire systems are commonly used for crusher stations with service weights up to 745 t. Hydraulic walking pads have the advantage of high manoeuvrability; they can travel in all directions without difficulty. However, with

regards to travel speeds and operational availability they are inferior. Crawler tracks are the most common transport mechanism for large fully-mobile crusher stations. They are well suited to work in line with electrical rope shovels or hydraulic excavators as the time and speed required to move is similar. Crawler tracks have low ground pressure and enable a smooth and quick relocation without the necessity to shut down the crusher. The drawbacks are high service weights and the associated capital and maintenance costs. They are usually used in stations with higher service weights or where ground conditions require low ground pressure. Fully-mobile crusher stations with crawler tracks achieve travel speeds between 8 – 12 m/min for large stations and 17 - 20 m/min for smaller stations. The service weight of the station and the ground conditions determine the number of tack rollers and the permissible ground pressure determines width and length of the base plates.

Relocation of semi-mobile and semi-fixed crusher stations is realised with transport crawlers or self-propelled modular transporter (SPMT) (Figure 2-15). Transport crawlers are autonomous crawler tracks, which are able to carry loads up to 1,500 t on a maximum gradient of 10%. They can be equipped with or without an operator's cabin. A self-propelled modular transporter is a platform vehicle with a large array of wheels which can be combined to transport objects. They individually achieve maximum transport loads up to 216.5 t with a maximum gradient of 12% [48]. Both transport machines are equipped with electronic control systems which regulate hydraulic cylinders to keep the load level even on rough terrain and steep gradients.


*Figure 2-15 a) Transport crawler (Sandvik); b) SPMT* [49]

### 2.3.3 Crusher System Summary

Table 2-2 summarizes and complements characteristics of the different crusher types. It can be determined that each crusher type holds advantages under certain parameters.

*Table 2-2 Summary of main crusher station parameters*

| Characteristic | Fully mobile | Semi mobile | Semi fixed | Fixed |
|---|---|---|---|---|
| Relocation frequency | permanent | multiple | multiple | not intended |
| Retention time at site of operation | hours | weeks to years | annual to perennial | mine or service life |
| Mobilisation time | non | hours | days to weeks | - |
| Number of main parts to relocate | 1 | 1 | 2 - 6 | - |
| Distance of relocation | within meters | hundreds of meters | hundreds of meters to kilometers | - |
| Location | operating face | working level | centroid of mass | at or near pit rim |
| Undercarriage | integrated | adaptable | adaptable | not intended |
| Substructure/ Foundation | undercarriage | steel sleepers, steel footings | steel or concrete footings | concrete |

## 2.4 CONVEYOR SYSTEM

In surface mining operations, the term conveyor system is used to refer to an arrangement of belt conveyors which are selected and connected in a way that they facilitate the transport of material out of the pit (ex-pit dump, stockyard or leach pad) or within the pit (in-pit dump) from the crusher system to the disposal system in compliance with the mining conditions [50]. Belt conveyors are continuous conveyors and consist of an endless belt which runs around the drive pulley (head station) and idler pulley (tail station) and can be driven by one or multiple drive pulleys using static friction. Between the pulleys the belt is supported by load bearing idlers. The required belt tension is controlled by the tension system. The material is commonly charged onto the conveyor in proximity to the tail station using a loading hopper and transported on top of the belt to the head station where it is discharged.

### 2.4.1 Belt Conveyor Types

Just like crusher stations, belt conveyors can be classified by the degree of mobility, structural design and location of operation into:

- fully-mobile,
- portable,
- shiftable,
- semi-fixed, and
- fixed belt conveyors.

The following section describes various types of belt conveyors, their components and application. It furthermore focuses on troughed belt conveyors; other belt conveyors types that also find application in surface mines such as cable belt conveyors, air supported belts, suspended belt conveyors and enclosed belt conveyors are not explained but information can be found in [51]–[53].

**Fully-Mobile Belt Conveyors**

Fully-mobile belt conveyors have the ability to change position by system integrated transport mechanisms (almost exclusively with crawler tracks). All components as described in section 2.4.2 are integrated in the structure. Fully-mobile belt conveyors are typically associated with fully-mobile IPCC systems where they are utilised as a link between fully-mobile crusher and shiftable conveyor at the operating face. Additionally, the following secondary functions are realised by fully-mobile conveyors:

- to allow multiple block and bench operation, and
- to increase the overall block width and block height.

Thus the production time between two shifting operations of a shiftable conveyor increases which results in a higher utilisation of the entire material handling systems.

There are two main fully-mobile belt conveyors types (Figure 2-16) which are applicable in IPCC operations:

- belt wagons, and
- bridge conveyors.

Belt wagons may also be built semi-mobile and are relocated by transport crawlers (e.g. Yimin He coal mine, China).

The main difference with regards to design between the types is the number of crawler track sets and the boom construction. Belt wagons commonly use a single crawler track set which is connected to the superstructure including independently luffable and slewable receiving and discharge boom. Bridge conveyors use two sets of crawler tracks which support the receiving and discharge side of a single boom.


*Figure 2-16 Fully-mobile belt conveyor a) belt wagon (Sandvik); b) bridge conveyor*

An additional type of fully-mobile belt conveyors are fully-mobile horizontal conveyors (Figure 2-17). They are levelled conveyors which have a receiving hopper over the full length. They are located at the dump or heap leach pad.

*Figure 2-17 Fully-mobile horizontal conveyor (TNT)*

Table 2-3 summarizes the technical parameter of fully-mobile belt conveyor. All parameters provided are based on data from [54]–[57]

*Table 2-3 Design parameters of fully-mobile conveyors*

| Parameter | Belt Wagon | Conveyor Bridge | Horizontal Conveyor |
|---|---|---|---|
| Max. receiving boom length [m] | 50 | 150 | 87 |
| Max. discharge boom length [m] | 50 | | |
| Max. capacity [loose m³/h] | 10,000 | 20,000 | 4,000 |
| Belt width [mm] | 2,500 | 2,800 | 1,600 |
| Service weight [t] | 550 | 300 | - |

**Portable Belt Conveyors**

The portable belt conveyors (Figure 2-18), also referred to as grasshoppers, are inclined conveyors with a maximum length of 42 m comprised of a tail skid and a set of non-powered tires located near the balance point. Designs may include crawler tracks which are self-propelled. All components as described in section 2.4.1 are integrated in the structure. Their function is to link a fully-mobile in-pit crusher station at the operating face to a further stage in the conveyor system [58]. Another purpose of portable conveyors is to transport material at the downstream end of the system across active dump/heap areas where they are connected to a radial stacker. They are able to follow the crusher station as it moves along the operating face, and can be moved by the crusher station itself or other mobile equipment to a safe distance for blasting. Each conveyor can be moved individually or in combination of two or three units. Maximum capacities of 3,000 t/h are achieved with 1,600 mm belts and 28 t service weight [59], [60].


*Figure 2-18 Portable belt conveyor a) in limestone quarry (Metso); b) at heap leach; c) at waste dump (both Terra Nova Technologies)*

**Shiftable Belt Conveyors**

Shiftable belt conveyors (Figure 2-19) comprise of 4 - 6 m long portable conveyor modules spaced along their longitudinal axis. The modules are mounted on steel sleepers and consist of steel frames that hold the carrying and return roller. Steel rails are connected to the steel sleepers to maintain a predetermined spacing between the modules. The steel rails allow the shiftable conveyor to be moved without dismantling in lateral direction by pipe laying dozers with a trackshifting head. The dozer engages the conveyor and applies lateral shifting forces to bend the conveyor. Shiftable conveyors are located either inside the pit parallel to the operating face or at the dump face. They are moved periodically to follow the operating face advance or dump advance. Shiftable belt conveyors are usually associated with mobile or semi-mobile drive stations mounted on steel pontoon, steel sleepers or crawlers. The following three shifting patterns are possible: parallel shifting in which all modules of the shiftable conveyor are shifted over the same distance; radial shifting where one end (head or tail end) of the shiftable conveyor remains in the same position and functions as a pivot point while the other end is swung around this end; and combined shifting which uses both shifting techniques parallel and radial in a way that one end of the conveyor is shifted further than the other. The shifting process time depends on ground conditions, conveyor length, shifting width and available work and equipment force. It typically takes between 8 - 24 h and is split up into 3 processes including preparation for shifting, shifting process, and alignment & start-up process.


*Figure 2-19 Shiftable belt conveyor a) trackshifting* [61]*; b) drive station mounted on crawler* [62]*; c) at operating face* [63]

**Semi-Fixed Belt Conveyors**

Semi-fixed or relocatable belt conveyors (Figure 2-20) are wherever infrequent relocation or extension/shortenings are necessary such as on ramps or tunnels for pit exit, or as overland conveyors. They consist of 4 – 6 m long portable conveyor modules spaced along the longitudinal axis of the conveyor. The modules are mounted on concrete sleepers and consist of steel frames that hold the carrying and return roller. Prior to relocation the entire conveyor needs to be dismantled and each segment carried to a different position. They are usually associated with semi-mobile or fixed drive stations mounted on steel or concrete pontoons.

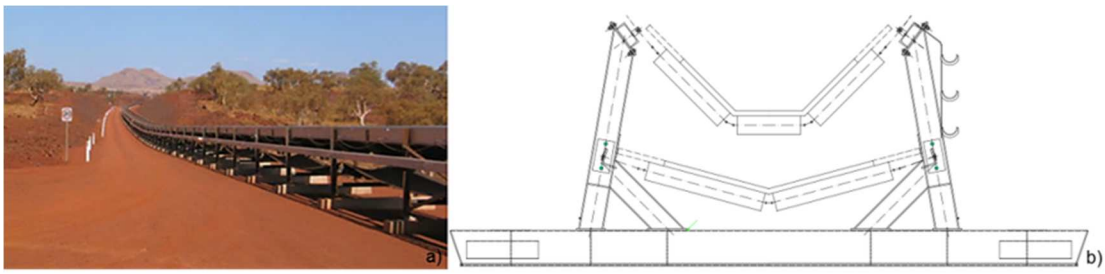



*Figure 2-20 Relocatable belt conveyor a) overland conveyor); b) cross section (Sandvik)*

**Fixed Belt Conveyors**

Fixed belt conveyors are used whenever relocation is not required during the life of mine. Fixed belt conveyors can take on many different design forms. They are usually located ex-pit as overland conveyors to overcome difficult terrain, and usually associated with fixed drive stations mounted with concrete foundations.

High angle conveyors (HAC) and conveyor distribution points represent a special type of fixed belt conveyors.

HAC are designed to overcome the conventional conveying angle limitations of 20°. HAC are designed in various forms to transport material out of the pit by the shortest distance via the pit wall. HAC designs exist with crawler tracks mounted on receiving and discharge side to follow the advance of a heap leach dump. They use a sandwich belt approach which employs two conventional rubber belts. The belts sandwich the material and provide additional friction between material-to-belt and material-to-material interface to avoid back sliding of material [64]. The HAC structure is anchored to the mine slope and is mounted on concrete footings. The biggest installation in surface mining operation was installed 1992 in Majdanpek copper mine (former Yugoslavia), had belt width of 2000 mm, a capacity of 4.000 t/h at a conveying angle of 35.5° and realised 93.5 m elevation height. Although they realise the shortest distance possible, they are limited to a rock size of 250 mm and require a certain size distribution [65], [66].

Conveyor distribution points, also referred to as mass distributer, are used whenever different material are transported with a conveyor system. They provide the ability to route material to different destinations by the use of shifting heads.


*Figure 2-21 Fixed belt conveyor a) installation in coal mine; b) to power plant; c) HAC[1]*

[1] Photo taken by Karl Ingmarson – Sandvik at Vale Carajas N2 pit iron ore mine

### 2.4.2 Belt Conveyor Configuration

#### General Components

The essential components of a belt conveyor displayed in Figure 2-22 are the following [67]:

- Drive station including drive pulley (1) with rubber or ceramic lining, bearings, with or without transmission, electrical motor with or without coupling
- Deflection pulley (2) to increase friction angle
- Return rollers (3)
- Supporting structure (4) made of fabricated steel profiles, which sustains the load bearing rollers
- Return pulley with tension system (5) including take-up pulleys (spindle-nut system or gravity take-up)
- Loading hopper (6) with drop zone pads (7)
- Troughed load bearing rollers (8), commonly three or four are connected to a garland
- Guide rolls
- Conveyor belt (9)
- Discharge with discharge chute if necessary (discharge chute requires wear resistant lining)
- Belt cleaners and scrapers (10)
- Safety facilities such as pull-rope, rotational speed monitors, belt misalignment switches and belt cut registration

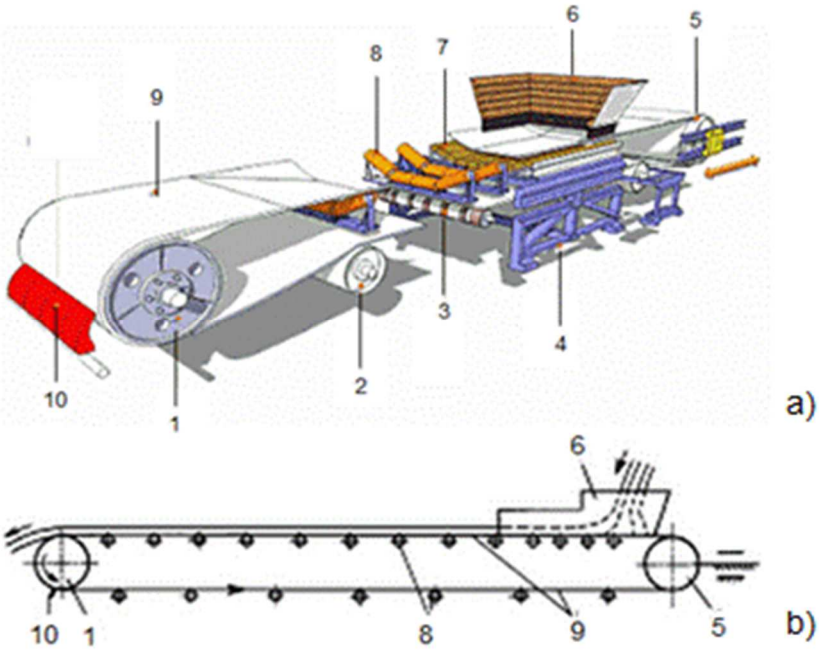



*Figure 2-22 Belt conveyor components a) exploded view* [67]*; b) schematic view* [50]

**Head and Tail Station**

The head station (most commonly the drive station) essentially consists of the drive pulley, with rubber or ceramic lining, and the electrical motor with or without coupling supported by a steel structure. The drive of the head station may consist of one or multiple drive units. They are differentiated into mobile, semi-mobile and fixed stations depending on the frequency and the way of relocation. The installed drive capacity covers a range from 2 times 160 kW to 6 times 2,000 kW with service weights up to 2,000 t [68], [69]. Mobile and semi-mobile stations are mounted on steel pontoons, hydraulic walking pads or crawler tracks and are tied down by earth anchoring for quick relocation. Fixed drive stations usually have concrete foundations and do not require any anchoring.

Tail stations consists of the return pulley incorporated into the steel structure. Whenever additional drive force is required they may be equipped with an electric motor to drive the return pulley. Just like head stations they are either mobile, semi-mobile and fixed stations. As they are considerably lighter than head stations, they are usually mounted on steel pontoons and can be dragged by a dozer. At the operating or dump face they may also be mounted on crawlers for quicker relocation.

**Conveyor Belt**

The conveyor belt is the most important component of a belt conveyor. Their function is to receive crushed material and to transport it longitudinally. The belt requires sufficient tensile strength in longitudinal and lateral direction, resistance against impact energy at the loading point, and to withstand temperature and chemical effects, without losing elasticity to adapt to the troughed structure of the carrying idlers. They are therefore built in multiple layers comprised of pulley side cover, carcass, and carrying side cover framed by full rubber edges.

The pulley and carrying side cover are made of smooth rubber or PVC. The carrying side cover may also include profiles, cleats, or corrugated edges for inclined conveyors. The carrying side is up to 3 times thicker than the pulley side for wear and impact protection. Stresses and strains are absorbed in the centre of the belt by the carcass. The carcass may be reinforced by textile ply (polyester, polyamide or aramid) or steel cords and are manufactured in single or multilayers.

Belt width and tension are standardised by the manufacturers. Currently, belt widths in the range of 800 to 3,200 mm are utilised in the surface mining industry. Belt tension rating ranges between ST 1,000 to ST 10,000 [70]. The belt breaking strength rating stands for the amount of pulling force that belt is able to withstand and is measured in N/mm.

The connection of belts is accomplished either mechanically or by vulcanisation process. Vulcanisation (hot or cold) is most commonly used in the mining industry. In

a hot vulcanisation process the reinforcements are spliced in a certain pattern, then splices are heated and cured under pressure with a vulcanising press. Cold vulcanisation uses a bonding agent which causes a chemical reaction to splice the two belt ends together [71]. Vulcanisation requires a 24 h setting period. For this reason, the frequency of belt extensions/shortenings should be minimized in a FMIPCC operation.

## 2.5 DISCHARGE SYSTEM

The discharge system represents the last element of an IPCC system. Its function is to continuously unload the material from the conveyor system in an orderly and efficient manner to its final destination (waste dump) or to an intermediate storage location (heap leach pad, stockyard). Discharge system equipment (Figure 2-23) can be distinguished by the type of material discharged and the associated location of operation into:

- spreaders,
- stackers, and
- stackers/reclaimers.

Spreaders operate at the dump site and are utilised for overburden and waste material. Stackers handle low grade ore at heap leach pads or stack ore/coal material at stockyards. Stackers/reclaimers are machines for unloading material onto storage piles and reclaiming when required.

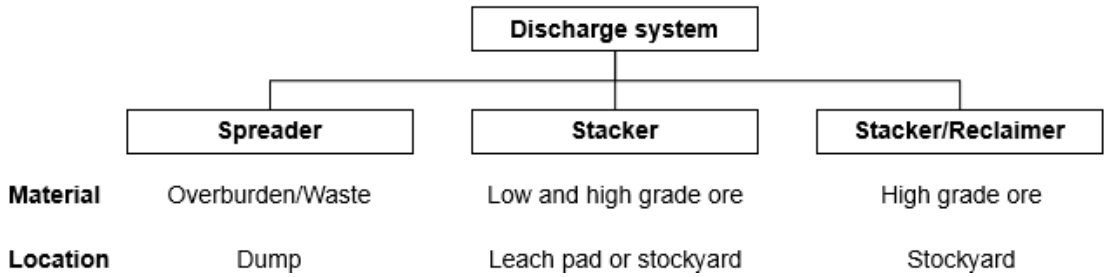



*Figure 2-23 Discharge system equipment types by material and location*

### 2.5.1 Spreader

Spreaders are mobile continuous operating discharge machines. The functions of a spreader within an IPCC system are to receive overburden material from a tripper car and to discharge it in a stable manner on a high or low cast dump with a certain degree of compaction. While discharging, the spreader travels on its self-made working level which usually has a lower ground bearing pressure than the surrounding bedrock capacity [72].

Contemporary conveyor belt spreaders designs can be categorized by their constructional design into compact type and C-frame type spreader (Figure 2-24). The main difference between the two types is the counter weight arrangement. The counter

weight of the compact type spreader is attached below the receiving boom, allowing it to create flatter final dump slopes by operating on a sublevel below the shiftable conveyor, whereas the counter weight of a C-frame type spreader is above the receiving boom. A spreader basically consists of five components:

- a receiving boom with or without crawler track support,
- a superstructure, supported by
- a substructure mounted on crawler tracks,
- a discharge boom, and
- a counter weight.

The superstructure can be slewed relative to the substructure by ± 300° and the receiving boom can be slewed by between ± 90 and 115°. The receiving boom may have one or two parts. In one-part design the receiving boom is hinged into the superstructure of the spreader and supported by the tripper car. This design represents the option with the lowest service weight but can only be realised for small to medium receiving boom length (< 50 m) and capacities (< 15,000 t/h) to enable transport without disassembly [73]. In two part designs the receiving boom has a further intake boom, either as an integral part of the spreader or part of the tripper car, and is additionally supported by crawler tracks. Although the intake boom tends to have high wear due to its short design and increased overall service weight, it enables bigger block width.

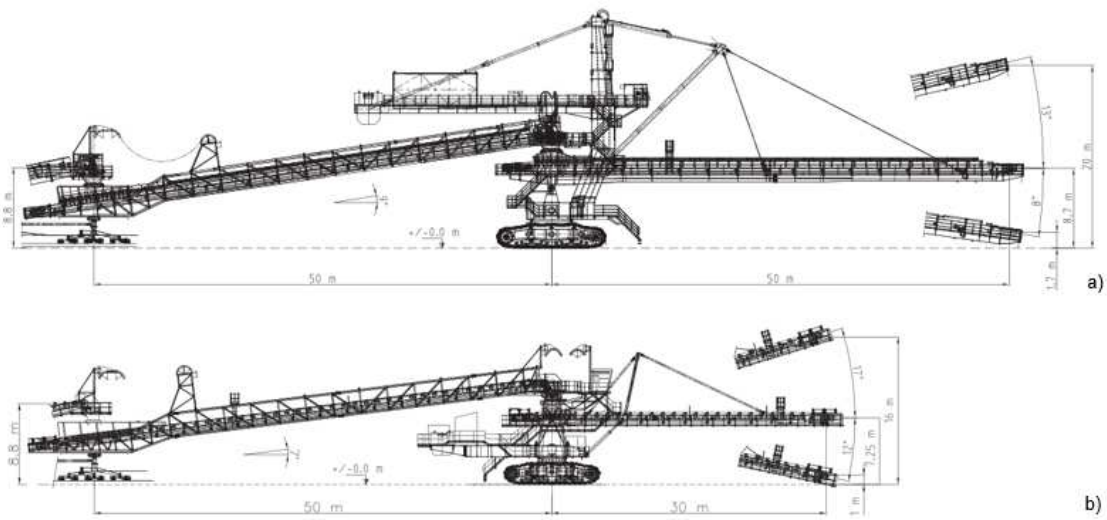



*Figure 2-24 Spreader a) C-frame type; b) compact type (Sandvik)*

A special type of spreader is a cross pit spreader (Figure 2-25). They are part of a direct dumping system which transports material directly above the uncovered ore and realizes the shortest transport distance possible by a long discharge boom (up to 260 m). Cross pit spreaders usually work in combination with bucket wheel excavators but also represent a feasible combination with fully-mobile crusher.

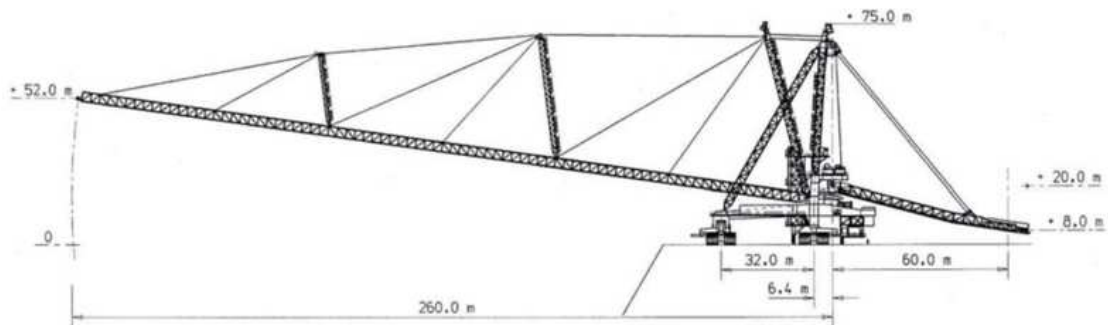



*Figure 2-25 Cross pit spreader (Sandvik)*

Table 2-4 summarizes the main design parameter of spreaders. All parameters provided are based on data from [57], [74]–[77]

*Table 2-4 Design parameters spreader*

| **Parameter** | **Spreader** | | |
|---|---|---|---|
| Design variation | Compact | C-frame | Cross Pit |
| Design features | luffable, slewable | luffable, slewable | luffable, slewable |
| Undercarriage | crawlers | crawlers | crawlers, hyd. walking pads |
| Max. capacity [t/h] | 15,000 | 20,000 | 20,000 |
| Max. boom length [m] (receiving/discharge) | 50/50 | 100/70 | 100/300 |

### 2.5.2 Stacker

Stackers are mobile, continuous operating discharge machines. The functions of a stacker within an IPCC system are to receive ore at a stockyard or low grade material at a heap leach pad by from the conveyor system and to stack it in a stable manner on a stockpile. They can be categorised by their design into single and double boom stackers. Single boom stackers are mainly used at heap leach pads and have a similar configuration as portable conveyors but are commonly crawler track mounted. At stockyards, rail mounted double boom stacker are widely used.

Figure 2-26 shows a double boom stacker on rail and an extendable single boom stacker.


*Figure 2-26 Stacker a) double boom on rails (Sandvik); b) extendable single boom on crawlers (TNT)*

Mobile stacking conveyors (MSC) represent special designs for stackers which may be used for heap leach operation and for overburden removal. The entire bridge of MSC is supported by several crawler tracks. A small boom can travel along the entire bridge and stacks material in up and downcast modus. The advantage of MSC is decreased downtimes for shifting and reduced linear work compared to spreaders and stackers with long discharge boom; disadvantageous is the limited horizontal and vertical reach. The length of MSC is between 75 and 700 m with capacities of 200 to 10,000 t/h.

*Figure 2-27 Mobile stacking conveyor* [78]

Table 2-5 summarizes the main design parameters of stackers. All parameters provided are based on data from [57], [78]–[82]

*Table 2-5 Design parameters of stackers*

| **Parameter** | **Stacker** | | |
|---|---|---|---|
| Design variation | Double Boom | Single Boom | MSC |
| Design features | luffable, slewable | movable, slewable | - |
| Undercarriage | Crawlers, rails | Crawlers, tires | crawlers |
| Max. capacity [t/h] | 20,000 | 2,800 | 10,000 |
| Max. boom length [m] | 65 | 40 | 20 |

### 2.5.3 Stacker/Reclaimer

Stacker/reclaimers are combined continuous operating machines with the function to stack and recover material from a stockpile. They are categorised into bucket wheel and circular type. Bucket wheel stacker/reclaimer feature the same design characteristics as double boom stackers with the addition of a bucket wheel at the front and reversible belts for material reclamation. Circular types are commonly used for coal applications with covering domes and consist of a discharge boom and a scraper for reclamation.


*Figure 2-28 Stacker/Reclaimer a) bucket wheel type b) circular type (both Sandvik)*

Table 2-6 summarizes the main design parameters of stackers/reclaimers. All parameters provided are based on data from [57], [83]–[86].

*Table 2-6 Design parameters of stacker/reclaimer*

| **Parameter** | **Stacker** | |
|---|---|---|
| Design variation | Bucket wheel type | Circular type |
| Design features | luffable, slewable | 360° slewable |
| Undercarriage | rails | fixed |
| Max. capacity [t/h] | 18,000 | 4,000 |
| Max. boom length [m] | 65 | 60 |

## 2.6 ANALYSIS OF CURRENT IPCC TRENDS

IPCC systems have been installed globally in various mining applications over the last seven decades. The survey, mentioned in section 2.1, was used to analyse the trend of IPCC systems since the 1960s. With regards to IPCC system types, Figure 2-29 compares the quantity of IPCC system types by decade.

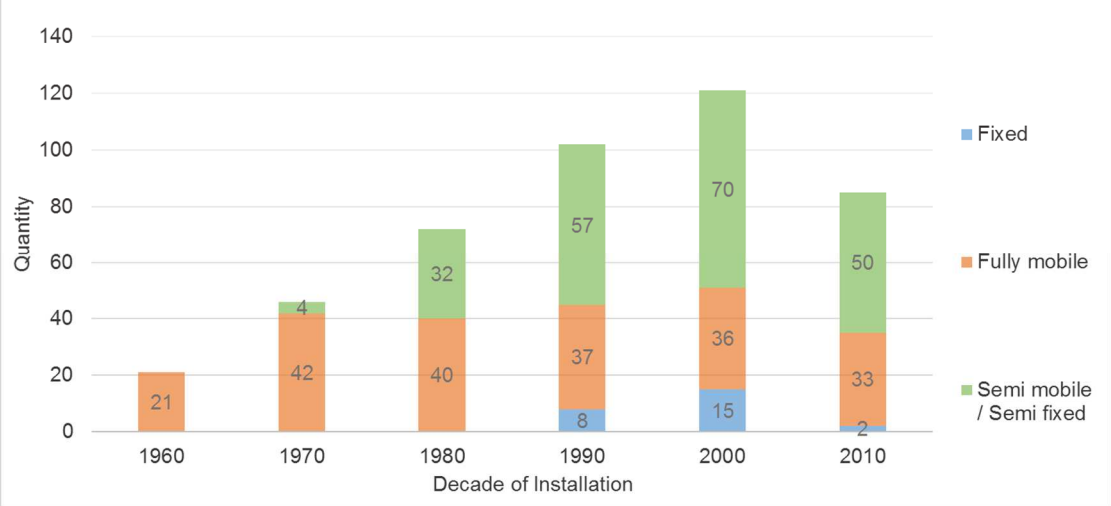



*Figure 2-29 IPCC installations by type*

In the 1960s the majority of applications were fully-mobile and used in limestone quarries. This might be due to a high demand for low-cost raw materials and aggregates after the Second World War. Contemporary quarry operators with conveyor belt background adapted the continuous haulage concept of German lignite mines in combination with in-pit crushers to solve the problem of size reduction for run-of-quarry material. During this period the design trend of in-pit crushers aimed to operate them as operating face equipment. These flexible crusher stations were generally fed directly by face shovels or front-end loaders and mainly eliminated truck transport. They were commonly mounted on an integrated transport mechanism, such as crawler tracks and hydraulic walking pads for manoeuvring. Smaller units, without integrated transport mechanism, were dragged by the face shovel or tracked dozers in order to follow the face development. To follow the crusher stations flexible conveyor belts mounted on tires were designed. Mainly small and dynamically balanced crushers such as impact crushers and single jaw crushers with capacities between 100 and 1,000 t/h were implemented. Although those types of crushers are relatively small and generate little vibrating forces, the inability to design tough platforms on which they were mounted was the limiting factor in installing higher capacity crushers.

The 1970s were still dominated by fully-mobile IPCC applications but as material and design quality increased during the 1970s larger capacity fully-mobile crusher stations (up to 3,000 t/h) with double toggle jaw, double roll and gyratory crushers were developed. Main examples of this period are the fully-mobile crusher stations at Alcoa´s

Huntly mine in Western Australia for bauxite ore from 1971 and at Exxaro´s Grootegeluk coal mine in South Africa for the overburden removal by gyratory crusher from 1979. To the best of the author's knowledge, the last gyratory crusher in a fully-mobile crusher station was built in 1984 due to high dynamic forces transmitted to the frame. These machines had capacities of 1,500 t/h and 3,000 t/h respectively.

To cope with the impacts of the oil crisis of 1979 and the subsequent escalation of costs for petroleum products, mine operators became more interested in the alternative haulage option to stay competitive. This period let IPCC systems leave the domain of small quarry operations to enter large surface mine environments. The first large surface mine operations that fully embraced the concept of IPCC were major copper companies. They realised the advantage in decreasing operating costs as grades were generally low while tonnages were high. These large operations required a reassessment of strategies and design for the use of IPCC systems. Because of large tonnages, high depth and narrow bench systems, locating the in-pit crusher station at the operating face would have the effect of constraining the space needed for the loading equipment [87]. To overcome this situation, the concept of semi-mobile / semi-fixed crusher stations was developed which is denoted by 39 installations of this type in the 1980s. Crusher stations were located at the bottom of the pit or at completed pushback areas. Therefore, a small residual truck fleet was required to deliver the material to the crusher station but their haulage distance was drastically reduced. This new IPCC concept enabled operators to take advantage of the flexibility of trucks without its inherent high cost for vertical haulage. Main IPCC examples for copper deposits of this period are Bingham Canyon Mine in 1986, Morenzi Mine 1988 and Chuquicamata with capacities of 9,000 t/h, 6,750 t/h and 9,600 t/h respectively.

From 1990 up to and including 2014, the trend from the 1970s remained relatively constant with slight increases tendency for semi-mobile and semi-fixed systems.

IPCC system throughput capacities have increased constantly regardless of their degree of mobility. They have now reached maximum capacities of 14,000 t/h for semi-fixed installations in oil sand deposits. Fully-mobile crusher stations have reached now 11,500 t/h for overburden material in iron ore deposits and 12,000 t/h for overburden material in coal deposits. In Figure 2-30, the marks indicate the maximum capacity per hour while the dotted lines show the trend for the different IPCC types. The trend lines demonstrate the significant increase in crushing capacity since the 1960s.

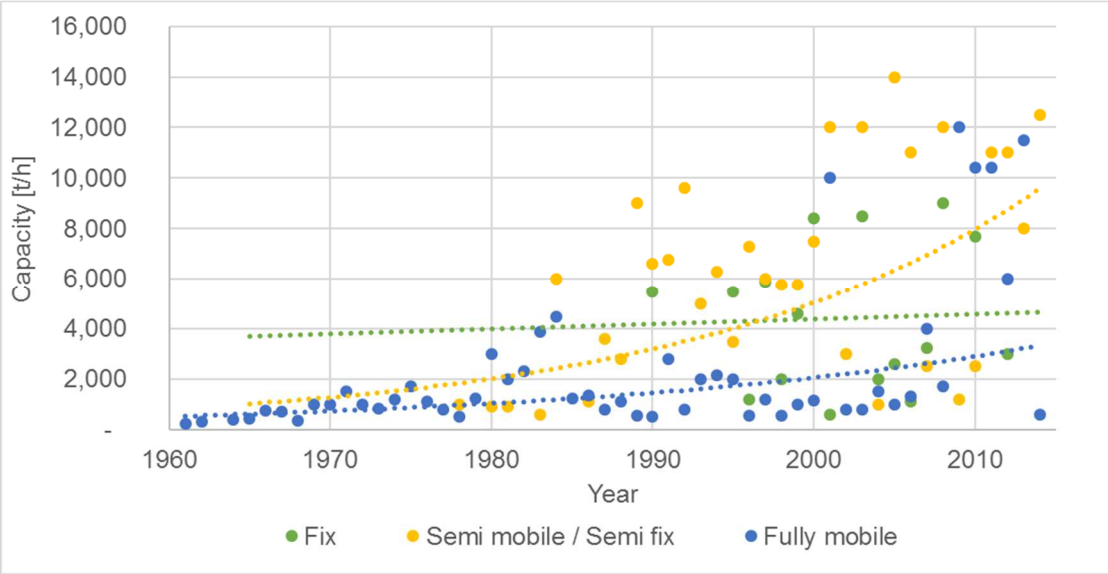



*Figure 2-30 IPCC system capacities*

Figure 2-31 indicates the number of IPCC installations for different material types. Eight different materials types could be identified. In the 1960s throughout the 2000s the majority of material processed were industrial or mass materials including limestone, dolomite, diorite, granite, marble, and basalt. Copper and coal gathered increased proportion beginning in the 1980s. Although only four years are considered in the last decade already 85 crusher stations have been installed, are currently in erection/manufacturing process or on order.

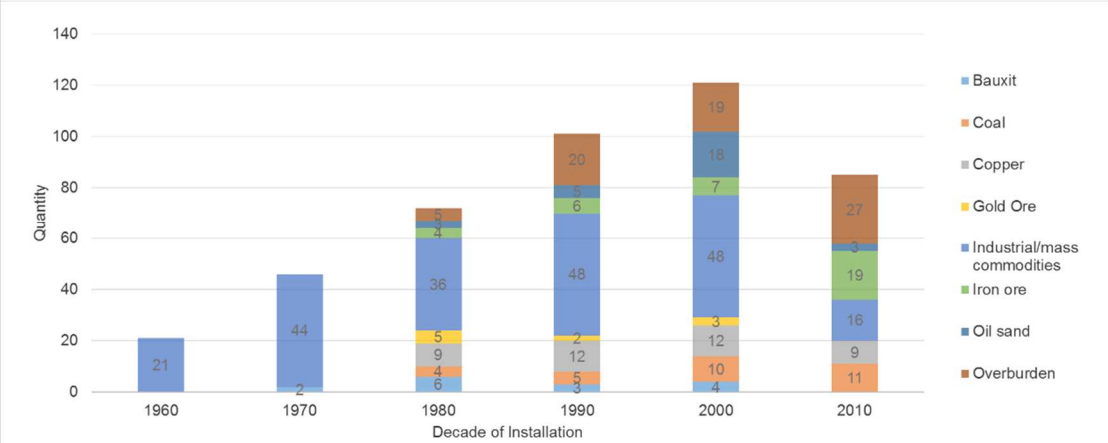



*Figure 2-31 IPCC applications for different material types*

It can be seen that installations for iron ore are increasingly gathering momentum. However, IPCC systems dedicated for overburden material represent the majority of installations with almost 32%.

In conclusion, increasing capacities for semi-mobile or semi-fixed crusher station for overburden material can be seen as an ongoing trend. The reasons may lie in decreasing ore grades in current ore deposits along with growing stripping ratios [88]

that require cost effective removal of larger waste material volumes and necessitate in-pit crusher stations capable of processing larger quantities.

## 2.7 SCOPE OF WORK

In light of this review the research focuses on the determination of the achievable capacity of a simplified SMIPCC systems for waste material (refer to Figure 2-32) under consideration of random behaviour of the individual SMIPCC system elements. SMIPCC system capacity is formally defined as the maximum achievable material the system is capable of handling per year. Although, semi-mobile and semi-fixed IPCC systems have been differentiated in section 2.1 for the purpose of explaining the degree of flexibility the two IPCC system types are from now on summarized as SMIPCC systems.

In this SMIPCC system a truck fleet, consisting of multiple trucks, is loaded by a single loader inside the pit. The trucks discontinuously transport the material to a semi-mobile crusher station inside the pit where it is crushed to a conveyable size. The material is then transported out of the pit by a conveyor system, consisting of multiple conveyors to a single spreader where it is discharged onto a waste dump.

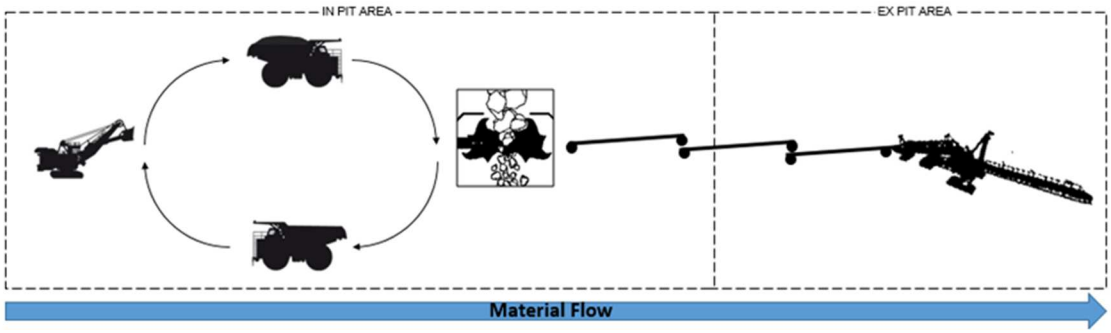



*Figure 2-32 Illustration of simplified SMIPCC system*

# CHAPTER 3:
# LITERATURE REVIEW

*As in any research work, a literature review has been performed continuously throughout this research work. This chapter provides a short background on system theory and reveals the current available methods and their disadvantages for capacity determination of SMIPCC systems.*

## 3.1 LITERATURE REVIEW

SMIPCC systems represent comprehensive machine systems which are used for extraction and transportation of material. Machine systems that consist of individual machines, utilised to facilitate the transport of material from one or several locations to an ultimate destination, are referred to as material handling system. According to the system theory [89], the individual machines are referred to as elements. In the context of material handling systems, these elements refer to equipment such as loaders, trucks, crusher stations, belt conveyors and spreaders, and can be best classified by their relation between themselves into the following main types:

- Winning elements are machines that load the materials handling system such as shovels, bucket wheel excavators, surface miners.
- Haulage elements are machines which receive material from other elements and pass it onto others such as conveyors, trucks and trains.
- Discharge elements, machines through which the material exits the material handling system such as spreaders, stackers and stacker/reclaimers.

Material handling systems are further classified based on the transport method into:

- material handling systems with continuous transport,
- material handling systems with discontinuous transport, and
- material handling system combined transport.

Material handling systems with continuous transport are present when the material is handled in a connected mass flow from winning to discharge elements. Bucket wheel or bucket chain excavators in combination with belt conveyors and spreaders, such as those in German lignite mines, characterise the typical continuous material handling system.

In material handling systems with discontinuous transport, the material is handled in discrete units. A typical example for discontinuous material handling systems are truck and shovel operation.

In this thesis material handling systems with combined material transport for hard rock surface mines are investigated where material is transported by a combination of discontinuous (trucks) and continuous (conveyor) means from the excavation area to the discharge area. The SMIPCC system represents one of the material handling systems with combined material transport. Therefore, the following literature review focuses on methods to determine capacity of these system types.

The mathematical description and theory of material handling systems with continuous transport was primarily developed in the 1960s up to the 1970s especially from Middle and Eastern Europe. The works from König et al. [90], Sajkiewicz [91], Gruschka and

Stoyan [92], Xi and Yegulalp [93] for surface mines and from Ryder [94] and Talbot [95] for underground mines are mentioned.

For capacity determination of material handling systems with discontinuous transport the last decades have been characterised by intensive developments in publications investigating this problem. A comprehensive literature review is provided by Czaplicki [96].

However, only few publications exist for SMIPCC systems or material handling systems with combined material transport. The methods to solve the capacity problem generally include:

- deterministic methods,
- analytical methods, and
- stochastic simulation methods.

Before computer systems were readily available, estimates of system capacity were made by approximating average times for specific activities such as loading, travelling, dumping, and delay times of system elements. The reliability of this deterministic approach varies widely based on the analyst's ability to obtain accurate average activity times. This deterministic method assumes that system elements require exactly the same amount of time for their activities and that the productive capacity of a system is not affected by the interaction and number of elements in the system. This method is not able to analyse variations between different activities or different operating periods which automatically leads to an over or underestimation of the actual system capacity [97].

Methods based on analytic methods can be further divided into methods based on queuing theory and methods based on probability theory. Fundamental work begins with Koenigsberg [98], who modelled single closed-loop or cyclic systems for mechanized room pillar mining operation with finite number of customers based on exponential service time distribution. Koenigsberg adapts equations to determine the probability that various entities are in a given state such as mean cycle time, idle time, daily output or waiting for service.
Maher and Cabrera [99], [100] applied cyclic queuing theory to civil engineering earthmoving projects, similar to haulage systems found in open pit mining. Queuing theory is used here to find the optimum number of trucks that should be used to minimize the cost per unit volume of earth moved. The haulage system is analysed with the option of considering loading and transit times to be constant or variable, fitting a negative exponential distribution. This study also recognises that with more than one excavator in operation the system can have either two separate queuing systems or one joint queue. The end result of this modelling is a set of charts for choosing the most

cost-effective number of trucks based on the ratio of the loading time and haulage time and the ratio of the costs to operate the loader and the trucks [100].

Only few published journal papers deal with the subject of capacity determination of SMIPCC systems using analytical methods. Muduli [101] studied the closed queuing network without capacity constrains at the crusher and proposed an Extended Mean Value Method. Czaplicki presented a procedure based on a G/G/k/r model in which no queue was presumed at the crusher station and refined his method in [102]. In this method Czaplicki describes a queuing system with a general distribution for the interarrival and loading time for trucks for multiple shovels for ore and waste and multiple trucks. Morriss [103] further developed a deterministic model for capacity calculation of SMIPCC and FMIPCC systems.
Publications dealing with simulation methods include works from Peng et al. [104], who developed a simulation model for the SMIPCC system at Qidashan iron ore mine to match the discontinuous and the continuous system. The model included random variables for truck loading time, truck payload, dumping time and throughput capacity of the crusher, which were found to follow a normal or log-normal distribution, as well as the repair and work time distribution of equipment elements, which were deemed to follow exponential or log-normal distributions. Kolonja et al. [105] also developed a discret-event simulation model using AutoMod. The model simulated the overburden removal at Pljevlja Coal Mine in Montenegro.
Another discrete event simulation model was developed by Albrecht [106] for a copper mine in southwest United States using SIGMA® software package. However, the model did not consider reliability of the system elements.
Zhang and Wang [107] developed a queuing network-based simulation model in which the crusher station is considered as an open queuing network and the whole shovel-truck-crusher system as a closed queuing network, with the crusher station as a special server. To fully account for the influence of blocking, Monte Carlo simulation is first used to obtain the performance parameters of the open queuing network for the crusher station. Blocking is referred to as a capacity constraint at the crusher. The closed queuing network for the entire system is solved by applying the Extended Summation Method, in which the crusher server is described by the simulation results. The model has been applied to the Yuanbaoshan open-pit coal mine to analyse its shovel-truck-crusher system and to improve its efficiency.

Furthermore, Todt [108] and Kahn [109] analysed so called “Zugmangelzeiten” or directly translated train shortage time, which results through the mutual interaction of individual unit operations winning, transport and discharge by means of simulation.

Queuing theory gained popularity as a method of fleet selection and haul cycle analysis in the 1970s and 1980s. Simulation models were a commonly used technique for analysis of shovel-truck systems during this time period because they could provide useful results that accounted for the variability inherent in the system [110]. A major

drawback of computer simulation was the method's requirement of computer memory and CPU time, which was costly and time consuming. Analytical modelling methods with little to no computing requirements, such as queuing theory, were viable alternatives to computer simulation models [111].

In conclusion, all mentioned publications have some notable shortcomings as they either neglect the disturbance behaviour or the random capacity behaviour of the system elements.

Based on the described above the following main research objective was identified:

1. Develop a stochastic simulation method to determine the annual capacity of SMIPCC systems as a closed queuing network, which include the random behaviours system elements based on a rational time usage model.

In order to achieve the research objective, the following sub-objectives need to be derived:

1. The annual capacity of a SMIPCC system directly depends on the mean hourly capacity of the discontinuous loader. Hence a suitable analytical model to determine the mean hourly capacity of a discontinuous loader needs to be developed (refer to chapter 4).
2. Based on empirical data distribution models need to be identified which describe the random disturbance and capacity behaviour adequately (refer to chapter 4).
3. With the intention of determine the annual capacity of a SMIPCC system a profound time usage model needs to be established that is capable of incorporating system dependent downtimes.

## 3.2 RESEARCH METHODOLOGY

The methodology adopted for the research and consequent limitations to scope of the research includes:

1. Discussion of initial outline with general objectives with supervisors.
2. Literature research.
3. Review of personal work history for relevant experiences.
4. Identification of issues needing resolution based on experience, peer discussions and literature research and developing strategies to realise solutions (refer to sub-chapter 1.2).
5. Identification of key capacity drivers of SMIPCC systems.
6. Collection and statistically analysis of actual data from operating open pit mines related to capacity and disturbance behaviour of all SMIPCC elements using the statistical data analysis and visualization package STATGRAPHICS™.

7. Identification of suitable distribution functions to describe the random behaviour of SMIPCC elements.
8. Development and computational implementation of a stochastic analytical equation to determine mean and variance of truck loading time as well as actual truck payload.
9. Development of a suitable time usage model applicable for SMIPCC systems.
10. Development of a simulation method to determine system-induced operating delays
11. Comparison of simulation method based on a case study
12. Interpret results and record outcomes.

As mentioned in step 6. collection and analysis of actual data from operating open pit mines was required. Analysis of that data has yielded descriptive statistics that provide a reliable means of modelling SMIPCC production activities for accurate prediction and forecasting of effective operating hours and capacity. All empirical data has been identified as continuous random variables. Data for bucket cycles is, of course, discrete. That the subsequent analysis assumes variables to be continuous and random, and that any subsequent modelling of distributions appears to yield reasonable, consistent and expected results is considered sufficient justification for any assumptions made.

Analytical procedures generally follow a series of simple activities:

- Data was collected from operations for all elements in a SMIPCC system included data with regards to equipment capacity such as truck payloads, bucket payloads, bucket cycle times, truck loading times, total hauling cycle time as well as data with regards to equipment disturbance such as mechanical breakdowns, electrical breakdowns, and other disturbances.
- Empirical data was generally assumed to be random and continuous, and could be modelled as such.
- Confidence interval limits for selected variables were found to be set by design or safety protocols, such as, 10/10/20 payload policy guideline described and considered in some detail in sub-chapters 4.3.3.
- Analytical process involved examining data for obvious false records and applying appropriate filtering. Any filtering applied to eliminate false data has generally been small, and is considered to have no major influence on the conclusions drawn from developed statistics.
- Distribution fitting was qualitative with selected verifications using the $\chi^2$ - test.
- Interpretations, implications and inferences that can logically be drawn from the statistical results are described and summarized at appropriate locations throughout the text, mainly in Chapter 4.

# CHAPTER 4:
# RANDOM BEHAVIOUR OF SMIPCC ELEMENTS

*The SMIPCC system behaviour is mainly dependent on the properties of its elements. In the context of this thesis, properties that characterise the random variation from the steady state of the system elements are of interest. Therefore, Chapter 4 addresses the random behaviour of SMIPCC system elements. At first an introduction of relevant distributions is given. Then the capacity variation of system elements is explained in detail and distributions, as well as actual values to approximate the behaviour, are provided. Emphasis is given to the element of the discontinuous feed system as discontinuous elements are only indirectly influenced by capacity variations. Furthermore, the disturbance behaviour of system elements is explained and values obtained from actual site data and literature are statistically analysed.*

## 4.1 INTRODUCTION

The capacity of a SMIPCC system generally depends on its arrangement and the properties of its elements. In the context of this thesis, properties that characterise the random variation from the steady state of the system elements are of interest. The following will illustrate the kind of distributions that are used to describe these variations. Variations that require characterisation are:

- Loader capacity variations,
- Truck capacity variations,
- Disturbance behaviour of system elements.

All these quantities are more or less dispersed random variables.
A random variable or stochastic variable is a variable whose value is subject to variation due to chance. It may adopt a set of possible different values, each with an associated probability, in contrast to other mathematical variables.

A random variable $X$ is characterised by its distribution function $F(x)$ [112]:

$$F(x) = P(X \leq x) \tag{4-1}$$

where $x$ is a real number and $P$ the probability. Therefore, the function value $F(x)$ at the point $x$ equals the probability that the random variable $X$ takes on a value which is smaller than $x$.
Random variables can be discrete, that is, taking any of a specified finite or countable list of values, endowed with a probability mass function; or continuous, taking any numerical value in an interval or collection of intervals, via a probability density function that is characteristic of a probability distribution.

In this thesis, continuous random variables are of main interest. For a continuous random variable $X$, the probability density function is

$$f(x) = F'(x) \tag{4-2}$$

with

$$\int_{-\infty}^{\infty} f(x)\, dx = 1. \tag{4-3}$$

The mean or expected value of a continuous random variable $X$, denoted as $\bar{X}$, is

$$\bar{X} = \int_{-\infty}^{\infty} x f(x) dx. \tag{4-4}$$

The variance of $X$, denoted as $\sigma^2$, is

$$\sigma^2 = \int_{-\infty}^{\infty} (x - \bar{X})^2 f(x) dx = \int_{-\infty}^{\infty} x^2 f(x) dx - \bar{X}^2 \tag{4-5}$$

The number of distribution functions used to describe the behaviour of system elements is quite rich, starting from rather simple functions like exponential and normal distribution to more sophisticated distributions such as Weibull, gamma, and Erlang distribution. In this thesis, following the guideline for stochastic models to model as simple as possible but not more so, the first two mentioned distributions and the gamma distribution are deemed to be sufficient to model the behaviour of system elements in a SMIPCC system. Other distributions are provided in the relevant chapters whenever required.

A random variable is referred to as normally distributed if the following relation holds:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \qquad -\infty < x < \infty \tag{4-6}$$

with parameters $\mu$ and $\sigma$ for mean and standard deviation, where $-\infty < \mu < \infty$ and $\sigma > 0$ with $\bar{X} = \mu$ and $\sigma = \sqrt{\sigma^2}$. The notation $\mathcal{N}(\mu, \sigma^2)$ is used to denote the fact that the random variable $X$ is normally distributed with parameters $\mu$ and $\sigma$.

A random variable is referred to as exponentially distributed if the following relation holds:

$$f(x) = \lambda e^{-\lambda x} \qquad \text{for} \qquad 0 \leq x < \infty \tag{4-7}$$

Mean and variance are

$$\bar{X} = \frac{1}{\lambda} \qquad \text{and} \qquad \sigma^2 = \frac{1}{\lambda^2}.$$

A random variable $X$ with probability density function:

$$f(x) = \frac{\lambda^r x^{r-1} e^{-\lambda x}}{\Gamma(r)} \qquad \text{for} \qquad x > 0 \tag{4-8}$$

is a gamma random variable with shape parameter $a > 0$ and scale parameter $s > 0$. Mean and variance are

$$\bar{X} = \frac{s}{a} \qquad \text{and} \qquad \sigma^2 = \frac{s}{a^2}.$$

## 4.2 OPERATIONAL BEHAVIOUR OF SYSTEM ELEMENTS

For the dimensioning of haulage elements and capacity calculations of the feed system, the operational behaviour of system elements and their variation must be considered. Capacity variations occur primarily on elements of the feed system (loader, truck). The elements of the continuous part of the IPCC system are only indirectly related to capacity variations.
Capacity calculation of the feed system represents a fundamental component for the determination of SMIPCC system capacity. As aforementioned, this thesis focuses on discontinuous loaders which are mainly used for SMIPCC systems, namely electric rope shovels or hydraulic excavators. The capacity of discontinuous loaders depends on bucket payload $c_L$ and bucket cycle time $t_L$. Truck capacity depends on truck payload $c_T$ and associated truck cycle time $t_T$ to deliver the payload to the crusher. The four quantities represent typical random variables.

## 4.3 DISCONTINUOUS LOADER CAPACITY

The problem of capacity calculation and capacity variation of discontinuous loaders is closely related to the general equipment selection problem, which is a wide research field in itself and has been extensively studied in the past by many researchers. Burt and Caccetta [113] outlined various modelling and solution approaches for this problem in their review paper. Further references are Hardy [114] and Kühn [115]. Although at a different time, both studied methods for capacity estimations of loaders through extensive time studies. In this part of the thesis a stochastic method is described to determine the average hourly capacity of discontinuous loaders $C_L$.

The theoretical hourly capacity of discontinuous loaders $C_{L_{th}}$ is defined as the theoretical maximum production per hour. It is the hypothetical production rate a loader could achieve in an hour by uninterruptedly cycling at a specific bucket cycle time $t_L$ in s with a specific bucket payload $c_L$ in t and is calculated as:

$$C_{L_{th}} = c_L \cdot \frac{3600}{t_L} \qquad \text{in t/h.} \qquad (4\text{-}9)$$

The factor 3600 is used for the conversion from seconds to hours.
Practically $C_{L_{th}}$ is reduced by a number of productivity constraints. Some constraints have distinct variations and are influential to loader capacity. These constraints include muckpile and material characteristics (in situ density, swell factor, compaction, cutting height), machine design parameters (bucket size and shape, boom lengths, motor power), loading methodology and operator skills [116]–[118]. The relationship of the abovementioned factors and the loaders capacity is illustrated in Figure 4-1.

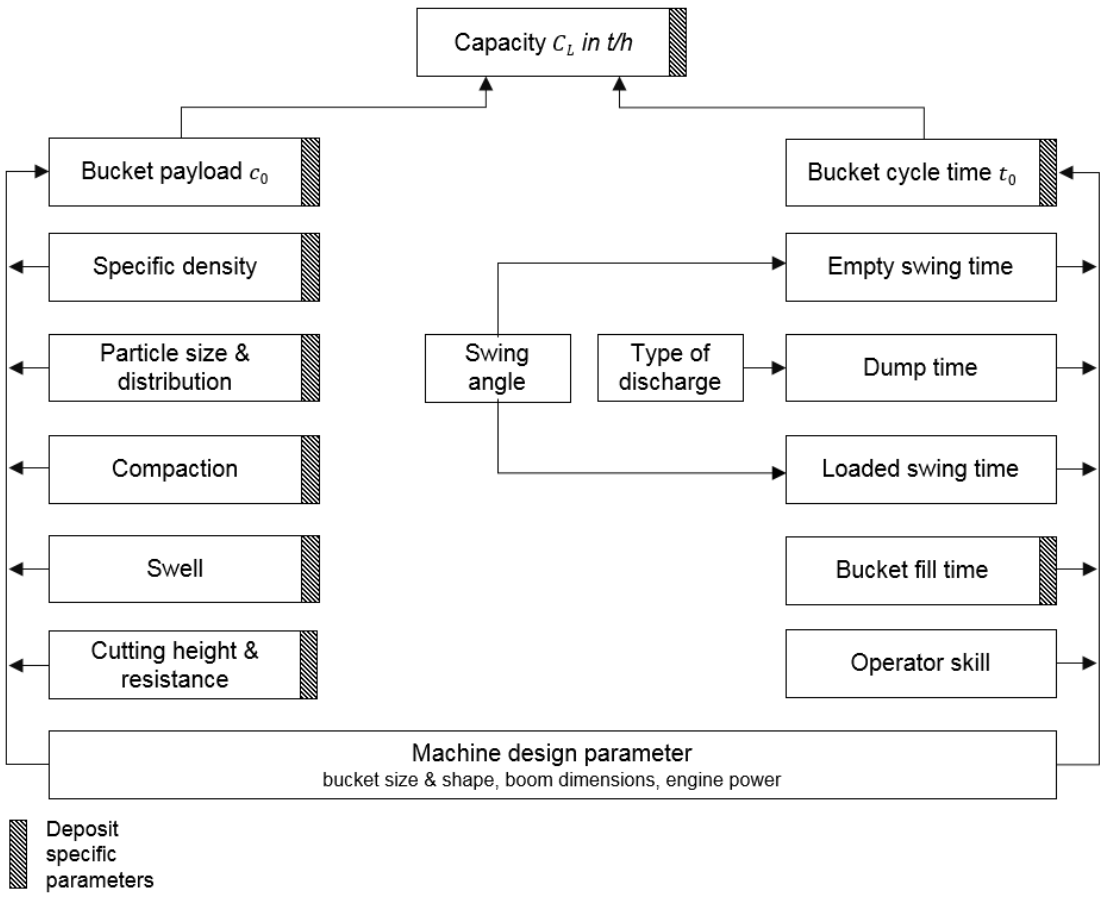



*Figure 4-1 Parameters influencing loader capacity adjusted after* [108]

Usually the mining industry applies multiple empirical correction factors $f_i$ to account for the above mentioned parameters. Using this deterministic approach, the practical capacity $C_L$ of discontinuous loaders is

$$C_L = c_L \cdot \frac{3600}{t_L} \cdot \prod_{i=1}^{n} f_i \qquad \text{in t/h.} \qquad (4\text{-}10)$$

Those factors $C_L$ include bucket cycle time correction factors based on variations of swing angle and non-optimum digging height/depth as well as efficiency factors such as propel factor. A detailed explanation to these factors can be found in [25], [115], [119], [120].

However, to calculate the mean hourly capacity of a discontinuous loader considering the random behaviour, $C_L$ becomes a function of truck payload $c_T$ in t, and the time taken to load each truck referred to as truck loading time $t_{Lo}$ in s, which in turn is a function of bucket cycle time $t_L$, the number of bucket cycles $N$ to load each truck and, to a degree, dependent on bucket payload $c_L$. Therefore

$$C_L = c_T \cdot \frac{3600}{t_{Lo}} \qquad \text{in t/h.} \qquad (4\text{-}11)$$

The quantities $c_T$, $t_{Lo}$ and their random behaviour are discussed further in the following sections.

Equation (4-11) is not trivial as in general the expected value of quotient of two random variables is unequal to the quotient of the expected values.

$$E\left(\frac{X}{Y}\right) \neq \frac{E(X)}{E(Y)}. \tag{4-12}$$

A mathematical proof is provided in Appendix II.

### 4.3.1 Bucket Cycle Time

The *bucket cycle time* $t_L$ consists of the *time to swing empty* $t_1$, *fill* $t_2$, *swing loaded* $t_3$ and *dump* $t_4$ the bucket. Therefore,

$$t_L = t_1 + t_2 + t_3 + t_4 \qquad \text{in s.} \tag{4-13}$$

Bucket cycle time is influenced by the material to be loaded, physical operating conditions and efficiency of loading equipment operator and machine design parameters. These influences, with the exception of machine design parameters, tend to be random in effect and are continuous random variables. Thus $t_L$ is a random variable.

Bucket cycle time distributions are intuitively positively (right) skewed. Positive skewness may be explained as minimum values are technically limited in range but maximum values are less restricted. For example, with a mean bucket cycle time of 30 s a minimum value below 15 s would be unrealistic as the minimum time required to fill, swing, dump and return is limited to machine design parameters such as rotation speed, swing angle and boom dimensions. However, maximum values are less inhibited as in practice time losses, such as attempts of loading equipment operator to achieve full bucket loads and occurrences of boulders, may add to bucket cycle time. Distributions of bucket cycle time can typically be modelled by gamma distributions [90], [114], [121], [122].

A bucket cycle times analysis was conducted at Mittelherbigsdorf basalt quarry for a Volvo EC460CL hydraulic excavator loading alternately a Volvo A30D articulated dump truck (28 t payload) and a CAT 771D rigid dump truck (41 t payload). It must be noted that the excavator was highly “undertrucked”. The term “undertrucked” refers to the situation when the loading machine is underutilised and trucks will receive their first bucket load immediately upon entering the loading area because the excavator will be waiting with its load ready to be dumped onto a truck. Subsequently, the excavator was able to prepare the muckpile and to fill the bucket before the subsequent truck arrived, which lead to very large bucket cycle time for the first pass. Therefore, the first bucket cycle was filtered out and analyses consider only of intermediate bucket cycles exclusive of the first. Table 4-1 summarizes the sample of bucket cycle times.

*Table 4-1 Summary of statistical analysis of bucket cycle times*

| Parameter | Intermediate Bucket Cycle Times [s] |
|---|---|
| # of Records | 485 |
| Maximum Value | 76 |
| Minimum Value | 16 |
| Range | 60 |
| Arithmetic Mean | 25.06 |
| Standard Deviation | 5.59 |
| Coefficient of Variation | 0.22 |

The corresponding histogram is shown in Figure 4-2. For comparison, the gamma distribution has been fitted with estimates for $a = 33.6$ and $s = 1.32$. A $\chi^2$ - test was run to assess whether the bucket cycle time data can be adequately modelled by a gamma distribution. The test divides the range of bucket cycle time data into non-overlapping intervals and compares the number of observations in each class to the number expected based on the fitted distribution. A $\chi^2$-value = 11.88 (with 37 degrees of freedom) and a P-value = 0.81 were obtained, which means that the hypothesis that bucket cycle comes from a gamma distribution can be accepted.

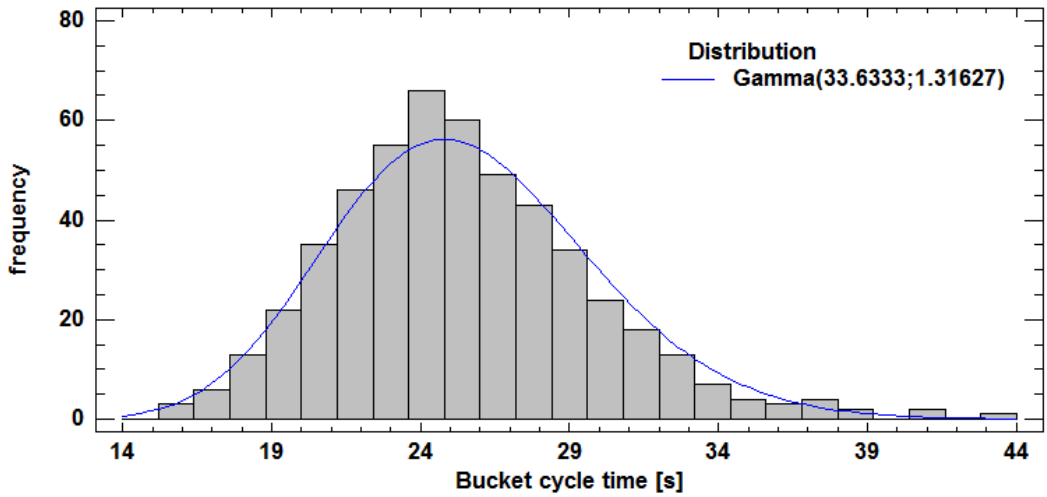



*Figure 4-2 Histogram of bucket cycle times of Volvo EC460CL*

The histogram shows that bucket cycle times can be sufficiently modelled by gamma distributions with $t_L \sim Gamma(a, s)$, shape parameter $a$ and scale parameter $s$. Hardy [114] confirms this observation in his work.

$$a = \frac{\mu_{t_L}^2}{\sigma_{t_L}^2} \tag{4-14}$$

$$s = \frac{\sigma_{t_L}^2}{\mu_{tL}} \tag{4-15}$$

The *variance of bucket cycle time* $\sigma_{t_L}^2$ can be calculated using the following equation

$$\sigma_{t_L}^2 = (\bar{t}_L \cdot c_v)^2, \tag{4-16}$$

where $c_v$ is the *coefficient of variation*. Typical values of $c_v$ are around 0.1 and 0.3 for bucket cycle time. Estimates for mean bucket cycle times of different loaders are provided in [114].

### 4.3.2 Bucket Payload

The *bucket payload* $c_L$, measured in t, is the random mass of digging material held in the bucket after disengaging from the bank [123] and is expressed as follows:

$$c_L = V \cdot \rho_i \cdot f_s \cdot f_f \qquad \text{in t} \tag{4-17}$$

where:

$V$ is the rated bucket volume in m³ resulting from geometrical bucket dimensions, which is calculated by agreed standards. The most common standards are (Figure 4-3):

- Struck capacity which refers to the amount of water that the bucket can hold at maximum when the upper bucket rim is held horizontal,
- Heaped capacity 1:1 (SAE – Society of Automotive Engineers) in which an extra amount of material with an embankment slope of 1:1 is added to the struck capacity, and
- Heaped capacity 1:2 (CECE – Committee of European Construction Equipment) in which an extra amount of material with an embankment slope of 1:2 is added to the struck capacity.

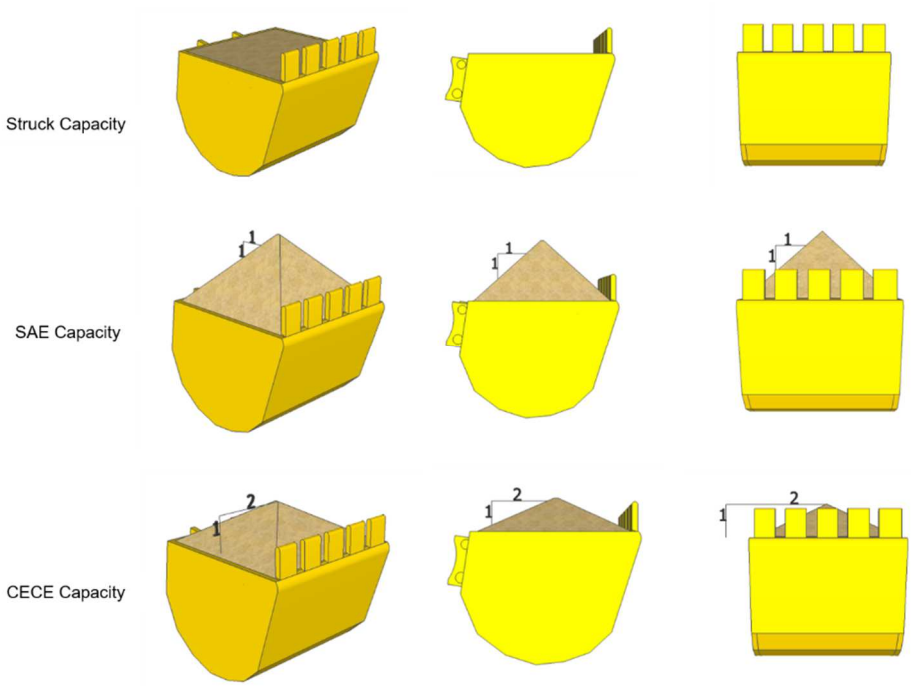



*Figure 4-3 Bucket capacity*

$\varrho_i$ is the *in situ density* in t/m³ which is an inherent property of the material to be mined.

$f_s$ is the *swell factor*. It refers change in volume of the mined material which occurs after disturbance by blasting and loading and can be expressed by the ratio of loose material density $\varrho_l$ and $\varrho_i$. In some literature, swell factor is defined as the ratio of insitu to loose material density, but for the purpose of easy factorisation the reciprocal is used

$$f_s = \frac{\varrho_l}{\varrho_i} \tag{4-18}$$

$f_f$ is the *bucket fill factor* which depends on muck pile conditions, the bucket geometry, loader dynamics and material properties [119]. It is defined as the ratio of the actual volume in the bucket and the rated bucket Volume $V$. The fill factor may be less than or greater than 1.0. Darling [14] provides a table to estimate fill factors for different material types.

The actual bucket payload in each pass in the process of loading a mining truck is influenced by several factors as discussed in the previous subchapter. These factors are strongly correlated. For instance, muckpile characteristics such as fragmentation that determines material swell likely influence the operator ability to achieve consistently high bucket fills and may also constrain digability by affecting penetration of the face. Additionally, bucket cycle time may also be influenced by the operator attempt to achieve high bucket fills. In general, factors influencing bucket payload variability are random, hard to predict and to control [124].

To describe the random behaviour of bucket payloads a literature review was carried out to obtain the required information.
Schwate [121] investigated in his PhD thesis the bucket payloads of a UB 1212, E302 and EKG 4.6 at a quarry in Germany. He showed that the variation of bucket payload increases with poor material fragmentation and may be approximated by a beta distribution with a coefficient of variation between 0.15 and 0.32. However, because of the lack of an appropriate scaling mechanism the bucket payload was estimated based on volumetric fill of the bucket, which leaves his results inconclusive.
Hardy [114] conducted a broad bucket payload study in his PhD thesis by analysing over 350 records from real time observations using Caterpillar's VIMS/TPMS (Vital Information Management System / Truck Payload Management System). Results from this study are summarized in Chanda and Hardy [124]. The interpretation of the results stated the following:

- Normal distribution can be used to predict the behaviour of all bucket payload variations.
- Bucket payload of the first pass is comparatively high as operators tend to have an abundance of time for first pass due to truck manoeuvre and spot time.

The results of the statistical analysis of bucket payload for two data sets, one based on a hydraulic excavator and the other based on a front end loader, are summarized in Figure 4-2 [114].

*Table 4-2 Summary of bucket payload data*

| Parameter | Data set 1 | Data set 2 |
|---|---|---|
| Loading equipment | Hydraulic excavator | Front-end loader |
| Truck payload [t] | 220 | 220 |
| Avg. number of bucket cycles | 4.44 | 8.88 |
| Mean bucket payload (all cycles) | 50.52 | 23.93 |
| Mean bucket payload (intermediate cycles) | 50.4 | 23.41 |
| Coefficient of variation – bucket payload (all cycles) | 0.275 | 0.269 |
| Coefficient of variation – bucket payload (intermediate cycles) | 0.223 | 0.187 |

Figure 4-4 illustrates the summary of bucket payloads of a 700 t hydraulic excavator with an approximate bucket payload of 50 t loading a 220 t truck in a histogram with an overlying normal distribution data used from [114].

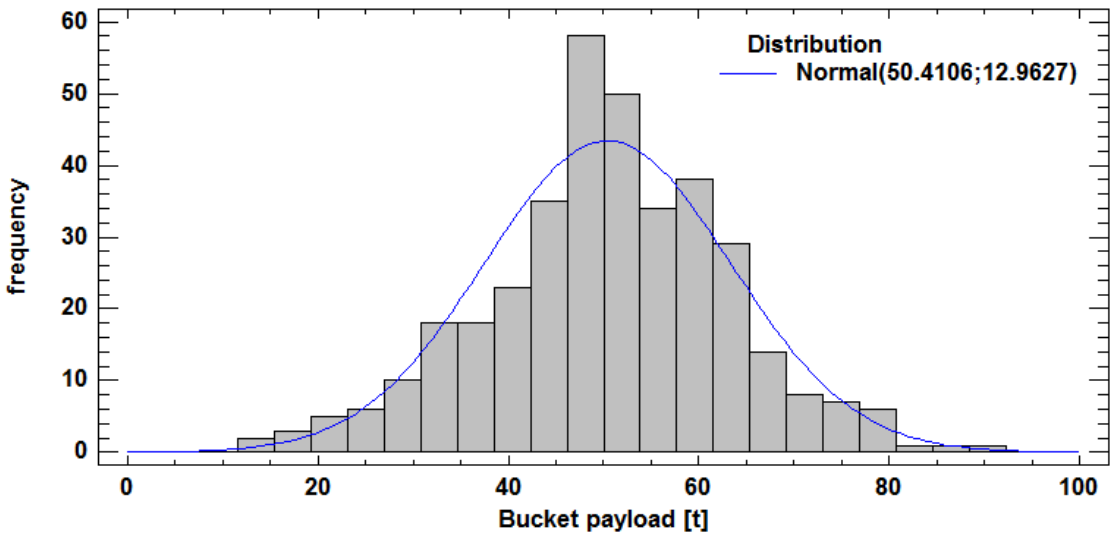



*Figure 4-4 Histogram of bucket payload (all cycles) of the 700t hydraulic excavator*

A $\chi^2$ - test was run to assess whether the bucket payload data can be adequately modelled by a normal distribution. The test divides the range of bucket payload data into non-overlapping intervals and compares the number of observations in each class to the number expected based on the fitted distribution. A $\chi^2$-value = 50.77 (with 37 degrees of freedom) and a P-Value = 0.07 were obtained and the hypothesis that bucket payload data comes from a normal distribution can be accepted.

In conclusion, it will be assumed that bucket payload can be approximated by a normal distribution with $c_L \sim \mathcal{N}(\mu_{c_L}, \sigma_{c_L}^2)$.
The mean bucket payload $\mu_{c_L}$ and its variance $\sigma_{c_L}^2$ can be calculated using the following equations

$$\bar{c}_L = V \cdot \rho_i \cdot f_s \cdot f_f \tag{4-19}$$

and

$$\sigma_{c_L}^2 = (\bar{c}_L \cdot c_v)^2. \tag{4-20}$$

Typical values of $c_v$ are around 0.1 and 0.3 for bucket payload.

### 4.3.3 Truck Payload

Recent literature suggest that the normal distribution fits truck payload data well [122], [124], [125]. Data provided by Hardy [114] reassures this assumption. However, as illustrated in Figure 4-5, which shows the histogram of 73 truck payloads of a 220 t class truck, the histogram is bound to a maximum value. That limit may be understood as the loader operator's commitment to follow the 10/10/20 loading policy.

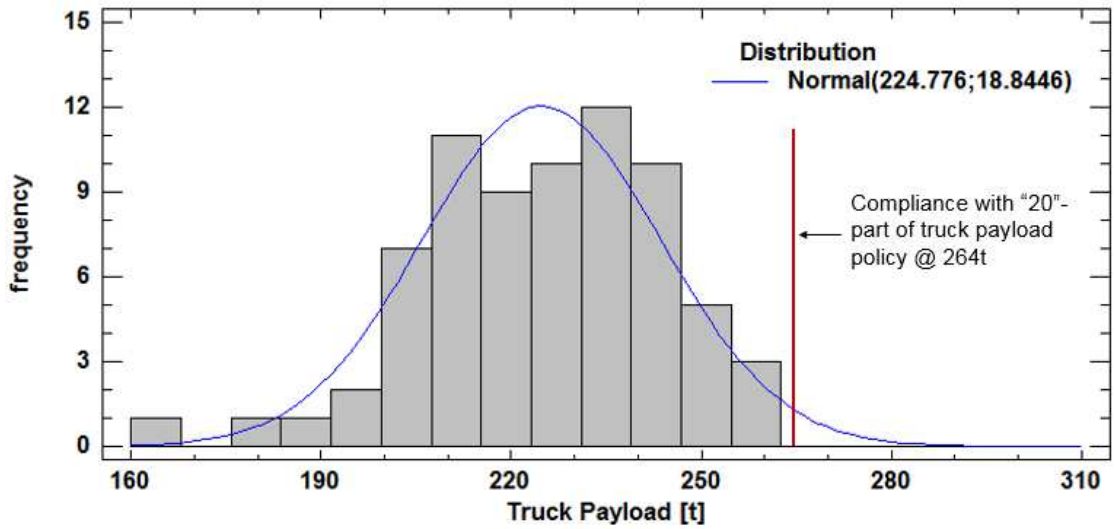



*Figure 4-5 Truck payload histogram*

The determination of *truck payload* $c_T$ in t required a more detailed analysis as it represents the sum of a limited number of bucket payloads. Consequently, the descriptive statistics of truck payloads are related to all bucket loads in the sub-sample, which means that in process of loading a truck the underlying variability of individual bucket payload in conjunction with the number of bucket cycles required to fill the truck determines the variability of truck payloads.
Therefore, as a prerequisite, it is required to determine the probability of the number of bucket cycles.

In general, the number of bucket cycles varies depending on the *maximum acceptable truck payload* $c_{T_{max}}$ and the *bucket payload* $c_L$. It must be noted that $c_L$ is a random variable as elaborated in subchapter 4.3.2. $c_{T_{max}}$ is a fixed parameter, which may be adjusted by a percentage of the nominal truck payload.
$c_{T_{max}}$ is based on a 10/10/20 payload policy guideline developed by various truck manufacturers, which states the following: actual payloads between 110% and 120% of rated payload $c_T$ are allowable but, must not exceed more than 10% of all loads in a given period, and no single overload greater than 120% of rated payload (*maximum overload factor* $f_{c_T}$) is allowed under any circumstances [126]. The following holds

$$c_{T_{max}} = f_{c_T} \cdot c_{T_{rate}} \quad . \tag{4-21}$$

A naïve deterministic approximation of the number of bucket cycles $N$ required to fill a truck is given by the ratio of the maximum acceptable truck payload and the mean of bucket payload.

$$N \approx \frac{c_{T_{max}}}{\overline{c_L}} \quad . \tag{4-22}$$

In practice, the truck payload is rarely an integer multiple of the bucket payload. Depending on the loading methodology of the mine, namely full truck or full bucket strategy, the loader may or may not pass an incomplete bucket to fill the remaining truck payload amount.

- The *full truck strategy* means that the loader operator aims to fill the truck even if the last pass only requires a part of the bucket payload.
- In the *full bucket strategy,* the aim is to only ever load the truck with full bucket loads.

The majority of mine operators have the objective to fully utilise the loader. Therefore, the following is based on the full bucket strategy.

As elaborated in the previous chapter bucket payload is a normally distributed random variable $c_L \sim \mathcal{N}(\mu_{c_L}, \sigma_{c_L}^2)$ and therefore the number of bucket cycles varies within a certain spread around the mean value depending on the amount of the individual bucket payloads.

For the subsequent truck payload and also truck loading time calculations it is necessary to determine the probability of number of bucket cycles. The following equations were elaborated during consultations with Dr. Felix Ballani from the Institute of Stochastics (TU Freiberg) and are based on established equations of probability theory.

Let $N$ be the random number of bucket cycles required to fill a truck. Furthermore, let $c_1, c_2, \ldots$ be a sequence of independent and identically distributed bucket payloads with

the same distribution as $c_L$ , $p_n = P(N = n)$ be the probability that exactly $n$ number of bucket cycles are required to fill the truck and $\Phi(x)$ be the distribution function of the standard normal distribution.
Set,

$$c_T{}^{(n)} = \sum_{i=1}^{n} c_i \tag{4-23}$$

for $n = 1,2, \ldots$ it holds

$$\begin{aligned} p_n = P(N = n) &= P\left(c_T{}^{(n)} \leq c_{T_{max}} \leq c_T{}^{(n+1)}\right) \\ &= P\left(c_T{}^{(n)} \leq c_{T_{max}}\right) - P\left(c_T{}^{(n+1)} \leq c_{T_{max}}\right) \\ &= P\left(\frac{c_T{}^{(n)} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}} \leq \frac{c_{T_{max}} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}}\right) \\ &\quad - P\left(\frac{c_T{}^{(n+1)} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}} \leq \frac{c_{T_{max}} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}}\right) \\ &= \Phi\left(\frac{c_{T_{max}} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}}\right) - \Phi\left(\frac{c_{T_{max}} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}}\right) \quad . \end{aligned} \tag{4-24}$$

For illustration, Figure 4-6 shows the probability distribution of $N$ for different coefficients of variation of $c_L$ using a P&H 4100XPC with a mean bucket payload $\mu_{c_L} =$ 102 t to load a Komatsu 960E with a nominal payload capacity of 327 t, which translates to a maximum truck payload $c_{T_{max}}$ of 359.7 t applying an overload factor of 1.1 to account for the “10” part of the 10/10/20 loading policy [127], [128]. Using the deterministic equation (4-24) a number of bucket cycles $N = 3.52$ is obtained.

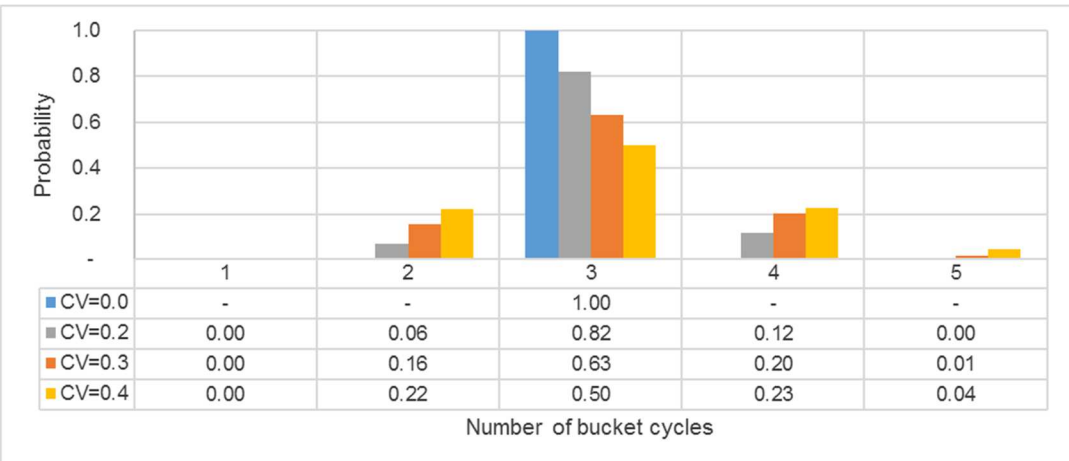



*Figure 4-6 Number of bucket cycles probability*

It can be seen that with increasing variation of bucket payload the variation of the number of bucket cycles required to fill the truck increases as well.

Based on the above it is now possible to describe the distribution function $F_{c_T}(x)$ of the truck payload. It is clear that $c_L \leq x \leq c_{T_{max}}$ . $F_{c_T}(x)$ can be expressed as

$$F_{c_T}(x) = \sum_{n=1}^{\infty} F_{c_T|N=n}(x) p_n \,, \tag{4-25}$$

Where $F_{C_T|N=n}(x)$ is the distribution function $F_{c_T}(x)$ under the condition that $n$ passes are handled and under the consideration of the truck payload policy.

Using

$$\begin{aligned} F_{c_T|N=n}(x) &= P\left(c_T^{(n)} \leq x \middle| N = n\right) = \frac{P(c_T^{(n)} \leq x, N = n)}{p_n} \\ &= \frac{P(c_T^{(n)} \leq x, c_T^{(n)} \leq c_{T_{max}} < c_T^{(n+1)})}{p_n} \\ &= \frac{P(c_T^{(n)} \leq x, c_{T_{max}} < c_T^{(n+1)})}{p_n} \end{aligned} \tag{4-26}$$

It can be seen that

$$\begin{aligned} F_{c_T}(x) &= \sum_{n=1}^{\infty} P(c_T^{(n)} \leq x, c_{T_{max}} < c_T^{(n+1)}) \\ &= \sum_{n=1}^{\infty} \int_{-\infty}^{x} \int_{c_{T_{max}}-x}^{\infty} \varphi(x; n\mu_{c_L}, n\sigma_{c_L}^2)\varphi(y; n\mu_{c_L}, \sigma_{c_L}^2) dx dy \\ &= \sum_{n=1}^{\infty} \int_{-\infty}^{x} \varphi(x; n\mu_{c_L}, n\sigma_{c_L}^2) \left(1 - \Phi\left(\frac{c_{T_{max}} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right) dx. \end{aligned} \tag{4-27}$$

Practically, the sum of $c_i$ only extends over a few $n$ (usually between 2 and 7 bucket cycles). In particular, for a sufficiently large $c_{T_{max}}$. Therefore, the probability density function of $c_T$ can be derived as the following holds

$$f_{c_T}(x) = \left[\sum_{n=1}^{\infty} \varphi\left(x; n\mu_{c_L}, \sigma_{c_L}^2\right)\right]\left(1 - \Phi\left(\frac{c_{T_{max}} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right). \tag{4-28}$$

Thus, the mean and variance of $c_T$ can be written as

$$\bar{c}_T = \int_0^{c_{T_{max}}} x \sum_{n=1}^{\infty} \varphi(x; n\mu_{c_L}, \sigma_{c_L}^2)\left(1 - \Phi\left(\frac{c_{T_{max}} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right) dx \tag{4-29}$$

and

$$\sigma_{C_T}^2 = \int_0^{c_{T_{max}}} (x - \bar{c}_T)^2 \sum_{n=1}^{\infty} \varphi(x; n\mu_{c_L}, \sigma_{c_L}^2 \left(1 - \Phi\left(\frac{c_{T_{max}} - x - \mu_{c_L}}{\sigma_{c_L}}\right)\right) dx \,. \qquad (4\text{-}30)$$

A program developed by the author is used to compare results from the above equations to actual site data.

Actual site data was provided by Clermont Coal Mine for the primary loading equipment (P&H 4100) while the truck fleet included Komatsu 830E and 930E. A data analysis of payload records for the P&H4100 and the Komatsu 930E was carried out and revealed the following parameters. The sample data can be found in Appendix III.

*Table 4-3 Data analysis parameters*

| Parameter | Value from site data | Values calculated based on equation (4-29) and (4-30) |
|---|---|---|
| **Loader parameter** | | |
| Mean bucket payload [t] | 105.26 | 105.26 |
| Standard deviation of bucket payload [t] | 25.57 | 25.57 |
| Mean bucket cycle time [s] | 20.82 | 20.82 |
| Standard deviation of bucket cycle time [s] | 5.09 | 5.09 |
| Mean number of bucket cycles [#] | 2.77 | 2.70 |
| Standard Deviation number of bucket cycles [#] | 0.43 | 0.48 |
| **Truck parameter (Komatsu 930E)** | | |
| Rated payload [t] | 276.8 | 276.8 |
| Maximal acceptable truck payload [t] | 332.2 | 332.2 |
| Maximum overload factor [-] | 1.2 | 1.2 |
| Mean truck payload [t] | 283.94 | 284.40 |
| Standard deviation of truck payload [t] | 25.57 | 37.32 |
| Number of samples | 306 | |

Figure 1-1 shows the distribution of number of bucket cycles of actual site data and the calculated values.

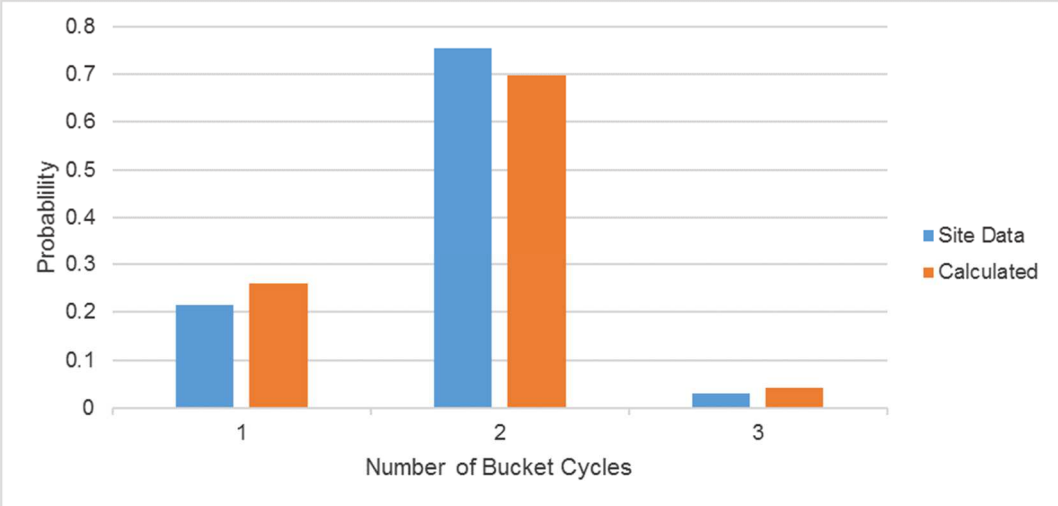



*Figure 4-7 Comparison of number of bucket cycles probability*

## 4.4 TRUCK CAPACITY

The mean hourly truck capacity $C_T$ is a function of the mean truck payload $\bar{c}_T$ and *truck cycle time* $t_{CT}$. It holds

$$C_T = \bar{c}_T \cdot \frac{3600}{t_{CT}} \qquad \text{in t/h} \qquad (4\text{-}31)$$

$\bar{c}_T$ was discussed in the previous section and *truck cycle time* $t_{CT}$ is comprised of four time components

- *truck loading time from the truck perspective* $t_{Lo}^T$,
- *travel time* $t_T$,
- *manoeuvre and spot at the loader* $t_S$,
- *manoeuvre and dump at crusher* $t_D$,

Therefore

$$t_{CT} = t_{Lo}^T + t_T + t_S + t_D \qquad \text{in s.} \qquad (4\text{-}32)$$

The individual time components are discussed in turn.

### 4.4.1 Truck Loading Time

Similar to truck payload, truck loading time $t_{Lo}$ is a random variable. Numerous distribution functions have been applied to describe truck loading times, starting from

- exponential distribution – which is not realistic, as in practice standard deviation of truck loading times ranges between 0.2 and 0.4 whereas for an exponential distribution the coefficient of variation is 1, but employed in queueing theoretical calculations because of its convenient properties [110], [129]–[133];
- through Weibull distribution with two or three parameters [134]–[136];

- logarithmic-normal distribution [137];
- Erlang distribution [138] and
- normal distribution [96], [124], [125], [139]–[141].
- Finally, Stoyan [142] and Wang et al. [143] suggested to model truck loading time using an inverse Gaussian distribution.

Before discussing the appropriate distribution of truck loading time it is necessary to review practical loading methods and the loading procedure itself, as this can have a significant impact on productivity [144].
Generally, four primary loading methods exist (refer to Figure 4-8 and Figure 4-9):

- single-side method,
- double-side method,
- drive-by method and
- modified drive-by method.

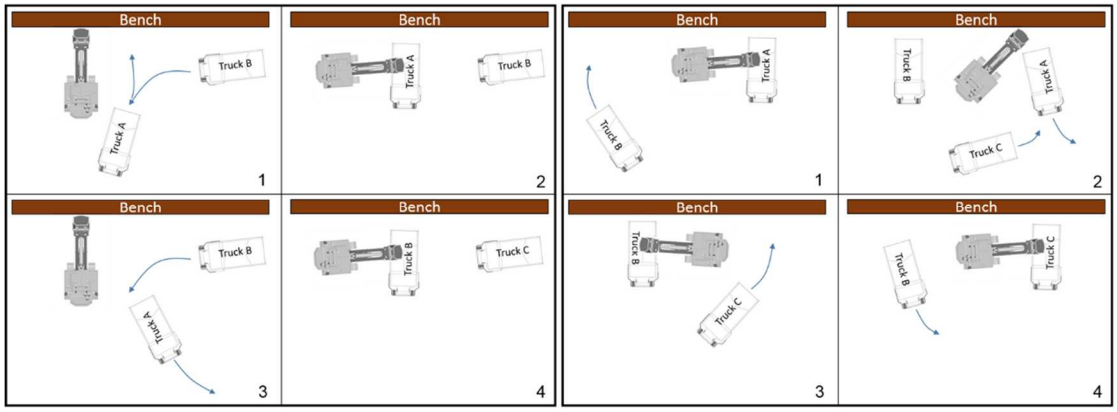



*Figure 4-8 Single-side method (left) and double-side method (right)*

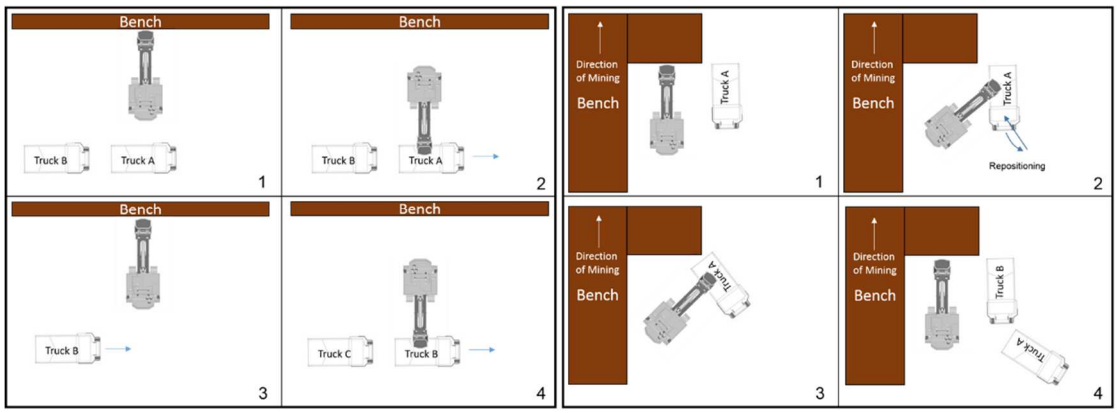



*Figure 4-9 Drive-by method (left) and modified drive-by method (right)*

Although promising efficiency improvements by double-side and drive-by loading methods can occur, the current standard loading method in Australian coal mines and others is single-side loading [145] with the trucks to the left when addressing the face and is therefore a basis for further discussions.

Two additional cases can be considered, which are shown in Figure 4-10 and Figure 4-11.

- *Case a* represents a scenario in which trucks queue in front of the loading zone ready to manoeuvre and spot into loading position.
- *Case b* represents a scenario in which the loader is waiting for trucks and a soon as the loader operator notices a truck approach the bucket cycle pass is initiated.

In both cases the loader will pause for a residual time until the spot position is reached and the shovel dumps. This time is referred to as *loader inherent wait time* $t_W$ and is the difference between manoeuvre and spot time of the truck at loader and the time required for the first bucket cycle.

$$t_W = t_L - t_S \tag{4-33}$$

Typical inherent wait time for loading equipment to be ready ranges between 10 and 15 seconds depending on the truck and loading equipment.

This time can be seen as inherent operating delay however it is inevitable in a single side loading operation and is therefore added to truck loading time.

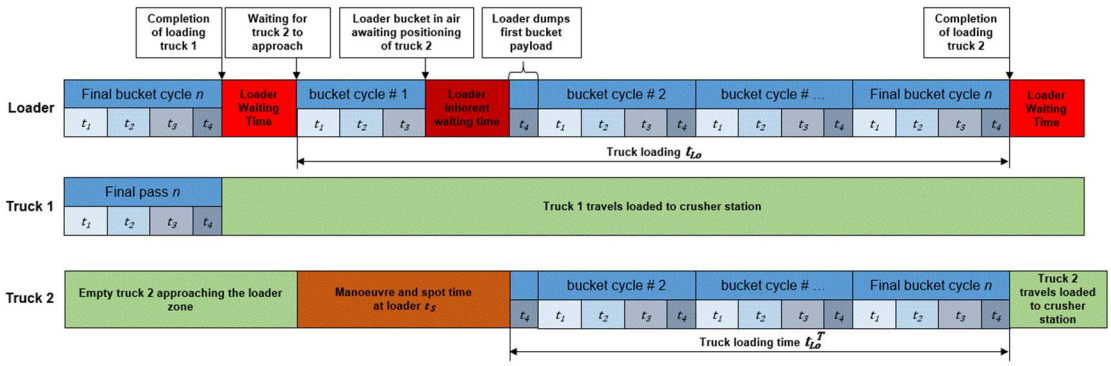



*Figure 4-10 Truck loading scenario - Case a*

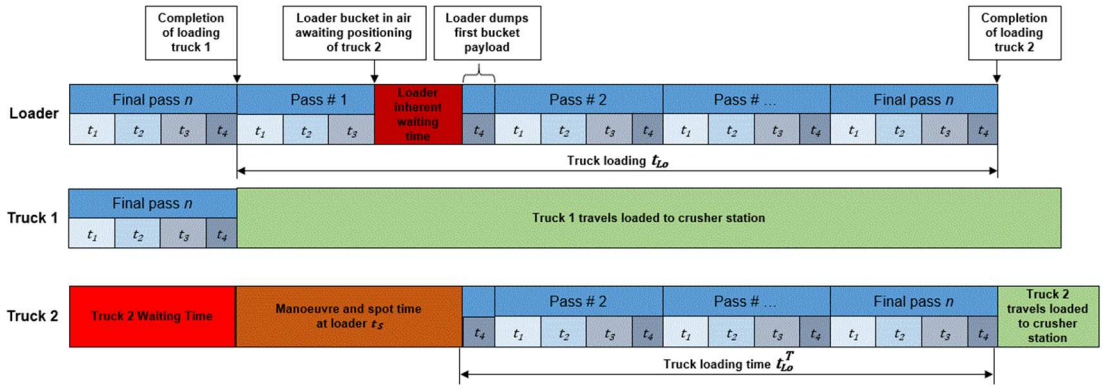



*Figure 4-11 Truck loading scenario - Case b*

Considering the above, truck loading time can be viewed from two perspectives. Firstly, from the loading equipment and secondly from a truck perspective.

- *Truck loading time from the loading equipment perspective* $t_{Lo}$ represents an accumulation of a limited number of bucket cycle times and inherent loader waiting time.
- *Truck loading time from the truck perspective* $t_{Lo}^{T}$ represents an accumulation of the dump time $t_4$ of the first bucket cycle immediately on spot – generally between 3 and 5 s depending on material properties, bucket load and release mechanism [114] – and the second through to the final bucket cycle to fill the truck according to payload policies.

This statement translates into the following deterministic equations

$$t_{Lo} = t_W + \sum_{i=1}^{N} t_{L_i} \qquad \text{in s.} \qquad (4\text{-}34)$$

$$t_{Lo}^{T} = t_4 + \sum_{i=1}^{N-1} t_{L_i} \qquad \text{in s.} \qquad (4\text{-}35)$$

According to the central limit theorem [112], the distribution of the sum of independent random variables tends to be normally distributed regardless of the distribution of the summed components. As shown in equation (4-34) truck loading time is equal to a certain number of bucket cycle times. Each bucket cycle time is a random variable (see sub-chapter 4.3.1) and the individual cycle times may be considered as independent of each other. It could therefore be expected that truck loading times are normally distributed [96], [124], [125], [139]–[141].

However, as elaborated in the previous section, truck loading time depends significantly on the number of bucket cycles required to fill the truck which in turn is dependent on the bucket payload for each pass. Therefore, the true distribution of truck loading time is a superposition (bimodal distribution) of a number of normal distributions, each having a specific mean and variance. Which means that multiple peaks for loading time are possible. A histogram (Figure 4-12) provided by Czaplicki [96] clearly shows this effect described above. In this example the mean bucket cycle time may be approx. 26 s, which translates into a total of 4 and 5 bucket cycles for the normal distributions indicated in blue and red, respectively.

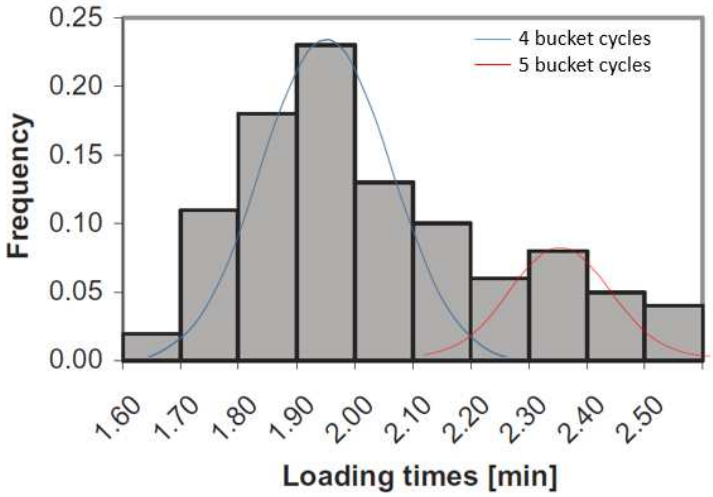



*Figure 4-12 Histogram of truck loading time with two superposed normal distribution*

Calculation for blue normal distribution

$$t_{Lo} = t_W + \sum_{i=1}^{N} t_{L_i} = 12s + \sum_{1}^{4} 26s \approx 1.9min \tag{4-36}$$

Calculation for red normal distribution

$$t_{Lo} = t_W + \sum_{i=1}^{N} t_{L_i} = 12s + \sum_{1}^{5} 26s \approx 2.3min \tag{4-37}$$

Similar to the calculation for $\bar{c}_T$ the described relationship for truck loading time can by determined as follows. Let $t_L$ be gamma distributed with $c_L \sim Gamma(a, s)$ as shown in sub-chapter 4.3.1, where $a = \mu_{t_L}^2/\sigma_{t_L}^2$ is the shape parameter and $s = \sigma_{t_L}^2/\mu_{t_L}$ the scale parameter, due to the convolution stability of the gamma distribution $c_L^{(n)} \sim Gamma(na, s)$ [146]. Under the assumption that $c_L$ and $t_L$ are stochastically independent the sequence of bucket cycle times is independent of the number of bucket cycle times $N$. The probability density functions $f_{t_{Lo}}(x)$ and $f_{t_{Lo}}^T(x)$, are then

$$f_{t_{Lo}}(x) = \sum_{i=1}^{\infty} g(x; n\sigma_{t_{Lo}}^2/\mu_{t_{Lo}}, \mu_{t_{Lo}}^2/\sigma_{t_{Lo}}^2) \cdot \tag{4-38}$$

$$\left[\Phi\left(\frac{c_{T_{max}} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}}\right) - \Phi\left(\frac{c_{T_{max}} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}}\right)\right]$$

and

$$f_{t_{Lo}}^T(x) = t_4 + \sum_{i=1}^{N-1} g(x; n\sigma_{t_{Lo}}^2/\mu_{t_{Lo}}, \mu_{t_{Lo}}^2/\sigma_{t_{Lo}}^2) \cdot \tag{4-39}$$

$$\left[\Phi\left(\frac{c_{T_{max}} - n\mu_{c_L}}{\sqrt{n}\sigma_{c_L}}\right) - \Phi\left(\frac{c_{T_{max}} - (n+1)\mu_{c_L}}{\sqrt{n+1}\sigma_{c_L}}\right)\right] \quad .$$

Independent of all distributional assumptions the mean truck loading times $\bar{t}_{Lo}$ and $\bar{t}_{Lo}^{T}$ are given by

$$\bar{t}_{Lo} = \bar{N}\bar{t}_L \qquad \text{in s} \qquad (4\text{-}40)$$

and

$$\bar{t}_{Lo}^{T} = (\bar{N}-1)\bar{t}_L + t_4 \qquad \text{in s.} \qquad (4\text{-}41)$$

Its variances are equal to

$$\sigma_{t_{Lo}}^2 = \bar{N}\sigma_{t_L}^2 + \sigma_{(N)}^2\mu_{t_L}^2 \qquad \text{in s}^2 \qquad (4\text{-}42)$$

and

$$\left(\sigma_{t_{Lo}}^{T}\right)^2 = (\bar{N}-1)\sigma_{t_L}^2 + \sigma_{(N-1)}^2\mu_{t_L}^2 \qquad \text{in s}^2. \qquad (4\text{-}43)$$

### 4.4.2 Travel Time

Truck travel time $t_T$ is an important figure for capacity calculations. The truck times on a haul road depend on the truck engine characteristics, the haul road profile and its conditions, the payload on the truck, and to a degree, even on the number of trucks (e. g. truck bunching [125]). Truck bunching or clumping refers to the process of faster trucks being delayed behind slower trucks. where overtaking is prohibited due to haul road restrictions. This is a source of considerable productivity loss for truck haulage systems in large open pits. The main influence on truck travel time is the truck payload. Travel time $t_T$ is therefore divided into *truck travel time unloaded* $t_{T_U}$ and *truck travel time loaded* $t_{T_L}$. It holds

$$t_T = t_{T_U} + t_{T_L} \qquad \text{in s.} \qquad (4\text{-}44)$$

To further account for the effect of haul road grade and conditions, haul roads are generally divided into segments corresponding to changes in gradient or surface conditions. The estimates for each segment are then added to provide an estimate of the total travel time.

Data provided by Panagiotou [133] also suggest that truck travel times are well fitted by an inverse Gaussian distribution (refer to Figure 4-13). A $\chi^2$ - test with a sample size of 93 reveals a P-value of 0.373 for an inverse Gaussian distribution compared to 0.138 for a normal distribution.

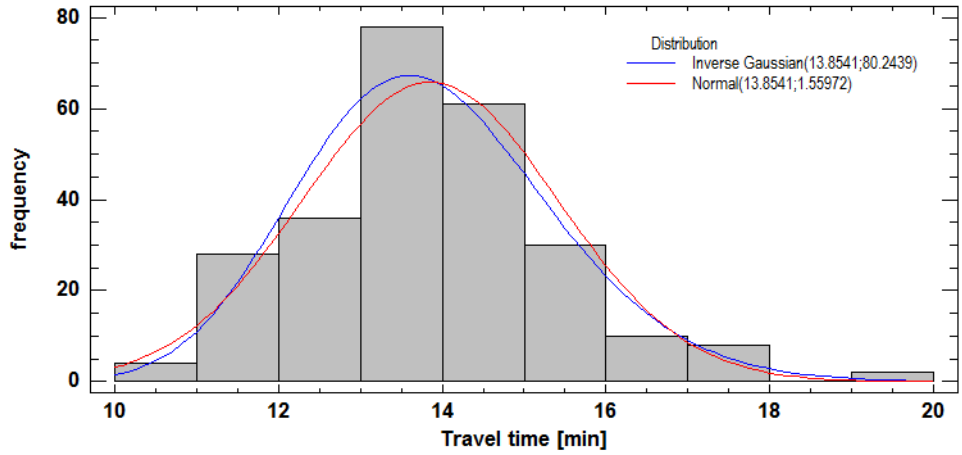



*Figure 4-13 Travel time distribution - data used from* [133]

According to relevant literature truck travel times may be successfully described by a normal distribution [90], [96], [139], [143], [147], [148]. Data obtained by the author reaffirm this assumption. Figure 4-14 shows histograms of travel times from loaded (left) and unloaded (right) trucks with overlaid IGD (inverse Gaussian distribution) and normal distribution. The data was obtained by the author during a time study at the basalt quarry Mittelherbigsdorf. The total sample size corresponds to 35 measurements. A $\chi^2$ - test indicated a p-value of 0.49 for loaded travel times and further 0.67 for unloaded truck travel time for a normal distribution. For comparison, the inverse Gaussian distribution is indicated in blue. Both distributions fit the samples quite well.

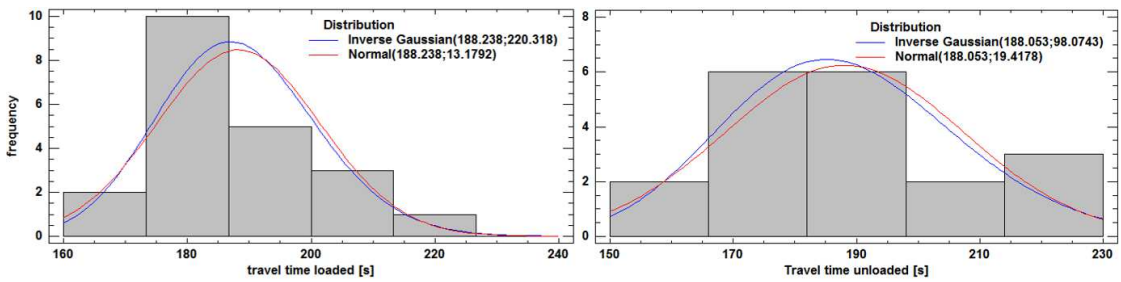



*Figure 4-14 Travel time distribution loaded (left) unloaded (right)*

Both distributions deliver sufficient results, depending on the purpose of the investigation. However, for pragmatic reasons, the normal distribution sufficiently represents truck travel times, which is therefore applied in this thesis.

The variance of $t_T$ can be predicted using estimates of coefficient of variation $c_v$. Hardy [114] states a $c_v$ of 0.12 to 0.53 in his PhD thesis. Barnes et al. [110] suggested a coefficient of variation between 0.1 and 0.2. A comprehensive truck travel time study under different operation conditions undertaken by Caterpillar [149] reaffirmed the suggested coefficient of variation from Barnes. Contradicting conclusions are made by Barnes and Stoyan [147] with regards to behaviour of variance of truck travel times and section lengths. Barnes states that variance of travel time decreases with increases in overall segment length whereas Stoyan states the opposite. However,

Stoyan's statement is purely based on the behaviour of the inverse Gaussian distribution in which the variance increases with higher mean values. The author agrees with the statements made by Barnes and Hardy that the variance of truck travel times decreases with section length, due to the fact that the truck operator has a certain control over the velocity within the mines speed regulations and will therefore attempt to regain lost time of one segment in the other.

The variance of truck travel time $\sigma_{t_T}^2$ can be calculated using the following equation

$$\sigma_{t_T}^2 = (\bar{t}_T \cdot c_v)^2. \qquad \text{in s}^2. \qquad (4\text{-}45)$$

### 4.4.3 Manoeuvre and Spot Time at Loader

Manoeuvre and spot time $t_S$ at the loader consist of the time to turn, reverse and spot the truck to get loaded. It depends on the physical parameters of the truck, manoeuvring safety practice and available bench space. As these times are relatively short the variation can be neglected and it is sufficient to use mean values. Mean times for truck spot times at the loader are suggested:

- "Usually between 0.4 to 0.7 minutes" [150]
- "Typically between 0.6 to 0.8 minutes" [151]
- "0.75 minutes for 220 tonne trucks is a typical value" [114]

### 4.4.4 Manoeuvre and Dump Time at Crusher Station

Manoeuvre and dump time $t_D$ consists of raising the body, the time required for the material to flow out of the body, lowering the body and the manoeuvre time. Combined $t_D$ are generally 60 s for rear dump trucks and 30 s bottom dump trucks [150]. Caterpillar [151] provides a typical range for $t_D$ of 60 - 80 s for rear dump trucks. The author's experience is that $t_D$ of 45 s for quarry trucks and 60 s for large mining trucks is a reasonable (and typical) value. Nevertheless, experience made by the author in oil sand operations (Aurora mine, Canada) showed that unloading time may be up to 75 s. The unusual high unloading time results from the sticky material behaviour. Similar to manoeuvre and spot time at the loader are manoeuvre and dump times; they are comparatively short and thus mean values are sufficient for approximations. Additionally studies made by Wang et al. [143] suggest that manoeuvre and dump times are relatively stable and conclude that they can be regarded as constant.

## 4.5 DISTURBANCE BEHAVIOUR OF SYSTEM ELEMENTS

The disturbance behaviour of individual elements has an essential impact on the behaviour of the entire system. Therefore, the disturbance behaviour of individual SMIPCC system elements will now be explained in detail. It can be described by the period of time of a respective disturbance and the operational time between two

subsequent disturbances. Those periods of times are, as it is clear, random variables and can be statistically analysed.

Since at this point only the individual elements are of interest, disturbances caused by other system elements are excluded from the following discussion. Furthermore, planned downtimes are omitted.
Schematically the system process can be illustrated as shown in Figure 4-15. Gladysz [152] called the corresponding stochastic process *general operation process*. The general operation process needs to be investigated when questions related to disturbance and repair behaviour of system elements are discussed.

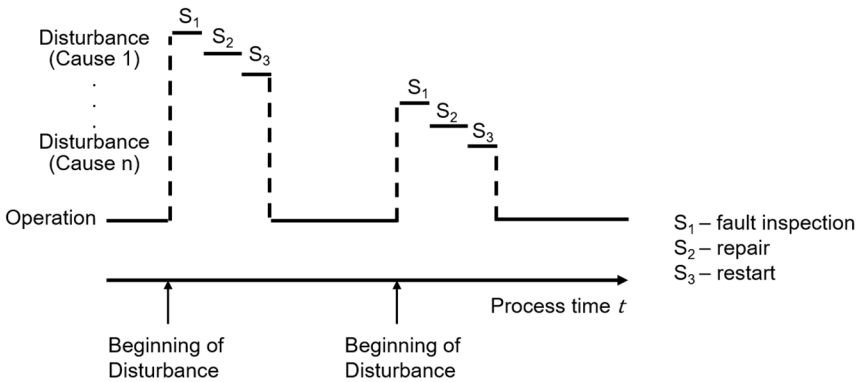



*Figure 4-15 Schematic illustration of general operation process of system elements*

However, in case of system capacity and time usage calculations the general operation process is far too complicated. It is therefore simplified by combining certain states. Gladysz suggested the *first reduction step* in which the process is simplified by only distinguishing between operational state and disturbance state. The resulting stochastic process is called *simplified operation process* and is illustrated in Figure 4-16.

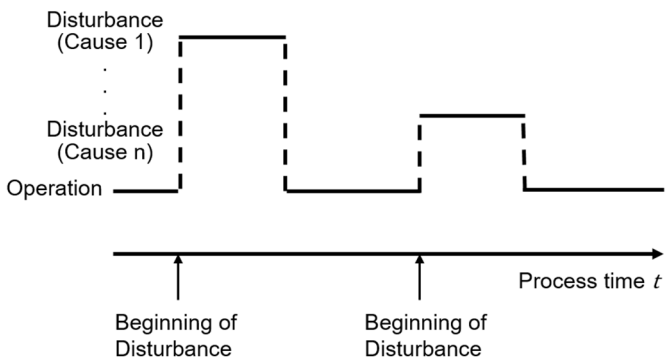



*Figure 4-16 Schematic illustration of simplified operation process of system elements*

The simplified operation process formally complies with a serial connection of abstract elements $E_1, \dots, E_n$ (e.g. motor, belt, alignment switch), which constantly alternate between “operation” and “disturbance”. This implies that when the simplified operation process is in operational state, all elements $E_1, \dots, E_n$ are operational.

Gladysz suggested the *second reduction step* to further simplify the process. In the second reduction step the disturbance cause is dismissed and the process is reduced to operational state and disturbance state. The resulting stochastic process is called *elementary operation process* and is illustrated in Figure 4-17.

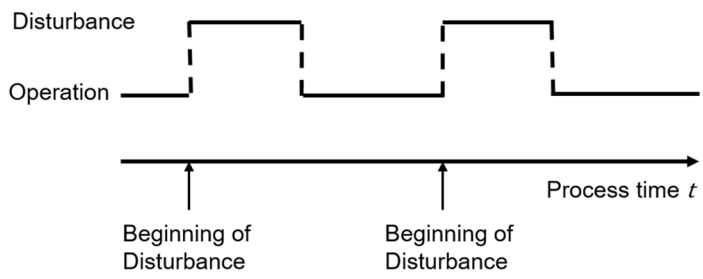



*Figure 4-17 Schematic illustration of elementary operation process of system elements*

### 4.5.1 Characteristics of Elemental Operational Process

The disturbance behaviour of system elements is characterised by the following three quantities:

1. distribution function of repair time
2. distribution function of work time,
3. repair ratio.

The term *repair time* is used to denote the period of time in which the element stands still due to inherent breakdown. Inherent breakdowns are e.g. due to operational, geological, mechanical, electrical and control failures. The failure time commonly comprises of waiting time for repair, repair time itself and preparation time to set the element back into operation.

The *work time*, also referred to as time to failure, is defined as the period of time between two inherent breakdowns of the considered element. This period of time may be interrupted due to planned maintenance or breakdowns of connected elements. Figure 4-18 illustrates schematically the time between two subsequent disturbance periods.

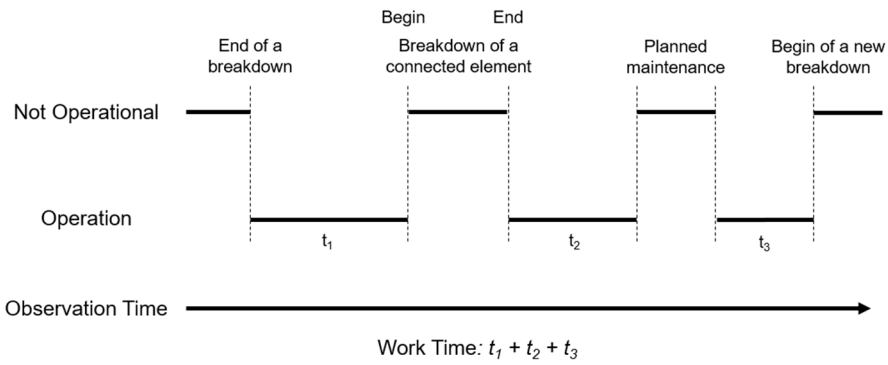



*Figure 4-18 Schematic illustration of work time of a system element*

The *repair ratio* is a quantity derived from the distributions of *repair time and work times.* It is simply the ratio of the mean values of *repair time and work times.*

In literature many distributions have been used to represent the disturbance behaviour of system elements. Generally, stationary distributions are used. For those, the probability distribution at any time $t_1, t_2, \dots t_n$ must be the same as the probability distribution at times $t_1 + \tau, t_2 + \tau, \dots t_n + \tau$, where $\tau$ is an arbitrary shift along the time axis [153]. In the context of maintenance, the assumption of a stationary process implies that the distribution of failures after any repair is the same after every repair. This also implies that the element is in the same condition after the repair as it was when new. In reality this is not true because of [154]

- replacement parts are not identical,
- variation in maintenance practice, and
- equipment life itself.

However, it is a necessary simplifying assumption.

To facilitate the research, data and information from computerized maintenance management systems of 11 different mining operations in five countries including Australia, Canada, Chile, China and Germany was obtained. Commodities included sub-bituminous coal and lignite, oil sand, copper and iron ore. Table 4-4 summarises the collected data.

*Table 4-4 Summary of data collection*

| Mining Operation | Country | Commodity | Observation period | SMIPCC system element | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Discontinuous system | | Continuous system | | |
| | | | | Loader | Truck | Crusher | Conveyor | Spreader |
| 1 | Australia | Coal | 4 years | x | x | x | x | x |
| 2 | Canada | Copper | 1 years | x | x | x | - | - |
| 3 | Canada | Oil Sand | 2 years | x | - | x | - | - |
| 4 | Chile | Copper | 3 years | - | - | x | - | - |
| 5 | China | Coal | 1 year | - | - | - | x | x |
| 6 | China | Coal | 1 year | - | - | x | x | x |
| 7 | China | Iron | 1 year | - | - | - | x | x |
| 8 | China | Copper | 2 years | - | - | x | x | x |
| 9 | Germany | Lignite | 4 years | - | - | - | x | x |
| 10 | Germany | Lignite | 4 years | - | - | - | x | x |
| 11 | Germany | Lignite | 2 years | - | - | - | x | x |

x data obtained - no data obtained

The raw maintenance time data was reviewed and three levels of filters were successively applied, including:

1. filter level 1 – filtering of obviously non-comparable, erroneous or anomalous records,
2. filter level 2 – filtering of planned downtimes $t_{D_p}$,
3. filter level 3 – categorising unplanned downtimes $t_{D_u}$ according to the time usage model described in chapter 5.1 whenever possible.

### 4.5.2 Repair Time

The repair time can be modelled as a random variable. Its actual duration is not readily predictable. If a system element is operating under similar conditions for a longer period of time it can be expected that the occurrence of individual repair time follows a certain distribution. It is thus presumed that for the repair times of elements fixed probability distributions exist, which of course depend on mining conditions, element types and quality of maintenance management.

The distributions of system element repair times have been analysed for many years, and many publications report on them. They include lognormal, gamma, exponential and Weibull distributions. Table 4-5 provides a summary of literature on repair times and their distributions of relevant SMIPCC system elements.

For the majority of distributions provided in Table 4-5 it remains unclear what raw data were taken into consideration. For example Temeng [155] divided repair data of trucks into electrical and mechanical types of repairs. He found that histograms electrical repair times were accurately described by an exponential distribution while for mechanical repair times gamma or Weibull distributions delivered better results.

Histograms of mechanical repair times and compound clearing times were frequently positively asymmetrical. Furthermore, mean repair times for loaders and trucks provided by Shama et al., Elevili et al. and Hall [156]–[158] are comparatively high. The reason might be that small disturbances have not been considered.

*Table 4-5 Literature on repair time and associated distribution*

| Source | Element | Material | Mean Repair Time [min] | Best-Fit Distribution |
|---|---|---|---|---|
| [159] | Spreader | Coal | 32.4 | Lognormal |
| | Conveyor | Coal | 10.2-29.4 | Lognormal |
| [156] | Truck | Copper | 230-321 | Lognormal |
| [160] | Crusher (Gyratory) | Bauxite | n.a. | Lognormal |
| | Conveyor | | 1.42 | Lognormal |
| [157] | Loader | Coal | 236-588 | Lognormal |
| [161] | Trucks | n.a. | 480 | Lognormal |
| [93] | Spreader | Coal | 78 | Exponential |
| | Conveyor | Coal | 84-90 | Exponential |
| [105] | Loader | Coal | n.a. | Weibull 3P |
| | Truck | | n.a. | Weibull 3P |
| | Crusher | | n.a. | Weibull 3P |
| [147] | Spreader | Lignite | 15-60 | Exponential |
| | Conveyor | Lignite | 15-60 | Exponential |
| [155] | Loader | Copper | n.a. | Gamma / Weibull |
| [162] | Conveyor (mobile) | n.a. | 24-48 | Exponential |
| | Conveyor (fixed) | n.a. | 42-72 | Exponential |
| | Spreader | n.a. | 90 | Exponential |
| [163] | Crusher | n.a. | 120 | Weibull |
| | Conveyor | n.a. | 114 | Weibull |
| | Spreader | n.a. | 162 | Weibull |
| [158] | Truck | n.a. | 317-355 | Lognormal |

In this thesis, the data analysis undertaken considered all disturbances (unplanned downtimes) except crusher and loader idle time (wait for trucks). Unplanned downtime causes common for all system elements include:

- electrical breakdowns,
- mechanical breakdowns,
- equipment protection trips,
- accidental damage.

Additional, element specific unplanned downtime causes are shown in Figure 4-19.

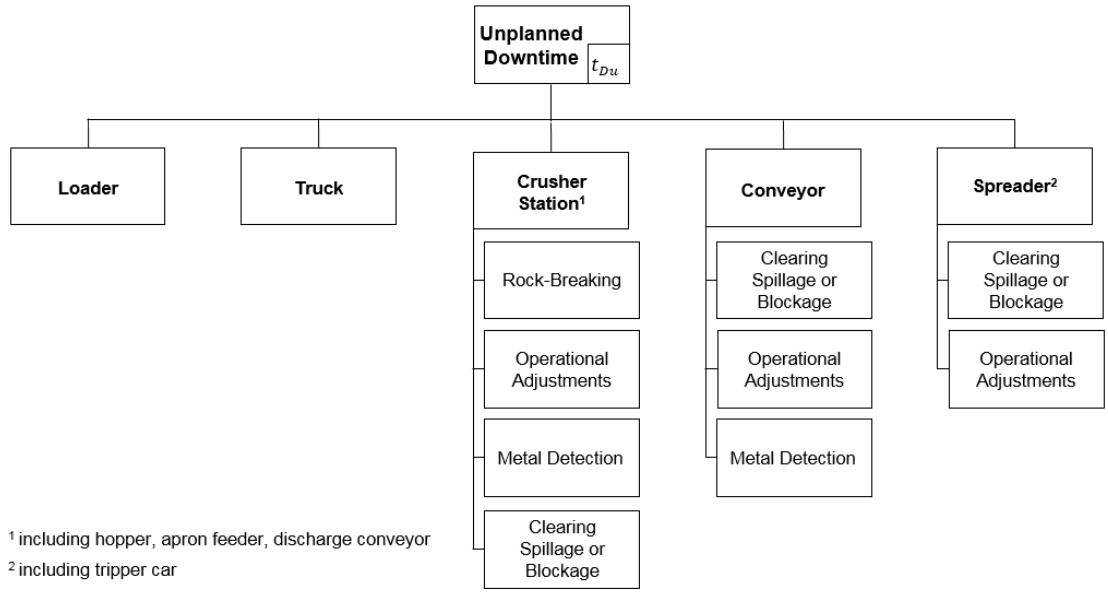



*Figure 4-19 Element specific unplanned downtime causes*

The results showed that the exponential distribution describes the empirical data of relevant equipment repair times well. As an example, Figure 4-20 shows the histogram of repair time data of a crusher station working in a coal mine for overburden removal and gives cause to an interesting discussion.

At first sight it seems that the data of repair times cannot be well fitted by an exponential distribution. Very small disturbances have a much higher frequency than expected for the fitted exponential distribution. In contrast, many authors work with distributions such as lognormal, gamma or Weibull (see Table 4-5), in which small disturbances are almost excluded.

The discrepancy may presumably be explained by different methods of data collection. While the author mainly used data recorded by automatic data collection systems, in which even the smallest disturbances were recorded, disturbance data from older literature was commonly recorded by an operator. In the latter case the data collection is highly influenced by subjective effects, which in turn may lead to results where small disturbances are either not recorded or rounded up to the next full minute.

For realistic and simple modelling, the exponential distribution appears most reasonable, as many very small disturbances have no influence on the operation. Thus, the part of repair times which has a high frequency between 0 and 1 minutes, should not be taken into consideration.

Selected site data for individual SMIPCC system elements repair time is provided in Appendix IV.

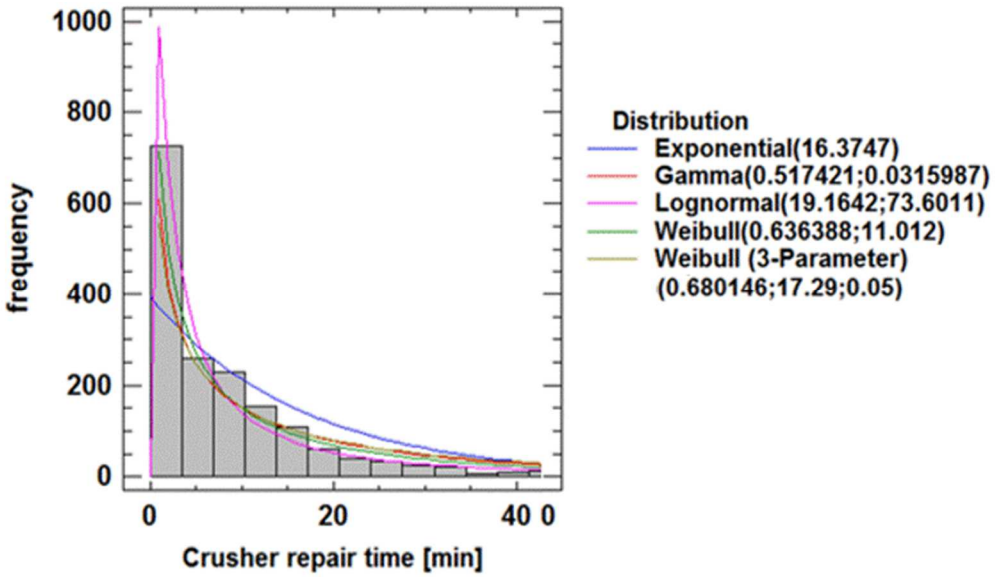



*Figure 4-20 Repair time histogram of a crusher station*

When recalling equation (4-7) the distribution function of the exponential distribution is given by

$$P(X < x) = 1 - e^{-\mu x}\,, \qquad x \geq 0, \tag{4-46}$$

where $X$ denotes the repair time. Equation (4-46) means that the probability that a repair with a duration smaller than $x$ occurs equals $1 - e^{-\mu x}$.
The mean repair time $\bar{t}_R$ equals

$$\bar{t}_R = \frac{1}{\mu} \qquad \text{in min.} \tag{4-47}$$

Thus, if the repair time is exponentially distributed the information on the mean repair time is sufficient to fully characterise the distribution. Mean repair time is possibly the most common measure or parameter in maintainability analysis and is utilised to determine corrective maintenance times.
The mean repair time can be interpreted as a measure of the maintenance organisation [147]. For small mean repair time the average times to repair a piece of equipment is short – repairs happen quickly. For large mean repair time certain deficiencies of the maintenance organisation are present (e.g. missing spare parts, insufficient personnel). Nonetheless, individual operational conditions of system elements are quite variable, so that large mean repair time may not necessarily indicate a bad maintenance organisation.
Statistically $\bar{t}_R$ is determined by the sample mean of repair times.
A summary of mean repair time based on the data collected by the author as described in Table 4-4 is indicated in Table 4-6.

*Table 4-6 Summary of mean repair time of SMIPCC system elements*

| Equipment type | Sample size | Mean Repair Time [min] | | | |
|---|---|---|---|---|---|
| | | Min | Mean | Max | CV |
| **Loader** | | | | | |
| cable shovel | 11 | 64.0 | 132.7 | 233.5 | 0.35 |
| hydraulic excavator | 13 | 134.2 | 288.1 | 626.5 | 0.54 |
| **Trucks** | 20 | 114.5 | 296.7 | 676.3 | 0.67 |
| **Crusher** | 10 | 14.7 | 33.1 | 55.9 | 0.46 |
| **Spreader** | 19 | 33.6 | 52.1 | 88.9 | 0.40 |
| **Conveyor** | | | | | |
| shiftable | 29 | 10.0 | 32.7 | 67.3 | 0.51 |
| relocatable | 21 | 10.1 | 31.8 | 60.8 | 0.45 |
| fix | 26 | 9.8 | 21.0 | 32.5 | 0.35 |

### 4.5.3 Work Time

The period between two consecutive disturbances/repairs is called work time. Work times is, just as repair time, a random variable. It also applies that under similar operating conditions a certain distributions functions for work times of system elements can be obtained. Publications which consider work times of system elements in mines are listed in Table 4-7.

*Table 4-7 Literature on work times and associated distributions*

| Source | Element | Material | Mean Work Time [min] | Best-Fit Distribution |
|---|---|---|---|---|
| [159] | Spreader | Coal | 8,950 | Weibull |
| | Conveyor | Coal | 1,559 -3,155 | Lognormal |
| [160] | Crusher (Gyratory) | Bauxite | n.a. | Weibull |
| | Conveyor | | 15.25 | Lognormal |
| [161] | Trucks | - | 120 | Exponential |
| [93] | Spreader | Coal | 900 | Exponential |
| | Conveyor | Coal | 1,710-2,040 | Exponential |
| [105] | Loader | Coal | n.a. | Weibull |
| | Truck | Coal | n.a. | Gamma |
| [158] | Truck | - | 688-869 | Lognormal |

The statistical analysis of work times of system elements in much more difficult than for repair time because interruptions of work time occur because of planned downtimes

and operating delays [147]. These times have to be subtracted from the individual work time of system elements (refer to Figure 4-18).
It seems to be natural to model the occurrences of disturbances by a Poisson process. This implies that the distance (period of time) between two disturbances is an exponentially distributed random variable [164]. Consequently, the work time of system elements can usually satisfactory described by exponential distributions see [90], [147], [152]. Czaplicki [96] confirms this statement for trucks and shovels.

Therefore, an analogue equation (4-46) holds with $\mu$ replaced by $\lambda$ and the mean work time $\bar{t}_W$ equals

$$\bar{t}_W = \frac{1}{\lambda} \qquad \text{in min.} \qquad (4\text{-}48)$$

Thus, if the work times follows an exponential distribution the information of mean work time is sufficient to fully characterise the distribution.
The mean work time can be interpreted as a measure of the disturbance vulnerability of an element [147].
Statistically, $\bar{t}_W$ can be theoretically determined in the same way as $\bar{t}_R$. However, as mentioned earlier the acquisition of the corresponding raw data is difficult. A more convenient way to determine $\bar{t}_W$ is to determine $\bar{t}_R$ and the repair ratio $\varkappa$ (refer to section 4.5.4). Then $\bar{t}_W$ is obtained by following equation:

$$\bar{t}_W = \frac{\bar{t}_R}{\varkappa} \qquad \text{in min.} \qquad (4\text{-}49)$$

A summary of empirical values of $\bar{t}_W$ based on the data collected by the author as described in Table 4-4 is indicated in Table 4-8.

*Table 4-8 Summary of mean work time of SMIPCC system elements*

| Equipment type | Sample size | Mean Work Time [min] | | | |
|---|---|---|---|---|---|
| | | Min | Mean | Max | CV |
| **Loader** | | | | | |
| cable shovel | 11 | 584 | 790 | 926 | 0.14 |
| hydraulic excavator | 13 | 579 | 1,991 | 4904 | 0.57 |
| **Trucks** | 20 | 325 | 963 | 1277 | 0.42 |
| **Crusher** | 10 | 79 | 458 | 1397 | 0.96 |
| **Spreader** | 19 | 486 | 1,147 | 2703 | 0.73 |
| **Conveyor** | | | | | |
| shiftable | 29 | 474 | 2,162 | 5838 | 0.73 |
| relocatable | 21 | 885 | 5,834 | 19377 | 0.91 |
| fix | 26 | 796 | 20,780 | 93358 | 1.33 |

For loaders, trucks, crusher stations and spreaders similar mean work times were obtained. The average values range between 7.5 and 33.2 h. Average values of mean

work time for conveyors are considerably higher and range from 36 to 346 h, respectively.

Obviously, has the amount and quality of preventative maintenance a substantial influence on the mean work time which may explains the relatively high coefficient of correlation of the provided data in Table 4-8.

### 4.5.4 Repair Ratio

The repair ratio $\varkappa$ of a system element is defined as

$$\varkappa = \frac{\bar{t}_R}{\bar{t}_W} = \frac{\lambda}{\mu} \quad . \tag{4-50}$$

The quantity $\varkappa$ is a non-dimensional parameter. It is a measure of the frequency of disturbances of a system element and is important for further calculations. For large $\varkappa$, the time in which an element is disturbed is large. The quantity $\varkappa$ can be decreased by increasing $\bar{t}_W$ (by enhanced preventative maintenance or constructive improvements) or/and by decreasing $\bar{t}_R$ (enhance maintenance organisation). Statistically $\varkappa$ is determined as follows. The operation time $t_O(\tau)$ and the unplanned downtime $t_{D_U}(\tau)$ of an element in the observation period $\tau$ (e.g. one or several months) are determined. Then $\varkappa$ is estimated by

$$\varkappa = \frac{t_{D_U}(\tau)}{t_O(\tau)} \quad . \tag{4-51}$$

Table 4-9 lists $\varkappa$ values which were statistically derived during the course of this thesis for relevant equipment. These values compare very well with those provided by other authors [90], [147], [165]. That the more recent values are smaller than the older ones can be explained by technological progress, such as increased component reliability and enhanced condition monitoring, over the last decades.

*Table 4-9 Summary of repair ratio values of SMIPCC system elements*

| Equipment type | Sample size | Repair Ratio | | | |
|---|---|---|---|---|---|
| | | Min | Mean | Max | CV |
| **Loader** | | | | | |
| cable shovel | 11 | 0.083 | 0.170 | 0.270 | 0.35 |
| hydraulic excavator | 13 | 0.091 | 0.157 | 0.299 | 0.40 |
| **Trucks** | 20 | 0.0310 | 0.1280 | 0.2300 | 0.50 |
| **Crusher** | 10 | 0.035 | 0.117 | 0.238 | 0.62 |
| **Spreader** | 19 | 0.022 | 0.059 | 0.118 | 0.48 |
| **Conveyor** | | | | | |
| shiftable | 29 | 0.004 | 0.019 | 0.043 | 0.77 |
| relocatable | 21 | 0.001 | 0.012 | 0.050 | 1.06 |
| fix | 26 | 0.000 | 0.007 | 0.035 | 1.41 |

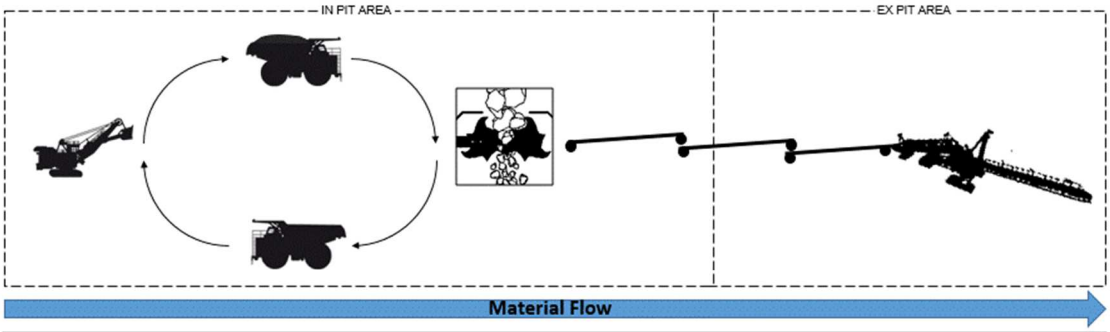
# CHAPTER 5:
# SMIPCC CAPACITY DETERMINATION METHOD

*Based on the random behaviour of system elements a method is developed to determine the annual capacity of a SMIPCC system. In this chapter a detailed structure is provided to determine the effective operating hours of the system.*

## 5.1 GENERAL SMIPCC SYSTEM CAPACITY DETERMINATION

SMIPCC systems are complex material handling systems including various elements with the function to excavate, haul and discharge material from the operation face in the mine to a designated destination. As such, variations in capacity of one element can affects the capacity of other elements of the system.

The SMIPCC system can be defined as an L/T-C/B/D system where L/T stands for the discontinuous part of the system and C/B/D for the continuous part. Where L is the number of loader, T is the number of trucks, C is the number of crusher stations, B is the number of belt conveyors, and D is the number of spreaders. The most simplistic but also most common system is shown schematically in Figure 5-1.




| SMIPCC System | | | | |
|---|---|---|---|---|
| Discontinuous System | | Continuous System | | |
| Feed system | | Crusher System | Conveyor System | Discharge System |
| Loader | Trucks | Crusher Station | Conveyors | Spreader |
| $L = 1$ | $T=n_T$ | C=1 | $B = n_C$ | $D = 1$ |

*Figure 5-1 Schematic illustration of simplified SMIPCC system*

The capacity of such SMIPCC system for longer time periods is influenced by process and element specific characteristics as well as by the overall system layout. The operation of a SMIPCC systems is characterized by a high level of mechanization and automation as the majority of the transport distance is realized by conveyors. This creates the requirement for high utilisation of the machine system. The logical consequence is that capacity planning is carried out in relation to the machine system. Whereby the winning element (loader) acts as the capacity determining element under consideration of their technological connections. Once the average hourly capacity of the winning element $C_L$ is known, the capacity of the entire SMIPCC system $C_S$ can be determined based on the *effective operating time* $t_{O_e}$ of winning element in h. It holds

$$C_S = t_{Oe} C_L \qquad \text{in t/a.} \qquad (5\text{-}1)$$

The determination of the average hourly capacity of the loader $C_L$ is demonstrated in detail in section 4.3. The following section describes a method to

determine the effective operating hours of the system under consideration of the system aspect.

## 5.2 TIME USAGE MODEL

The prerequisite for the calculation of $t_{O_e}$ and to commence selection of equipment of suitable capacity is to investigate the different operational and downtime states of system elements. This is achievable by a time usage model, which is also referred to as time allocation model or calendar time structure.

Developing a defined time usage model is an imperative management initiative to enable determination of time components relevant to productivity determination. It forms a common basis for benchmarking of mining equipment by providing standardized definitions and methodologies for measuring reliability, availability and utilisation performance of equipment in a mining environment. It is also a critical input to establish required equipment performance and a realistic estimation, in particular for a “greenfields” project, or determination from historical data, in-house or industry-wide, of the number of productive hours per year, that can be adopted as a robust basis for required productivity determinations.

Despite current efforts made by the Global Mining Standards and Guidelines Group [166], [167] the mining industry has not yet developed a common standard of deriving or stating equipment performance [168], [169]. Most large mining companies have their internal “standard” nomenclature and time usage model. Figure 5-2 to Figure 5-4 show current examples of time usage models from three major mining companies.

<table>
<tr><td colspan="12">Calendar Time (CT)</td></tr>
<tr><td colspan="10">Scheduled Time (ST)</td><td rowspan="5">Unscheduled Time (UT)</td></tr>
<tr><td colspan="8">Working Time (WT)</td><td colspan="2">External Idle Time (IT)</td></tr>
<tr><td colspan="6">Available Time (AT)</td><td colspan="2">Maintenance Time (MT)</td><td rowspan="3">Other External Idle Time (OE)</td><td rowspan="3">Weather External Idle Time (WE)</td></tr>
<tr><td colspan="2">Operating Time (OT)</td><td colspan="4">Operating Delay Time (OD)</td><td rowspan="2">Unplanned Maint. Time (UM)</td><td rowspan="2">Planned Maint. Time (PM)</td></tr>
<tr><td>Dynamic Operating Time (DT)</td><td>Non-dynamic Operating Time (NT)</td><td>Process Delay Time (PD)</td><td>Unplanned Delay Time (UD)</td><td>Labour Delay Time (LD)</td><td>Standby Delay Time (SD)</td></tr>
</table>

*Figure 5-2 Open cut time model Xstrata* [170]

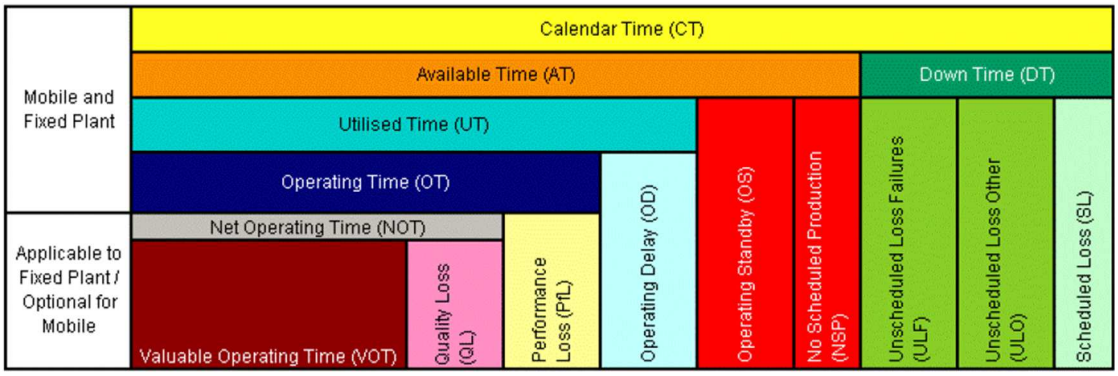



*Figure 5-3 Time allocation model Rio Tinto* [171]

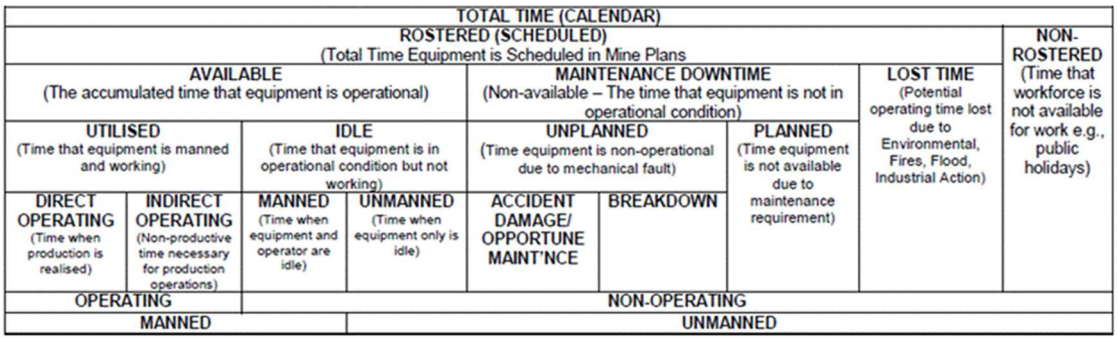



*Figure 5-4 Time usage model used by Western Premier Coal Limited* [114]

Time usage models are of course similar in structure, definitions and equations for availability and utilisation parameters. For example, *calendar time* is usually divided into utilised time, available time and downtime, and further broken down into subcategories. However, differences in definition behind equations and classification of occurring operational and downtime state of equipment during the course of a mining operation create inconsistencies in measuring and reporting.

In order to better analyse the time components of SMIPCC systems the time usage model shown in the previous section needs to be substantiated in accordance to TGL 32 - 778/01-15 [172]. The TGL is the GDR (German Democratic Republic) equivalent to the German Industry Standard (DIN). In the author´s opinion this standard represents the best foundation for material handling systems with combined material transport. However, as the TGL 32 - 778/01-15 was developed for material handling systems with continuous transport, several time quantities and their relation to each other were required to be adjusted.

A specific time usage model for SMIPCC systems (refer to Figure 5-5) is developed in order to apply a calculation model for the prediction of SMIPCC system capacities. The following time quantities refer to average values of the generally randomly fluctuating quantity.

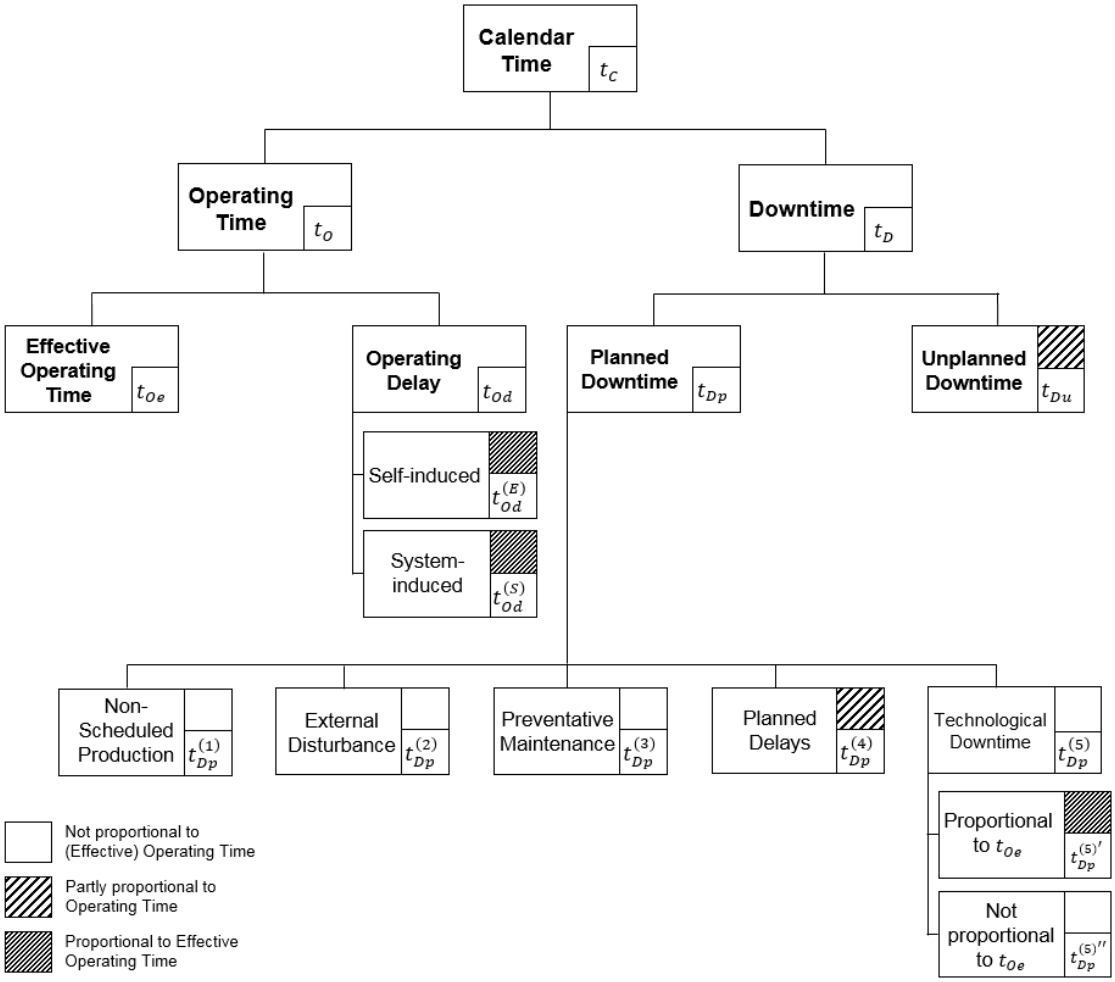



*Figure 5-5 SMIPCC time usage model*

The time usage model divides *calendar time* $t_C$ (8,760 h per year – ignoring leap years of 8,784 h per year), primarily into *operating time* $t_O$ and *downtime* $t_D$.

*Operating time* $t_O$ refers to the period in which the equipment is functioning which means the service meter unit is running (motor is running). In a certain portion of operating time the equipment is operating in an unproductive manner. This time refers to *operating delay* $t_{O_d}$. The time in which the element is considered to be operating at full effectiveness is referred to as *effective operating time* $t_{Oe}$. Hence,

$$t_O = t_{Oe} + t_{Od} \qquad \text{in h.} \qquad (5\text{-}2)$$

Operating delay is divided into *self-induced operating delays* $t_{Od}^{(E)}$ and *system-induced operating delays* $t_{Od}^{S}$. Self-induced operating delays include periods in which the equipment is performing its normal operating function, but is hampered by minor short-term delays such as minor pad preparations, face clean-ups, tramming etc. System-induced operating delays refer to times the system element is not able to operate due to the fact that another element $E_i$ is not available, which makes it impossible for the element to operate effectively. Typically, this time is also referred to as *idle time*. It holds

$$t_{Od} = t_{Od}^{(E)} + t_{Od}^{(S)} \quad \text{in h.} \tag{5-3}$$

Downtimes are initially divided into *Planned downtime* $t_{Dp}$ and *Unplanned downtime* $t_{Du}$.

*Unplanned downtime* $t_{Du}$ refers to the time the element is unavailable due to unscheduled maintenance in the form of disturbances or breakdowns.

Planned downtime includes time events that can be scheduled or approximated in advance. They are further subdivided according to their cause into the following:

$t_{Dp}^{(1)}$ – Non-scheduled production
$t_{Dp}^{(2)}$ – External disturbances
$t_{Dp}^{(3)}$ – Preventative maintenance
$t_{Dp}^{(4)}$ – Planned shift delays
$t_{Dp}^{(5)}$ – Technological downtime

Then:

$$t_{Dp} = t_{Dp}^{(1)} + t_{Dp}^{(2)} + t_{Dp}^{(3)} + t_{Dp}^{(4)} + t_{Dp}^{(5)} \quad \text{in h.} \tag{5-4}$$

*Non-scheduled production* $t_{Dp}^{(1)}$ includes the period of time in which the equipment is technically available but not scheduled to operate due to factors such as:

- Non-worked holidays,
- Training on equipment,
- No production due to regulations (environmental, governmental).

*External disturbances* $t_{Dp}^{(2)}$ includes the period of time in which the equipment is technically available but not utilised due to external factors such as:

- Bad weather (e.g. heavy snow or rain fall, lightning, wind etc.),
- Workforce disputes,
- Power outages.

Although occurrence and duration of external downtimes are in principle not predictable and should therefore, following the definition be categorized into unplanned downtimes, regional differences create a strong variation among those downtimes. For example, a coal mine in Inner Mongolia experiences up to 3 months of downtime due to harsh winter conditions whereas an Iron ore mine in the Pilbara only experiences 3 to 5 day downtimes due to bad weather, mostly heavy rainfalls [173], [174]. Similar variations among regions apply to workforce disputes and power outages.

Consequently, external disturbances would heavily distort results for unplanned downtime for individual elements (see sub-chapter 4.5). In addition, downtimes due to external factors are difficult to assign to a specific element as they usually effect the entire system.

*Preventative maintenance* $t_{Dp}^{(3)}$ includes the period of time in which the equipment is not scheduled to operate in order to carry out preventative maintenance measures or preparation for such measures. Maintenance practices vary greatly throughout the mining industry and do not appear to be correlated with the operation size or mining method. Many mining companies follow manufacturer´s recommendations, while others developed their own specific maintenance strategy. Recent Literature that is dealing with this topic includes [175]–[177].

*Planned shift delays* $t_{Dp}^{(4)}$ are proportional to operating time $t_O$ and refer to periods that occur as regular shift events. These regular shift events included delays such as travel time to and from the pit, shift change, meal breaks, equipment inspections and safety meetings.

*Technological downtimes* $t_{Dp}^{(5)}$, also referred to as process related downtime, occur regularly and include time in which the equipment is not operating due to required mine development or technological changes of the system. This includes

- relocations of crusher stations or conveyors,
- trackshifting of conveyors,
- conveyor belt extensions or shortening
- blasting.

In accordance to the respective IPCC system some of the mentioned time components may not occur. Those need then to be set to zero. It holds

$$t_C = t_{O_e} + t_{O_d} + t_{D_p} + t_{D_u} \qquad \text{in h} \qquad (5\text{-}5)$$

Equation (5-5) can be used to determine the period of times of interest – primarily $t_{O_e}$.

## 5.3 CALCULATION OF EFFECTIVE OPERATING TIME

For the calculation of the effective operating time $t_{Oe}$ each time component described in section 5.1 needs to be determined. The majority of the time components can be easily approximated as constants. This includes the time components $t_{Dp}^{(1)}$, $t_{Dp}^{(2)}$, $t_{Dp}^{(3)}$ and $t_{Dp}^{(5)''}$.

*Non-scheduled production* $t_{Dp}^{(1)}$

Non-scheduled production time is basically the sum of all time components the entire production process is not scheduled to operate.

*External disturbances* $t_{Dp}^{(2)}$

External disturbances are basically the sum of all time components when the production process or a system element is scheduled to operate but is unable to operate as a result of bad weather (heavy rainfall, lightning, bad visibility due to fog or heavy winds), labour disputes and environmental regulations.

*Preventative maintenance* $t_{Dp}^{(3)}$

Similar to the time components described above preventative maintenance is basically the sum of all times in which an element is not scheduled to operate due to:

- Scheduled maintenance as agreed in the confirmed maintenance schedule;
- Inspections and testing for preventive maintenance, instrument calibration & safety regulations – but excluding operator pre-start inspections,
- Capital work for modifications and expansions.

In case of the continuous part of the machine system (crusher station, conveyors, and spreader) maintenance is commonly realised periodically such as weekly, monthly, and annually [178]. This implies that whenever an element of the continuous part of the machine system requires preventative maintenance according to agreed intervals or predictive techniques, the entire system chain is not operating. It is therefore the maintenance manager's objective to schedule required preventative maintenance of continuous system elements as well-timed as possible to maximize operating time [179]. Thus, to approximate downtime due to preventative maintenance $t_{Dp}^{(3)}$ the maximum of required maintenance time of each continuous element $t_{Dp_{ij}}^{(3)}$ in each maintenance period needs to be considered. However, it also depends on whether sufficient maintenance resources are available for concurrent maintenance. Typically, a certain amount of preventative maintenance is outsourced to specialized companies. Considering the above mentioned the total preventative maintenance time component can be expressed as follows

$$t_{Dp}^{(3)} = \sum_{i=1}^{n} \sum_{j=1}^{m} max\left\{t_{Dp_{ij}}^{(3)}\right\} \qquad \text{in h} \qquad (5\text{-}6)$$

Here $i$ represents the elements crusher station, conveyors, spreader and $j$ the maintenance periods weekly, monthly, annual maintenance periods. In the special case which is considered in this thesis, of one loader feeding the

continuous part of the machine system, planned maintenance required for the loader is also included in this equation.

*Planned shift delays* $t_{Dp}^{(4)}$

Planned shift delays represent the sum of individual planned shift delays $t_{Dp_i}^{(4)}$ in h/shift multiplied by the available shifts per annum. To approximate the annual planned shift delays the following holds

$$t_{Dp}^{(4)} = \frac{t_C - t_{Dp}^{(1)} - t_{Dp}^{(2)} - t_{Dp}^{(3)} - t_{Dp}^{(5)\prime\prime}}{t_{Shift}} \sum_{i=1}^{n} t_{Dp_i}^{(4)} \quad \text{in h} \qquad (5\text{-}7)$$

*Technological downtime proportional to effective operating time* $t_{Dp}^{(5)\prime}$

The majority of technological downtimes are proportional to $t_{Oe}$. This includes but is not limited to times for blasting and conveyor trackshifts. It holds

$$t_{Dp}^{(5)\prime} = \tau t_{Oe} \quad \text{in h.} \qquad (5\text{-}8)$$

The factor $\tau$ is referred to *technological downtime ratio* and is dimensionless. Technological downtimes proportional to operating time include downtimes due to conveyor trackshifts and blasting occurrences. They are also based on a certain volume[1]. In the case of conveyor trackshifts, the volume represents the *maximum dump block volume* $V_D$. The dump block volume can be calculated depending on the shifting pattern. In the case of blasting delays, the volume represents the amount of material for each blast which is referred to as *blast volume* $V_B$. That means, as soon as the maximum dump block volume is exhausted the dump conveyor is required to be trackshifted. Similar to that, a blasting delay is initiated as soon as the loader depletes the blast volume (excavatable muckpile material).

The effective operating time $t_{Oe}^{(S)}$ and $t_{Oe}^{(B)}$ required to reach the maximum dump block volume or blast volume can be approximated by

$$t_{Oe}^{(S)} = \frac{V_D}{C_L} \quad \text{in h.} \qquad (5\text{-}9)$$

$$t_{Oe}^{(B)} = \frac{V_B}{C_L} \quad \text{in h.} \qquad (5\text{-}10)$$

If the time required for each *conveyor trackshifting* $t_{Sh}$ and each blasting $t_B$ is known, it is possible to determine $\tau$ by using the following relation

[1] Volume is in this thesis translated to tonnage based on a certain density

$$\tau = \frac{t_{Sh}}{t_{Oe}^{(S)}} + \frac{t_B}{t_{Oe}^{(B)}} \quad \text{in h.} \tag{5-11}$$

Conveyor trackshifts are required to follow the dump face advance. This operation is commonly accomplished using pipe layer-fitted bulldozers with an attached track-shifting head. The dozer engages the conveyor and applies lateral shifting forces to move the conveyor structure without the need to dismantle the conveyor. Three shifting patterns are possible (see Figure 5-6):

1. Parallel shifting, in which all modules of the shiftable conveyor are shifted over the same distance;
2. Radial shifting, where one end (head or tail end) of the conveyor remains in the same position and functions as a pivot point while the other end is swung around; and
3. Combined shifting, which uses both parallel and radial shifting techniques so that one end of the conveyor is shifted further than the other.

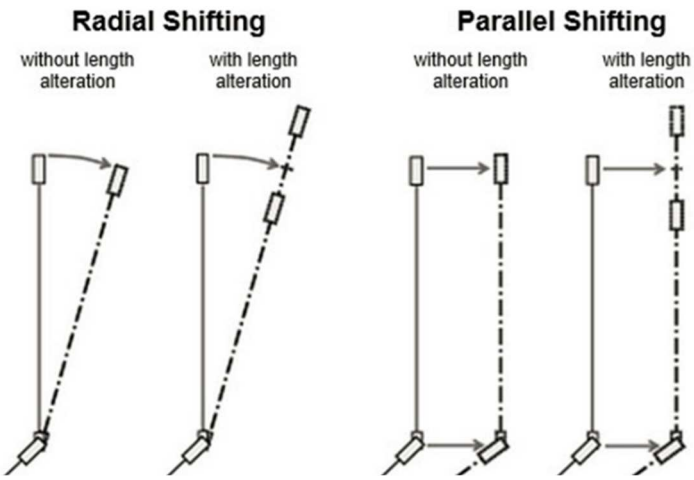



*Figure 5-6 Trackshift patterns*

Time required for conveyor trackshifting $t_{sh}$ depends on ground conditions, conveyor length, shifting width, shifting pattern and available workforce, and usually takes between 8 and 36 h. Whenever a trackshift includes length alteration of the conveyor, a fixed time component to splice and volcanise the belt is required. The entire process for the vulcanised splicing of a 24 inch belt requires about 6 - 11 h, depending on working conditions for wider belts it takes approx. 24 h [67], [71]. Further information for approximations of trackshifting time can be found in [18], [180], [181].

However, it should be noted that for $t_s$ only those downtimes that cannot be coordinated with preventative maintenance are considered.
To approximate the time required for a particular trackshift $t_s'$ the following equation holds

$$t_s' = \frac{A_s}{r_s} + t_p \qquad \text{in h} \qquad (5\text{-}12)$$

where $A_s$ is the trackshift area in m², $r_s$ the combined trackshift rate in m²/h and $t_p$ is a fixed time component for trackshift preparation and alignment.

Minor repairs are usually carried out on the spreader or other system elements throughout the trackshifting process. Let this time be denoted as $t_{r-m}$. Then the accountable time required for conveyor trackshift $t_s$ equates to

$$t_s = max\{0, t_s' - t_{r-m}\} \qquad \text{in h} \qquad (5\text{-}13)$$

The downtimes for each blast $t_B$ depend on countries' individual mining laws and constitute the time required to evacuate the pit and handle some minor preparation work. Typical value range between 30 and 60 min per blast.

*Technological downtime not proportional to effective operating time* $t_{Dp}^{(5)''}$

Technological downtimes, such as crusher station relocations or major conveyor reconstructions occur in a predetermined number and well-defined time frame within the planning period. These technological downtimes are denoted with $t_{Dp}^{(5)''}$.
Relocation of the crusher station depends on crusher station type (refer to subchapter 2.3.1), workforce, available machinery and relocation distance. The relocation time is measured from the moment the crusher station is out of operation to the moment all parts are reassembled and put back into operation. Typical downtimes due to crusher station relocation ranging from 5 up to 30 days.

Other time components are either proportional to operating time or effective operating time and depend therefore on the performance of the system. These time components include $t_{Dp}^{(4)}$, $t_{Dp}^{(5)'}$, $t_{Du}$, $t_{Od}^{(E)}$ and $t_{Od}^{(S)}$ as illustrated in Figure 5-5.

*Unplanned downtime* $t_{Du}$

Unplanned downtimes proportional to $t_{Oe}$. Which means that with increasing operating time unplanned downtimes increase as well. According to equation (4-51) unplanned downtimes can be estimated by the following equation:

$$t_{Du} = \varkappa t_O \qquad \text{in h.} \qquad (5\text{-}14)$$

*Self-induced Operating Delays* $t_{Od}^{(E)}$

Self-induced operating delays are proportional to $t_{Oe}$ and occur according to operational processes which include delays for repositioning, clean-ups, scaling walls, cable moves or refuelling, and pad preparations. The relation can be expressed by equation (5-15).

$$t_{Od}^{(E)} = \nu t_{Oe} \quad \text{in h} \tag{5-15}$$

The factor $\nu$ refers to *operating delay ratio* and is dimensionless. Typical values of $\nu$ range between 0.05 and 0.1.
Realistically some minor operating delays also occur at the discharge element, including repositioning the spreader for different dump-pile or walk around the tail end of the dump conveyor. However, this time component is a very small portion of the total operating time, certainly less than 1%, and typically in a range of 0.4% down to 0.1%. Therefore, those time components are not included in spreader operating delays but accounted for, even though not technically correct, in $t_{Du}^{(1)}$ of the spreader (refer to sub-chapter 4.5.2).

*System-induced operating delays* $t_{Od}^{(S)}$

Similar to self-induced operating delays, operating delays induced by other system elements are proportional to $t_{Oe}$. These times occur whenever an element is ready for operation but is not able to operate because it has to wait for other elements of the system. Typical examples are:

- Loader needs to wait for trucks
- Truck waits in loader or crusher queue
- Hopper of crusher station runs empty and receives no new material from trucks.

$$t_{Od}^{(S)} = \zeta t_{Oe} \quad \text{in h} \tag{5-16}$$

The factors $\zeta$ refers to *system delay ratio* and is dimensionless. The system delay ratio can be interpreted as the proportion of time the loader; truck or crusher station is not utilised.

This can also be described as idle probability [182]

$$\pi_0 = \frac{t_{Od}^{(S)}}{t_{Oe} + t_{Od}^{(S)}} = \frac{\zeta}{(1+\zeta)} \tag{5-17}$$

Using the equations above it is possible to rearrange equation (5-5) to the following

$$t_C = t_{O_e} + (\nu + \zeta)t_{O_e} + t_{Dp}^{(1)} + t_{Dp}^{(2)} + t_{Dp}^{(3)} + t_{Dp}^{(4)} + \tau t_{Oe} + t_{Dp}^{(5)''} + \varkappa(1 + \nu + \zeta)t_{Oe}.$$

Then

$$t_{O_e} = \frac{t_C - t_{Dp}^{(1)} - t_{Dp}^{(2)} - t_{Dp}^{(3)} - t_{Dp}^{(4)} - t_{Dp}^{(5)''}}{(1 + \nu + \zeta + \tau) + (1 + \nu + \zeta)\varkappa} \quad \text{in h.} \tag{5-18}$$

Based on the above it becomes obvious that in order to approximate $t_{Oe}$ the missing part which has not yet been determined is the system delay ratio $\zeta$. This quantity is the focus of the following sections and will be determined by simulation methods.

When working with equation (5-18) it is crucial to consider that certain overlaps of individual time periods are possible. This relates predominantly to $t_{O_d}$, $t_{Dp}^{(3)}$ and $t_{Dp}^{(5)}$. Certain *Operating Delays* such as pad preparation or manoeuvring are coordinated with idle time; likewise, efforts are made to perform planned maintenance and technological downtimes such as trackshifting simultaneously.
To avoid double-counting the following rule was used in the data analysis: time overlaps of operating delays occur, these time periods are counted as $t_{Od}^{(1)}$; occurrence time overlaps with *technological downtimes* and *planned maintenance*, and these time periods are counted as $t_{Dp}^{(3)}$.

## 5.4 PRINCIPLE OF REDUCTION OF SERIES SYSTEMS

By definition a series system is a system that has elements connected in a series if, and only if, any disturbance of any element results in the disturbance of the whole system. For the continuous part of the SMIPCC system (crusher station, conveyor segments and spreader) each individual elements relies on the functionality of the other element. Therefore, the continuous part of the IPCC system can be treated as a series system.
In order to simplify the following calculations, it is the aim to substitute the individual elements $E_1, E_2, \dots E_n$ in series by a single element $E_S$. This procedure was developed by Gladysz [152]. In case of exponentially distributed repair and work time of the individual system elements the following holds: The intensity of failures in a system $\lambda_S$ of $n$ elements connected in a series is the sum of the intensities of its elements $\lambda_i$. The same statement holds for the repair ratio $\varkappa_S$.
The following relations hold

$$\lambda_S = \sum_{i=1}^{n} \lambda_i \quad , \tag{5-19}$$

$$\varkappa_S = \sum_{i=1}^{n} \varkappa_i \quad . \tag{5-20}$$

If the exponential distribution assumption is not true, equations (5-19) and (5-20) hold also if the system operates over a long period of time [183].

Based on equation (5-21) the mean repair time of a series system can be written as:

$$\bar{t}_{R_S} = \frac{\varkappa_S}{\lambda_S} \quad . \tag{5-21}$$

However, in general the repair time $\varkappa$ of a series system is not exponentially distributed but rather the following holds [90]:

$$P(X < x) = 1 - \sum_{i=1}^{n} p_i e^{-\mu_i x} \tag{5-22}$$

Thus, the repair time of the series system follows a so-called hyper-exponential distribution with parameter

$$p_i = \frac{\lambda_i}{\lambda_S} \quad . \tag{5-23}$$

$p_i$ can be interpreted as the probability that a disturbance of element $E_i$ is the cause of a disturbance of the series system.

## 5.5 METHODS TO DETERMINE THE SYSTEM DELAY RATIO $\zeta$

Recalling the simplified SMIPCC system, in which a relatively small truck fleet $n_T$ commutes between the loader and the crusher station (refer to Figure 5-7), the system delay ratio $\zeta$ depends primarily on the truck loading time, the truck cycle time and their fluctuation. However, its value also depends on the disturbance behaviour of each SMIPCC system elements and the number of trucks. Regardless of the precise shape of its probability function per definition (refer to equation (5-16), it can be expected that the system delay ratio increases from zero (as $\eta_T$ approaches infinity) to infinity (when $\eta_T = 0$).

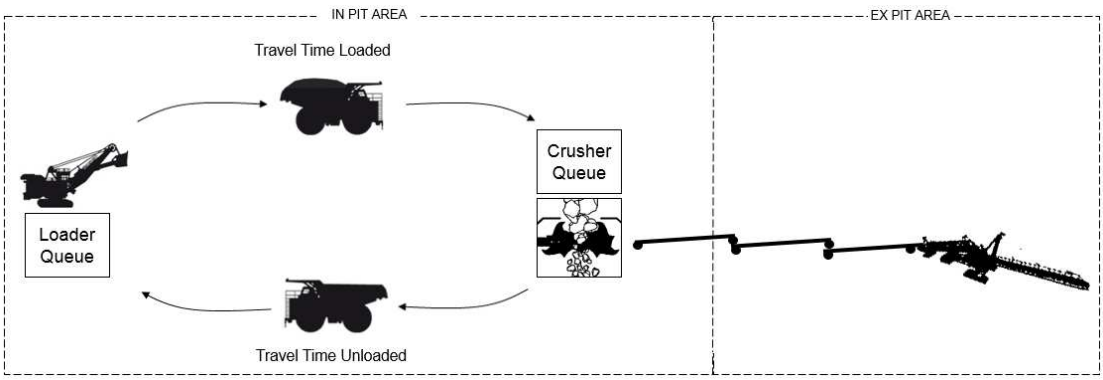



*Figure 5-7 Schematic illustration of the SMIPCC system*

In general, one can use probability theory, queuing theory (particularly the theory of finite source queues and cyclic queues) or simulation to quantify the system delay ratio.

### 5.5.1 Analytical Methods

**Approximation by Stoyan**

Stoyan [147] suggested an approximation for the determination of $\zeta$ based on probability theory that not only incorporates the fluctuation of truck loading time and truck cycle time, but also the disturbance behaviour of the loader. In this approach the system delay ratio is defined by the ratio of the mean waiting time of the loader between two consecutive loading procedures $\bar{t}_W^{(L)}$ and by the mean truck loading time $\bar{t}_{Lo}$.

It holds

$$\bar{t}_W^{(L)} = \mu\phi\left(\frac{\mu}{\sigma}\right) + \sigma k\left(\frac{\mu}{\sigma}\right) = \sigma\psi\left(-\frac{\mu}{\sigma}\right) \tag{5-24}$$

The parameters $\mu$ and $\sigma$ are provided by

$$\sigma^2 = \sigma_{CT}^2 + (n_F - 1)\sigma_{Lo}^2 \tag{5-25}$$

The value $\mu$ needs to be iteratively derived by solving the following equation

$$\mu + (n_F - 1)\sigma\psi\left(-\frac{\mu}{\sigma}\right) + (n_F - 1)\bar{t}_{Lo} - \bar{t}'_{CT} = 0 \quad . \tag{5-26}$$

Stoyan´s approximation determines the system delay ratio very precisely compared to simulations which do not incorporate any disturbances. However, it underestimates them as soon as large loader disturbances are involved.

**Modified approximation of Stoyan**

Daduna et al. [184] describe a modified form of the Stoyan approximation, in which the accuracy for large disturbances of the loading process is enhanced while the simplicity is maintained. In the algorithm, the out-of-order times are excluded as during these times no contribution to the (annual) capacity of the system is possible. Additionally, the capacity during times of normal usage of the loader is then evaluated by the standard algorithms as described above.

The modified approximation of Stoyan increases the accuracy for large loader disturbances and represents a greater advancement. However, it does not incorporate any disturbances of other system element disturbances.

**Other approximations**

Two other methods have been developed to determine the system delay ratio by Soumis et al. [185] and Ta et al. [182]. However, both methods do not incorporate any disturbances. Soumis et al. present a three step approach to allocate trucks and incorporate system induced operating delays via a nonlinear truck waiting time expression. Whereas, Ta et al. quantify and validate the nonlinear relation between

system induced operating delays and the number of trucks assigned to a shovel via a simple approximation, based on the theory of finite source queues. The approximation determines the "shovel idle probability" $\pi_0$ which can be translated to the system delay ratio by the following equation

$$\zeta = \frac{\pi_0}{(1 - \pi_0)} \quad . \qquad (5\text{-}27)$$

The general analytical approach of the interdependent behaviour of individual system elements is extremely complicated. From a temporal perspective, the combined SMIPCC system can adopt multiple different characteristic states which initially need to be defined. Only after this, can an appropriate mathematical method for calculating the transition probability be applied.

In conclusion, analytical methods for addressing the issue of system delay times can only be enhanced through further development of cyclic queueing theory. Cyclic queuing models which comply with the SMIPCC model as described in this thesis are not described in literature. For this reason, the mathematical approach to this problem is closely tied to development work within the field of mathematic statistics. This development work is not subject of this thesis.

### 5.5.2 Simulation Method

#### Introduction

In the previous chapters, numerous SMIPCC capacity random and sensitive variables have been identified and discussed. Some variables have also been modelled individually and models have been validated using field data from actual mining operations. In order to encompass the entire range of variables a robust tool is required. Simulations offer the capability to investigate the complexity of the whole SMIPCC system including random variables and their interrelated dependencies. In particular, disturbances of trucks and the continuous part of the system can be incorporated. The primary aim of the simulation is to determine the system delay ratio $\zeta$.

The following describes the development of the SMIPCC system capacity simulation. Emphasis is paid on the open design, and hence, on fundamental concepts of a flexible and adaptable code for applications in surface mines.

#### Simulation Environment

Simulation models can be developed by using available simulation software or computer languages. Common simulation programs in the mining industry are for example Arena® Simulation (Software by Rockwell Automation) or SimMine® Simulation. Model creation using simulation software requires experience and/or training as well as good knowledge of simulation theory. Alternative approaches use

general-purpose programming languages. For this thesis, the combination of Microsoft Office Excel® and Visual Basic for Application (VBA) is chosen. An important fact is that Excel is widely accepted throughout the mining industry and results can be easily adapted for further calculations.

### Simulation Model Description

The continuous simulation model is described by using the simulation flow chart as shown in Figure 5-8. In the following the simulation is described for each decision routine indicated in the diamond flow chart shape.

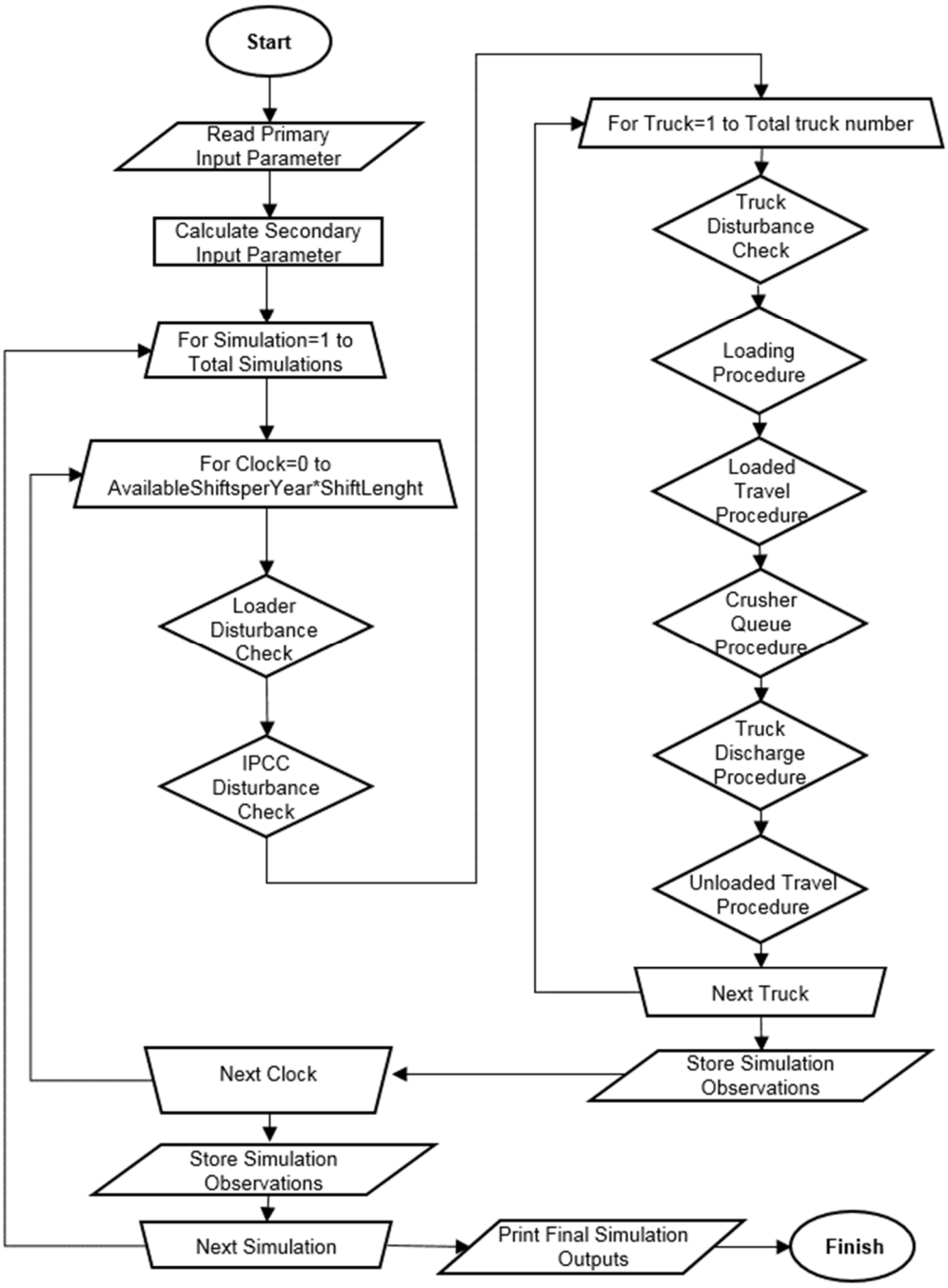



*Figure 5-8 Simulation model flowchart*

*Simulation Start for Initialization of Simulation Run*

The simulation starts by reading the input parameters including equipment parameters related to capacity, disturbance behaviour and travel time parameters as listed in Table 5-1. It is assumed that downstream elements of the continuous part of the IPCC system have the same capacity as the crusher station.

*Table 5-1 Simulation input parameters*

| Primary Input Parameters | Unit |
|---|---|
| **Loader Parameters** | |
| Bucket size | [m³] |
| Coefficient of variation of bucket payload | [-] |
| Mean bucket cycle time | [s] |
| Coefficient of variation of bucket cycle time | [-] |
| Repair ratio loader | [-] |
| Mean repair time loader | [min] |
| **Truck Parameters** | |
| Rated payload | [t] |
| Maximum overload factor | [-] |
| Repair ratio truck | [-] |
| Mean repair time truck | [min] |
| **Crusher Station Parameters** | |
| Design capacity | [t/h] |
| Hopper Volume | [m³] |
| Number of truck dump points | [-] |
| Repair ratio crusher station | [-] |
| Mean repair time crusher station | [min] |
| **Conveyor Parameters** | |
| Repair ratio conveyors | [-] |
| Mean repair time conveyors | [min] |
| **Spreader Parameters** | |
| Repair ratio spreader | [-] |
| Mean repair time spreader | [min] |
| **Travel Time Parameters** | |
| Truck travel time loaded | [s] |
| Truck travel time unloaded | [s] |
| Coefficient of variation of truck travel time | [-] |
| Manoeuvre and spot at the loader | [s] |
| Manoeuvre and unload time at crusher | [s] |
| **Time Usage Model** | |
| Calendar time | [h/a] |
| Non-scheduled production | [h/a] |
| External disturbances | [h/a] |
| Preventative maintenance | [h/a] |
| Technological Downtimes (Not proportional) | [h/a] |
| Shift Duration | [h] |
| Maximum dump block volume | [t] |
| Blast volume | [t] |
| Trackshift time | [h/trackshift] |
| Blast Delay | [h/blast] |
| Planned Delays | [h/shift] |
| Operating Delay Ratio | [-] |
| **Material Properties** | |
| Insitu density | [t/m³] |
| Swell factor | [-] |
| Bucket fill factor | [-] |
| **Simulation Inputs** | |
| Total Truck Number | [#] |
| Total Simulation Runs | [#] |

Based on the primary input parameters the secondary input parameters are calculated which are listed in Table 5-2.

*Table 5-2 Secondary simulation input parameters*

| Secondary Input Parameters | Unit | Equation |
|---|---|---|
| **Loader Parameters** | | |
| Mean bucket payload | [t] | (4-17) |
| Standard deviation of bucket payload | [t] | (4-20) |
| Standard deviation of bucket cycle time | [s] | (4-16) |
| Mean work time loader | [min] | (4-49) |
| **Truck Parameters** | | |
| Maximum Truck Capacity | [t] | (4-17) |
| Mean work time truck | [min] | (4-49) |
| **IPCC Parameters** | | |
| Repair ratio IPCC series system | [-] | (5-20) |
| Mean repair time IPCC series system | [min] | (5-19) |
| Mean work time IPCC series system | [min] | (5-22) |
| **Travel Time Parameters** | | |
| Standard deviation of truck travel time loaded | [s] | (4-45) |
| Standard deviation of truck travel time unloaded | [s] | (4-45) |
| **Time Usage Model** | | |
| Planned Delays | [h/a] | (5-7) |
| **Material Properties** | | |
| Loose density | [t/m³] | (4-18) |

Subsequently the simulation loop is initiated. For each simulation run the statistic observation such as effective operating time, total tonnage, total truck deliveries ect. are set to zero. In addition, the element operational states are set to “Working”, trucks position status is set to “In Loader Queue” and an initial element work time is calculated, just as all other random variable using the inverse transform method [186]. Excel provides several in-built inverse distribution functions which calculate the abscissa variable based on a random probability.

Consequently, the annual loop is initiated which is executed for every second of the year.

### Loader Disturbance Check

For each second within one year the loader disturbance check verifies the “LoaderRepairStatus”. For example, in case the work time of the loader is depleted a random repair time is calculated based on an exponential distribution and the loader is set to “In Repair” state. The reverse operation applies when the repair time is over in which case a new random work time is calculated and the element is set to “Working” state.

The code of the loader distribution check is shown in Code 5-1.

*Code 5-1 Loader disturbance check*

```
If Clock = LoaderWorkTime Then
    LoaderRepairTime = -(Application.WorksheetFunction.Ln(RandomNumber) / (1 /LoaderMeanRepairTime) * 60,
    0) + Clock
    LoaderRepairStatus = "InRepair"
End If

If Clock = LoaderRepairTime Then
    LoaderWorkTime = -(Application.WorksheetFunction.Ln(RandomNumber) /  (LoaderLamda) * 60, 0) + Clock
    LoaderRepairStatus = "Working"
End If
```

### IPCC Disturbance Check

Again, for each second within one year the IPCC disturbance check verifies the “IPCCRepairStatus”. The same procedure as described for the loader disturbance check applies. However, in the case of the IPCC disturbance check, each continuous element of the IPCC system (crusher station, conveyors and spreader) is considered by applying the principle of reduction of series systems as described in chapter 5.4.

The code of the loader distribution check is shown in Code 5-2.

*Code 5-2 IPCC disturbance check*

```
If Clock = IPCCWorkTime Then
    IPCCRepairTime = -(Application.WorksheetFunction.Ln(RandomNumber) / (1 / IPCCMeanRepairTime) * 60, 0)
    + Clock
    IPCCRepairStatus = "InRepair"
  End If

If Clock = IPCCRepairTime Then
    IPCCWorkTime = -(Application.WorksheetFunction.Ln(RandomNumber) / (IPCCLamda) * 60, 0) + Clock
    IPCCRepairStatus = "Working"
End If
```

### Truck Loop

Subsequently the truck loop is initiated in which the operational procedures are processed for each truck. Each individual truck passes through the following states (Table 5-3):

*Table 5-3 Truck states*

| Truck Status | Location |
|---|---|
| "TravelUnloaded" | Haul Road |
| "InLoaderQueue" | At Loader |
| "Spotting" | At Loader |
| "GettingLoaded" | At Loader |
| "TravelLoaded" | Haul Road |
| "InCrusherQueue" | At Crusher Station |
| "Discharging" | At Crusher Station |

### Truck Disturbance Check

Similar to the disturbance checks for the loader and the continuous part of the IPCC system, a disturbance check for trucks is also initiated. The disturbance check verifies if the work time / repair time of a truck is depleted and sets the TruckRepairStatus to the appropriate setting.

Code 5-3 shows the shortened code for the truck disturbance check

*Code 5-3 Truck disturbance check*

```
If Clock = TruckWorkTime(T) Then
    TruckRepairTime(T) = -(Application.WorksheetFunction.Ln(RandomNumber) / (1 / TruckMeanRepairTime) *
    60, 0) + Clock
    TruckRepairStatus(T) = "InRepair"
End If

If Clock = TruckRepairTime(T) Then
    TruckWorkTime(T) = -(Application.WorksheetFunction.Ln(RandomNumber) / (TruckLamda) * 60, 0) + Clock
    TruckRepairStatus(T) = "Working"
    Truckstatus(T) = "TravelUnloaded"
End If
```

### Loader Queue Procedure

Before loading of the truck can commence the truck status is changed to “InLoaderQueue” as shown in Code 5-4. However, the truck is only positioned in the loader queue if the unloaded truck unloaded travel time is completed and its truck status is “TravelUnloaded”.

*Code 5-4 Loader queue procedure*

```
If Clock = TruckTraveltimeUnloaded(T) And Truckstatus(T) = "TravelUnloaded" Then
    Truckstatus(T) = "InLoaderQueue"
    QueueLoader = QueueLoader + 1
End If
```

### Loading Procedure

As soon as the truck is in its final loading position, the loader status is set to “Working” and the loading procedure is initiated. Loader and truck statuses are changed to "Loading" and “GettingLoaded” respectively. Then a loading algorithm based on the equations described in subchapter 4.3.3 and 4.4.1 calculates random truck payloads and truck loading times.

The loading procedure code is shown in Code 5-5.

*Code 5-5 Loading procedure*

```
If Truckstatus(T) = "InLoaderQueue" And LoaderOperationalStatus = "NotLoading" And LoaderRepairStatus = "Working" Then
    QueueLoader = QueueLoader - 1
    Truckstatus(T) = "GettingLoaded"
    LoaderOperationalStatus = "Loading"
    Call loadingprocedure
    TruckloadingTime(T) = RandomTruckLoadingTime + Clock
    TruckPayload(T) = RandomTruckPayload
    TotalTonnageLoader = TotalTonnageLoader + TruckPayload(T)
End If
```

### Loaded Travel Procedure

The function of the loaded travel time procedure is to calculate a normally distributed loaded truck travel time based on mean loaded truck travel time and its standard deviation.

The code for the loaded travel procedure is shown in *Code* 5-6.

Code *5-6 Loaded travel procedure*

```
    If Clock = TruckloadingTime(T) And Truckstatus(T) = "GettingLoaded" Then
    LoaderOperationalStatus = "NotLoading"
    Truckstatus(T) = "TravelLoaded"
    Call random
    TruckTraveltimeLoaded(T) = WorksheetFunction.NormInv(RandomNumber, MeanTruckTraveltimeLoaded, StdTravelTimeLoaded), 0) + Clock
    End If
```

### Crusher Queue Procedure

Similar to the loader queue procedure the function of the crusher queue procedure is to serve a *first in first out* queue priority in a *Single-Queue-Multiple-Service-Points* arrangement.

The code for the crusher queue procedure is shown in Code 5-7.

*Code 5-7 Crusher queue procedure*

```
If Clock = TruckTraveltimeLoaded(T) And Truckstatus(T) = "TravelLoaded" And TruckRepairStatus(T) = "Working"
Then
    Truckstatus(T) = "InCrusherQueue"
    QueueCrusher = QueueCrusher + 1
End If
```

### Truck Discharge Procedure

The truck discharge procedures function is to process the discharge of the trucks at the crusher station. A truck can discharge its payload at one of the dump points of the crusher station when the sum of current hopper volume and the truck payload does not exceed the maximum hopper volume, the continuous part of the IPCC system is working, and a dump point is available. If the conditions are met the truck status changes to discharging, the crusher station queue is reduced by one truck and the used dump points are increased by one truck. The truck discharges the material for a fixed manoeuvre and dump time at the crusher station as described in subchapter 4.4.4. The hopper volume increases by the truck payload and the truck payload decreases to zero.

The code for the truck discharge procedure is shown in Code 5-8.

*Code 5-8 Truck discharge procedure*

```
If Truckstatus(truck) = "InCrusherQueue" And HopperVolume + TruckPayload(T) < HopperCapacity Then
    If IPCCRepairStatus = "Working" And UsedDumpPoints < NumberofDumpPoints Then
        Truckstatus(T) = "Discharging"
        QueueCrusher = QueueCrusher - 1
        UsedDumpPoints = UsedDumpPoints + 1
        TruckDischargeTime(T) = SpotTimeAtCrusher + Clock
        HopperVolume = HopperVolume + TruckPayload(truck)
        TruckPayload(T) = 0
    End If
End If
```

### Unloaded Travel Procedure

As soon as the truck has finished its discharge procedure the unloaded travel time procedure is initiated. A normally distributed unladed travel time is calculated by the mean unloaded truck travel time and the standard deviation. Additionally, the used dump points are reduced by one truck and the truck status is changed to “TravelUnloaded”.

The code for the truck discharge procedure is shown in Code 5-9.

*Code 5-9 Unloaded travel procedure*

```
If Clock = TruckDischargeTime(T) And Truckstatus(T) = "Discharging" And Then
    Truckstatus(T) = "TravelUnloaded"
    UsedDumpPoints = UsedDumpPoints - 1
    TruckTraveltimeUnloaded(T) = WorksheetFunction.NormInv(RandomNumber,
   MeanTruckTraveltimeUnloaded, StdTravelTimeUnloaded) + Clock
    End If
```

Finally, the statistical observations are recorded including effective operating time, unexpected repair time and tonnage processed for the loader and the continuous part of the IPCC system. Additionally, the average idle time of the trucks is recorded.

Table 5-4 summarizes the various states a system element can obtain. A state or status represents the condition in which an element is in at a specific point in time.

*Table 5-4 Element states*

| Element | Operational State | Repair State |
|---|---|---|
| Loader | Not Loading<br>Loading | In Repair<br>Working |
| Truck | In Loader Queue<br>Getting Loaded<br>Travel Loaded<br>In Crusher Queue<br>Discharging<br>Travel Unloaded | In Repair<br>Working |
| Continuous part of IPCC system | Not Processing<br>Processing | In Repair<br>Working |
| System | Trackshifting<br>Not Trackshifting<br>Blasting<br>Not Blasting | |

# CHAPTER 6:
# CASE STUDY

*In this chapter a case study based on a hypothetical coal mine is conducted. The objective of the case study is to draw descriptive conclusions with regards to annual capacity, productivity and system-induced operating delays of elements in a SMIPCC system.*

## 6.1 INTRODUCTION & CASE STUDY PARAMETERS

For the case study a hypothetical coal deposit was created which is loosely based on the characteristics found at the Clermont coal mine in Queensland, Australia. The hypothetical mine consists of a 60 m overburden layer divided into 4 regular benches with a bench height of 15 m. The overburden layer is mined using a SMIPCC system in which the overburden material is excavated by a P&H4100 electric rope shovel. The shovel loads a homogeneous truck fleet consisting of Komatsu 930-4SE trucks. The trucks transport the overburden material along the indicated truck travel path (in blue) to the semi-mobile in-pit crusher station located at the permanent wall. The crusher station, with a nominal capacity of 9,400 t/h and a hopper capacity of 725 t, has 3 truck bridges which allows the trucks to discharge material into the hopper of the crusher station. The crusher station crushes the overburden material to a conveyable size and discharges it onto a conveyor system. The conveyor system has the same nominal capacity as the crusher station and consist of a series of 6 conveyors (CV1 - wall conveyor; CV2 - ramp conveyor; CV3 – overland conveyor; CV4 - dump ramp conveyor; CV5 - extendable dump conveyor; CV6 – trackshiftable dump conveyor). The conveyor system transports the material out of the pit to an ex-pit dump. At the ex-pit dump the material is discharged by a spreader. The hypothetical mine layout is shown in Figure 6-1.

Below the overburden a coal layer follows which is mined by conventional truck and shovel operation.

The overburden layer consists of consolidated sandstone with an average insitu density of 2.37 t/m³. After blasting, the loose density of the material amounts to 1.78 t/m³ applying a swell factor of 1.33.

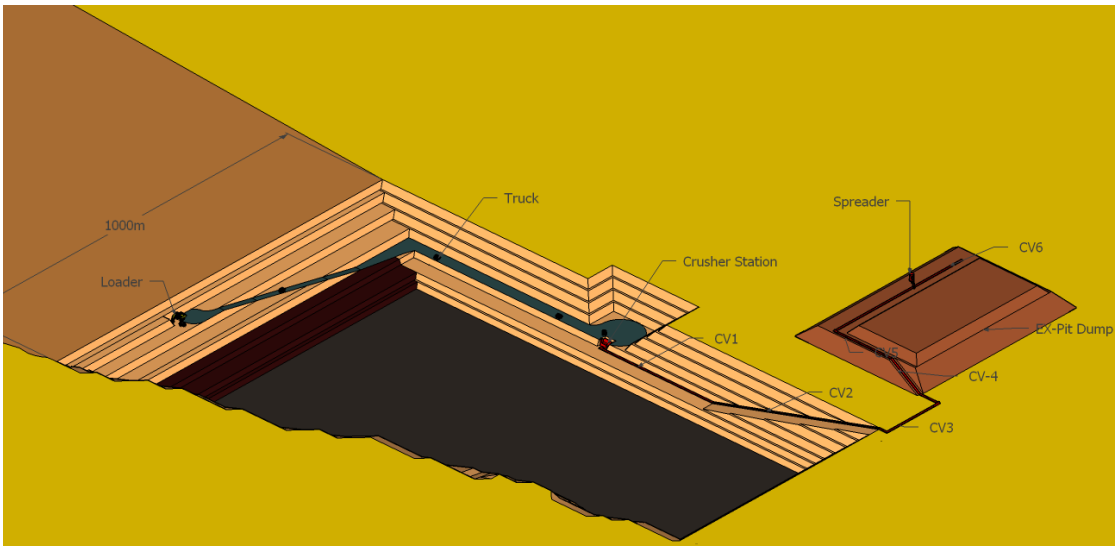



*Figure 6-1 Hypothetical coal mine layout*

The hypothetical mine is planned to operate 362 days per annum, allowing 3 days for non-worked holidays, in two 12 hour shifts per day. It is estimated that the mine stops operation due to bad weather conditions and other external downtimes for a total of 5 days per year. Preventative maintenance for the continuous part of the IPCC system is scheduled for 16 hours (4 hours to clean / 12 hours to maintain) every second week. Furthermore, an annual maintenance shutdown period is planned for 7 days. For the P&H 4100 the preventative maintenance schedule is planned to commence every week for 12 hours of which 50% is done in sync with the preventative maintenance for the continuous part of the IPCC system. By using equation (5-6) the total time for preventative maintenance $t_{Dp}^{(3)}$ is planned to amount to 896 hours per annum.

For every shift one hour of planned delays are approximated to allow for meal breaks, equipment inspection and safety rounds. Using equation (5-7) the annual planned shift delays $t_{Dp}^{(4)}$ are approximated to 640 hours.

Table 6-1 summarizes the relevant loader and truck parameters in order to calculate the mean hourly loader capacity.

*Table 6-1 Loader and truck parameters*

| Loader and Truck Parameters | Unit | Value |
|---|---|---|
| **Loader Parameters** | | |
| Bucket size | [m³] | 63 |
| Coefficient of variation of bucket payload | [-] | 0.10 |
| Mean bucket cycle time | [s] | 33 |
| Coefficient of variation of bucket cycle time | [-] | 0.20 |
| Bucket fill factor | [-] | 0.86 |
| **Truck Parameters** | | |
| Rated payload | [t] | 290 |
| Maximum overload factor | [-] | 1.2 |

Using equation (4-24), (4-29) and (4-40) the mean truck payload $\bar{c}_T$ and mean truck loading time $\bar{t}_{Lo}$ was determined to $\bar{c}_T = 291.61t$ and $\bar{t}_{Lo} = 111.7s$ at a mean number of required bucket cycles $N = 3.023$ which leads to a mean hourly loader capacity of $C_L = 9{,}398\text{t/h}$.

$$C_L = 291.61t \cdot \frac{3600}{111.7s} = 9{,}398t/h$$

The operating delay ratio $\nu$ of the loader was estimated to 0.08 to account for minor short-term delays such as minor pad preparations, face clean-ups, tramming, etc.

Maximum dump block volume and blast volume were approximated to 2.4 Mm³ and 0.375 Mm³, respectively. The required trackshifting time $t_{Sh}$ and blasting time $t_B$ were estimated to 24 hours and 1.5 hours, respectively. Using equation (5-9) to (5-11) the technological downtime ratio $\tau$ could be calculated.

$$t_{Oe}^{(S)} = \frac{V_D}{C_L} = \frac{(1{,}000m * 48m * 50m) * 1.78t/m^3}{9{,}398t/h} = 454h$$

$$t_{Oe}^{(B)} = \frac{V_B}{C_L} = \frac{(500m * 50m * 15m) * 1.78t/m^3}{9{,}398t/h} = 71h$$

$$\tau = \frac{t_{Sh}}{t_{Oe}^{(S)}} + \frac{t_B}{t_{Oe}^{(B)}} = \frac{24h}{454h} + \frac{1.5h}{71h} = 0.074 \quad .$$

The mean truck travel time unloaded $t_{T_U}$ and truck travel time loaded $t_{T_L}$ were estimated to 190 s and 290 s, respectively. The coefficient of variation of loaded and unloaded travel time was estimated to 0.15. In addition, a 45 s manoeuvre and spot time at the loader $t_S$ and a 60 s manoeuvre and dump time at the crusher $t_D$ was projected.

The estimated disturbance parameter for the system elements are listed below.

*Table 6-2 Disturbance parameters of SMIPCC system elements*

| Element Disturbance Parameters | | Mean repair time [min] | Repair ratio | Mean Work Time [min] |
|---|---|---|---|---|
| **Loader** | | 132.7 | 0.170 | 782 |
| **Truck** | | 288.1 | 0.128 | 2251 |
| **Crusher Station** | | 33.1 | 0.117 | 282 |
| **Conveyor** | | | | |
| | CV1 | 31.8 | 0.012 | 2661 |
| | CV2 | 21.0 | 0.007 | 3205 |
| | CV3 | 21.0 | 0.007 | 3205 |
| | CV4 | 21.0 | 0.007 | 3205 |
| | CV5 | 31.8 | 0.012 | 2661 |
| | CV6 | 32.7 | 0.019 | 1722 |
| **Spreader** | | 52.1 | 0.059 | 878 |

## 6.2 CONDUCTED CALCULATIONS

The following calculations were conducted:

- Calculation 1 – Capacity determination of SMIPCC system for various truck quantities
- Calculation 2 – Economic analysis
- Calculation 3 – Sensitivity analysis
- Calculation 4 – Introduction of small stockpile in front of crusher station
- Calculation 5 – Comparison to conventional truck and shovel operation

**Calculation 1**

To analyse the SMIPCC system capacity for various homogenous truck quantities, the input parameters as specified in section 6.1 were applied to the simulation model described in section 5.5.2. A total of 1,000 simulations were conducted. Figure 6-2 shows the resulting annual SMIPCC system capacity for various truck quantities.

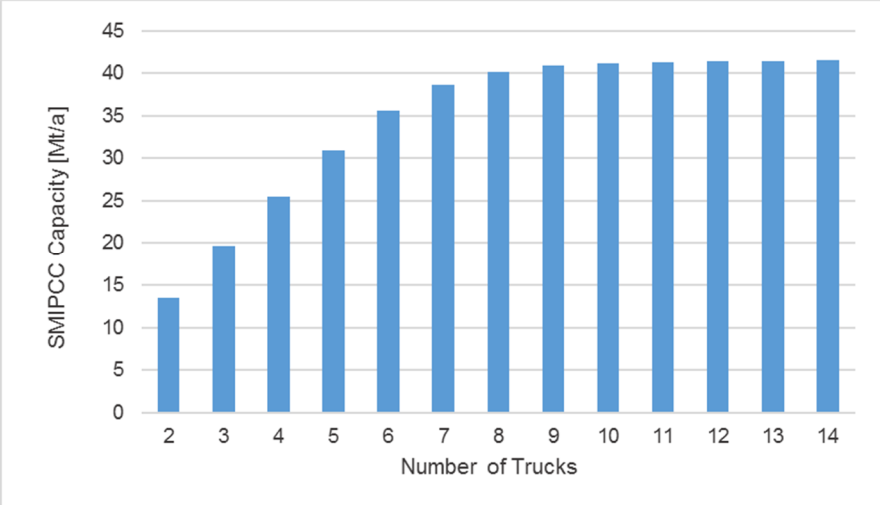



*Figure 6-2 SMIPCC system capacity for various number of trucks*

It can be seen that the annual SMIPCC system capacity increases significantly between 2 and 7 trucks while only minor capacity increases occur between 8 and 14 trucks. For instance, the SMIPCC system capacity increases by 21% from 25.47 Mt/a to 30.88 Mt/a when employing 5 instead of 4 trucks. However, only 4% of SMIPCC system capacity is added when employing 8 instead of 7 trucks. Figure 6-3 indicates the relative change in SMIPCC system capacity for incremental truck number increase.

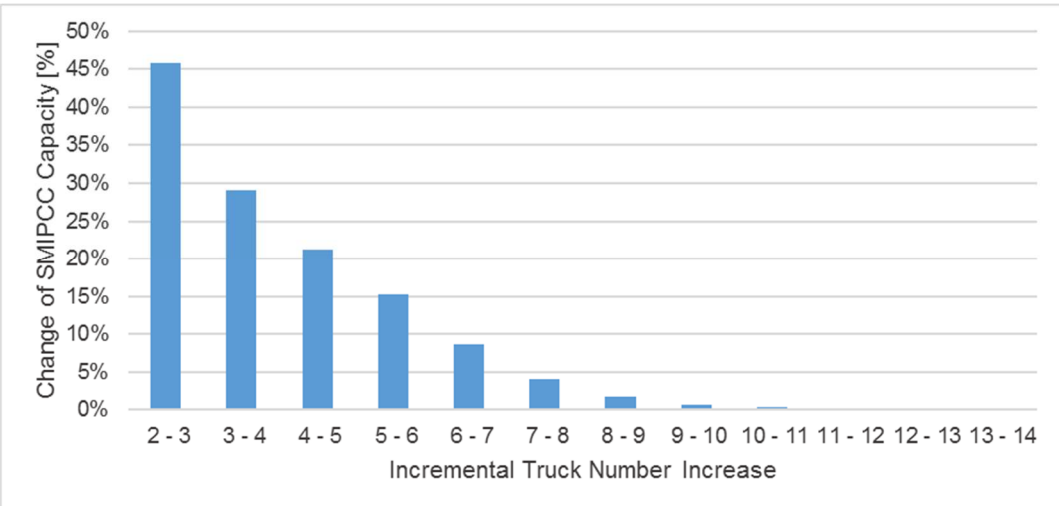



*Figure 6-3 SMIPCC system capacity change for various trucks*

The reason for this significant decrease originates from the system delay ratio of the loader and trucks. Figure 6-4 shows that the system delay ratio for the loader has an inverse trend compared to the SMIPCC system capacity (Figure 6-2), which indicates

that the time the loader is ready for operation but is waiting for trucks decreases with the employed number of trucks in the system. However, the progression of the system delay ratio of the loader is not linear but rather follows a power function and approaches a limit of approximately $\zeta_L = 0.21$ at 14 trucks.
Contrary effects are obtained for the system delay ratio of trucks. The more trucks that are introduced to the system, the more time an individual truck is waiting in front of the loader or crusher. The progression of the system delay ratio of trucks follows approximately an exponential function.

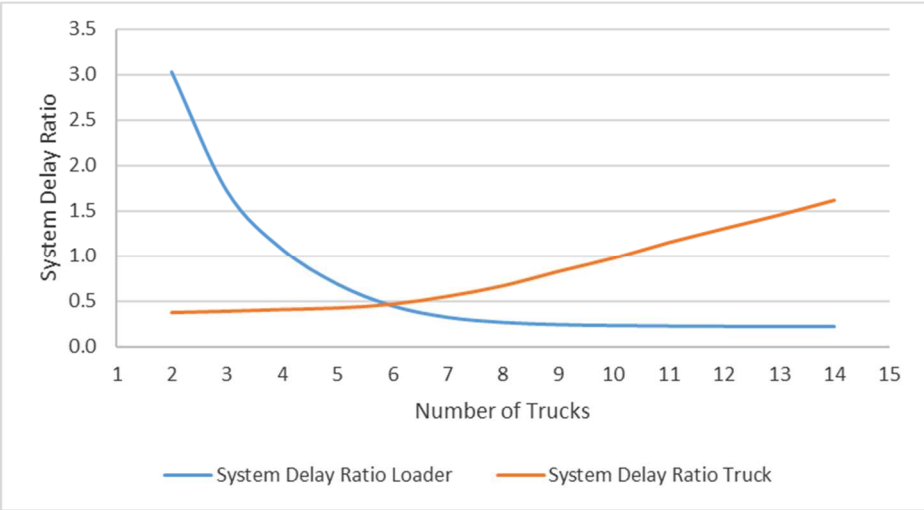



*Figure 6-4 System Delay Ratios for loader and truck for various number of trucks*

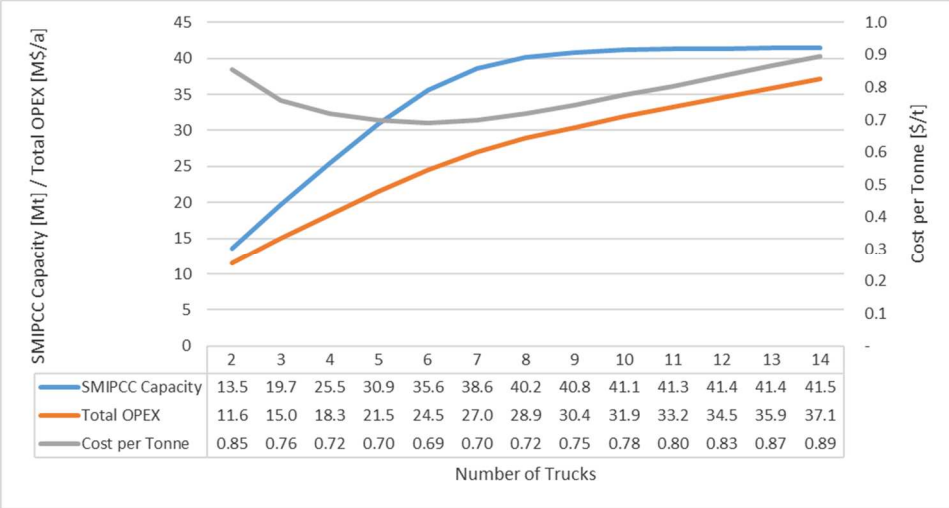
**Calculation 2**

An economic analysis exclusively based on OPEX (Operational Expenditures) was undertaken in order to identify the optimal number of trucks. Maintenance and power cost for the P&H 4100 as well as for the 930-4SE were obtained from [187] while the OPEX cost for the continuous part of the IPCC system (crusher station, conveyors and spreader), as well as the labour costs for each system element, were estimated by the author. The OPEX for each system element when idle are based on the labour cost. Table 6-3 summarises the OPEX parameters of the system elements used for the analysis.

*Table 6-3 OPEX parameters for system elements*

| OPEX Parameters | Unit | P&H 4100 | 930-4SE | IPCC |
|---|---|---|---|---|
| Maintenance Cost (including wear & spear parts, labour, lubrication) | [$/h] | 434 | 312 | 481 |
| Power/Fuel Cost | [$/h] | 87 | 94 | 387 |
| Labour Cost | [$/h] | 170 | 150 | 500 |
| **Total OPEX while operating** | **[$/h]** | **691** | **556** | **1368** |
| Percentage of OPEX while Idle | [%] | 30% | 32% | 42% |
| **Total OPEX while Idle** | **[$/h]** | **205** | **178** | **568** |

Figure 6-5 shows the SMIPCC system capacity, total OPEX and cost per tonne for various truck quantities. It can be seen that the cost per tonne of the SMIPCC system decreases by 0.16 $/t between 2 and 6 trucks, where it reaches its minimum at 0.69 $/t before it increases moderately for the remaining truck quantities.




| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SMIPCC Capacity | 13.5 | 19.7 | 25.5 | 30.9 | 35.6 | 38.6 | 40.2 | 40.8 | 41.1 | 41.3 | 41.4 | 41.4 | 41.5 |
| Total OPEX | 11.6 | 15.0 | 18.3 | 21.5 | 24.5 | 27.0 | 28.9 | 30.4 | 31.9 | 33.2 | 34.5 | 35.9 | 37.1 |
| Cost per Tonne | 0.85 | 0.76 | 0.72 | 0.70 | 0.69 | 0.70 | 0.72 | 0.75 | 0.78 | 0.80 | 0.83 | 0.87 | 0.89 |

*Figure 6-5 Economic analysis on OPEX*

The reason for this trend can be found in the developments of effective operating time and system-induced operating delay and their associated OPEX for the individual system elements (refer to Figure 6-6). While the loader and the IPCC system elements show similar trends for their time components, in which effective operating time increases and system-induced operating delays decrease as more trucks are introduced to the system, the time components for the truck show opposite trends.

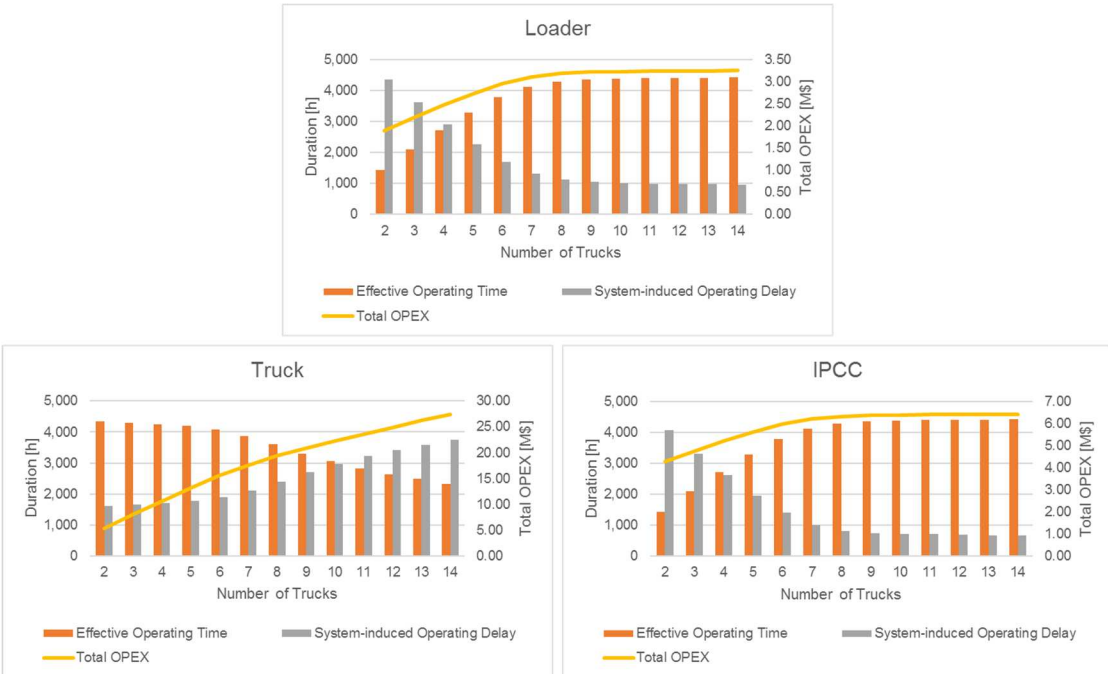



*Figure 6-6 Effective operating time and system-induced operating delays of Loader, Truck and IPCC*

**Calculation 3**

To some degree a mining company can influence the mean repair time by improving the maintenance organisation. This can be realised by ensuring that frequent spare and wear parts are available at any time, having skilled and experienced maintenance personnel and necessary tools close to the equipment at all times, and using equipment fault diagnostics.

A sensitivity analysis was carried out based on 6 trucks to analyse the effects of the maintenance organisation on SMIPCC system capacity. For each system element the original mean time for repairs (Table 6-2) was varied between ± 30%.

Figure 6-7 indicates the relative change of SMIPCC system capacity for different mean time for repairs of system elements.

Generally, the SMIPCC capacity increases as the mean repair time of the system element decreases. The largest impact on SMIPCC system capacity is the change of the mean repair time for the continuous part of the IPCC system (crusher station, conveyors, spreader). By reducing the mean repair time of these elements by 10%, 20% and 30%, an annual capacity increase of the entire SMIPCC system of 4%, 7% and 11% can be achieved, respectively. Therefore, efforts toward the reduction of the mean repair time of the continuous part of the SMIPCC promise highest achievement.

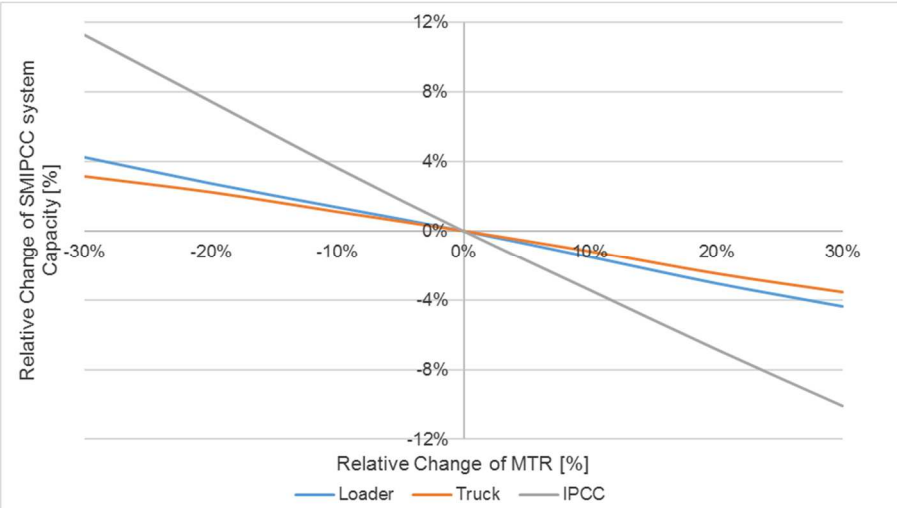



*Figure 6-7 Sensitivity analysis on mean time to repair*

**Calculation 4**

To analyse the effect of a little stockpile in front of the crusher, additional calculations were conducted through a minor alteration of the simulation code as described in section 5.5.2. The alteration of the code is shown in Code 6-1. The modelling of a small stockpile in front of the crusher station was accomplished by ignoring the following conditions:

- *IPCC Repair Status = "Working"* and

- *UsedDumpPoints < NumberofDumpPoints*

*Code 6-1 Truck discharge procedure - alteration*

```
If Truckstatus(truck) = "InCrusherQueue" And HopperVolume + TruckPayload(T) < HopperCapacity Then
        Truckstatus(T) = "Discharging"
        QueueCrusher = QueueCrusher - 1
        UsedDumpPoints = UsedDumpPoints + 1
        TruckDischargeTime(T) = SpotTimeAtCrusher + Clock
        HopperVolume = HopperVolume + TruckPayload(truck)
        TruckPayload(T) = 0
    End If
End If
```

An analysis was carried out based on 6 trucks to analyse the effects of a small stockpile in front of the crusher station. Therefore, the hopper capacity was gradually increased from 2,000 t to 18,000 t in 2,000 t intervals.

Figure 6-8 shows the annual SMIPCC capacity for various stockpile capacities. As expected, the SMIPCC system capacity increases the more that stockpile capacity is available. However, the progression of the graph indicates that the SMIPCC system approaches a limit. For example, the results indicate that by introducing an 18,000 t stockpile (which approximates an area of 95 m by 95 m at a truck dump height of 2 m), the SMIPCC system capacity can be increased by 5.1 Mt/a in comparison to the base case.

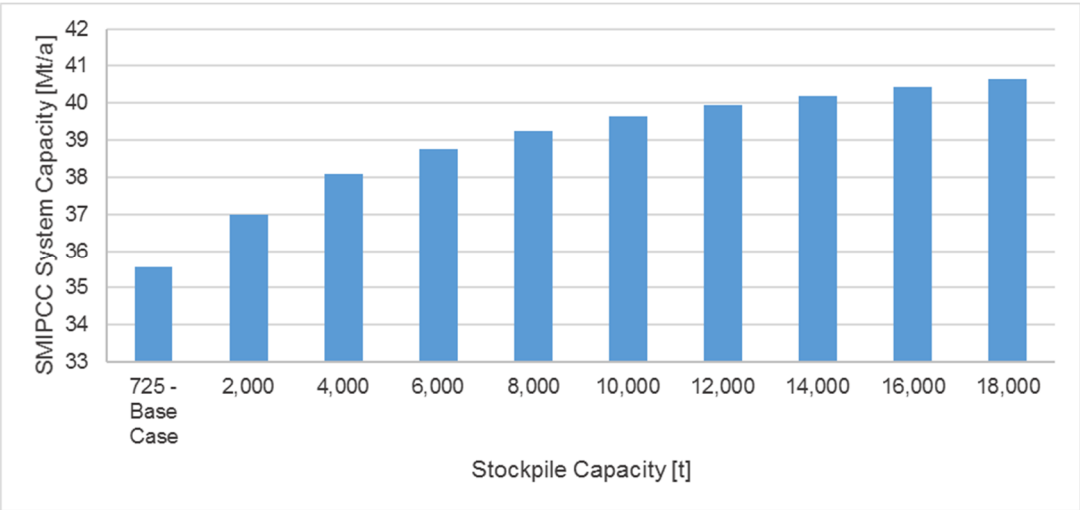



*Figure 6-8 SMIPCC system capacity vs. stockpile capacity*

To analyse whether or not the introduction of a stockpile in front of the crusher station makes economic sense, the cost per tonne based on the parameters specified in Table 6-3 for each case were calculated. Figure 6-9 shows the cost per tonne of the SMIPCC system for various stockpile capacities. It can be seen that the cost per tonne decreases as the stockpile capacity increases. Still, the results indicate that the cost

per tonne for the SMIPCC system can only be reduced by 0.046 $/t (6.7%) compared to the base case when introducing an 18,000 t stockpile.

It therefore remains questionable whether or not the introduction of a small stockpile in front of the crusher station is economically advantageous for the following reasons:

- additional equipment such as front end loaders are required to feed the crusher station with stockpile material at the required feed rate capacity, which means that additional cost of rehandling material from the stockpile would apply.
- additional space needs to be created in order to accommodate the stockpile, which might lead to significant increased material movements.

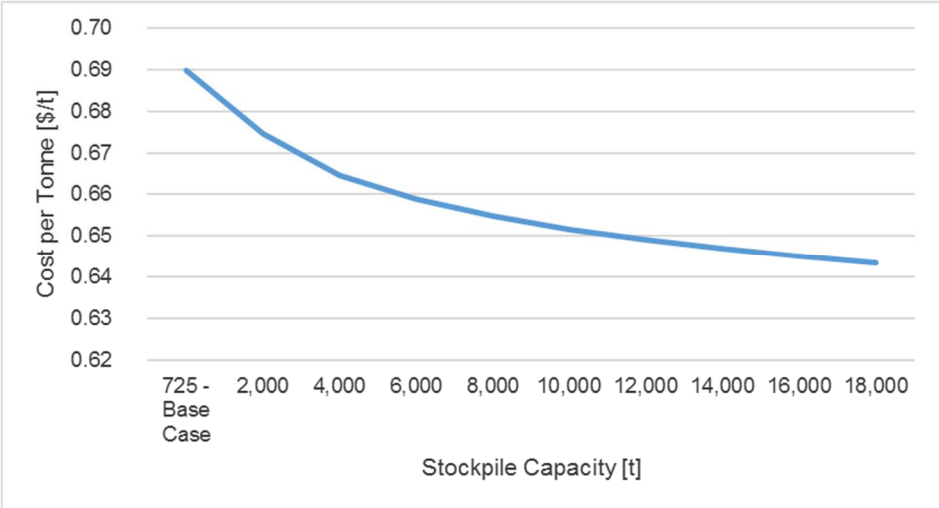



*Figure 6-9 Cost per tonne of SMIPCC system for various stockpile capacities*

However, the results also indicate diminishing marginal returns. Therefore, even a small increase of the hopper capacity (which requires no additional equipment) results in an increase in SMIPCC system capacity and hence in a reduction of cost per tonne. This occurs because the highest cost per tonne reduction of the SMIPCC system can be realised by increasing the stockpile capacity from the base case to 2,000 t (Figure 6-10).

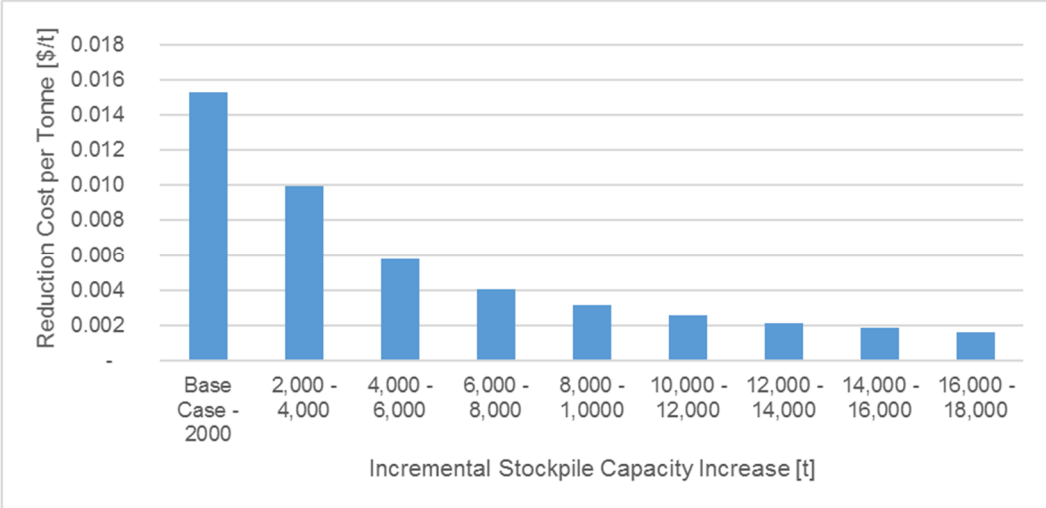



*Figure 6-10 Reduction of SMIPCC system cost per tonne by stockpile capacity increase*

**Calculation 5**

Further calculations were conducted in order to compare a conventional truck and shovel system to a SMIPCC system in terms of time usage model and OPEX. To facilitate this analysis minor alterations of the simulation code as described in section 5.5.2 were required. The modelling of a conventional truck and shovel operation was accomplished through the following parameter changes:

- *IPCCRepairStatus* was fixed to „Working" at any time
- *NumberofDumpPoints was set to infinity*

Additionally, for the conventional truck and shovel system the mean truck travel time unloaded $t_{T_U}$ and truck travel time loaded $t_{T_L}$ were increased by a factor of 2.5 to 475 s and 725 s respectively, in order to account for increased vertical and horizontal travel distances. Furthermore, the manoeuvre and dump time was reduced to 45 s to account for easier dumping conditions at the waste dump.

All other input parameters as specified in section 6.1 remained unchanged.

In Figure 6-11 the effective operating time and the system-induced operating delay of the loader for both competing systems is depicted. It can be seen that the effective operating time of the conventional truck and shovel system increases approximately linear from 2 to 14 trucks as the number of trucks increases. Beyond the number of 14 trucks the effective operating time of the conventional truck and shovel system begins to level off. Furthermore, it can be seen that the SMIPCC system yields higher effective operating hours per additional truck however it levels off at a lower truck quantity in comparison to the truck and shovel system. The reverse effects can be seen for the system induced operating delays of the two systems.

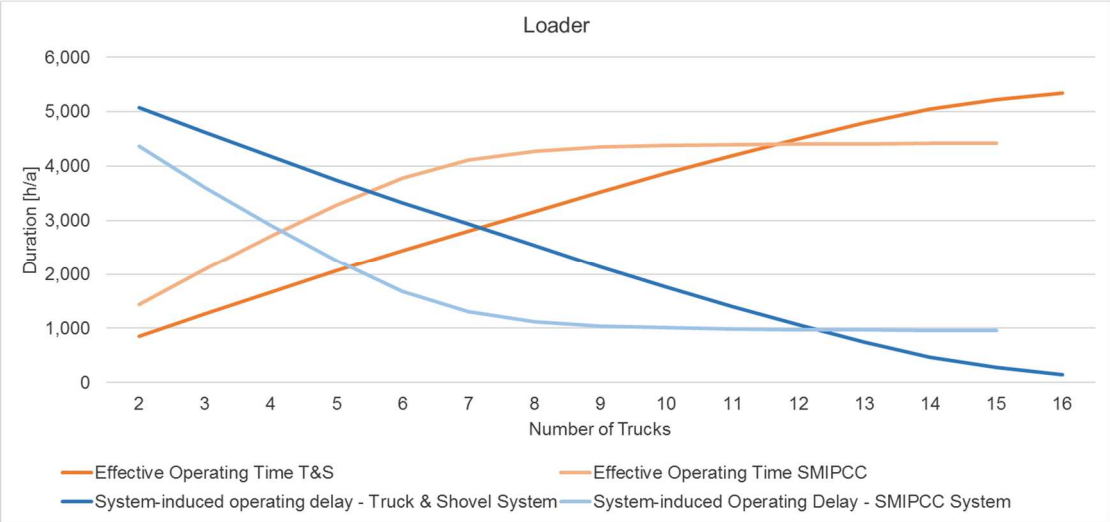



*Figure 6-11 Comparison of effective operating time and system-induced delay of the loader*

In Figure 6-12 the effective operating time and the system-induced operating delay of the trucks (average) for both competing systems is depicted. It should be noted that the effective operating time of each truck decreases more rapidly with the SMIPCC system in comparison to the truck and shovel system; as more trucks are introduced into the system, they experience more wait time rather than effective operating time. This can be clearly seen in the system-induced operating delays of the trucks in the SMIPCC system. This effect is not as profound in the conventional truck and shovel system.

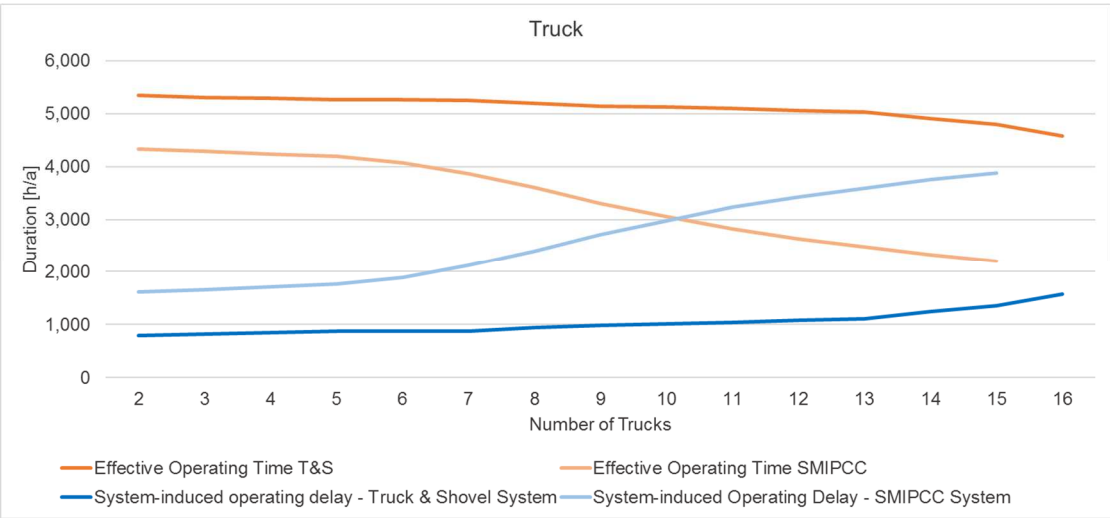



*Figure 6-12 Comparison of effective operating time and system-induced delay of the truck*

However, despite the increasing ineffectiveness of individual trucks (Figure 6-12), the annual effective operating hours of the SMIPCC system nevertheless increases more significantly for each additional truck compared to the conventional truck and shovel system, up to a certain truck quantity (Figure 6-11). As stated before, this is assuming the truck travel time for conventional truck and shovel systems is 2.5 times higher than for SMPICC systems.

Figure 6-13 indicates annual system capacity and the total OPEX of the two competing systems. It can be seen that the annual system capacities have identical progressions as compared to the effective operating hours. In general, it can be seen that the annual system capacity as well as the total OPEX of the SMIPCC system is smaller for fewer truck numbers as compared to the truck and shovel system. In this particular case, the turning point is around 11 and 9 trucks for annual system capacity and total OPEX, respectively. Additionally, it can be seen that the annual system capacity the SMIPCC system approaches a limit at approximately 41.5 Mt while the annual system capacity of the truck and shovel system eventually approaches a limit at approximately 50.5 Mt. This effect can be explained by the time trucks queue in front of the crusher station in periods when the continuous part of the SMIPCC system experiences unplanned downtimes.

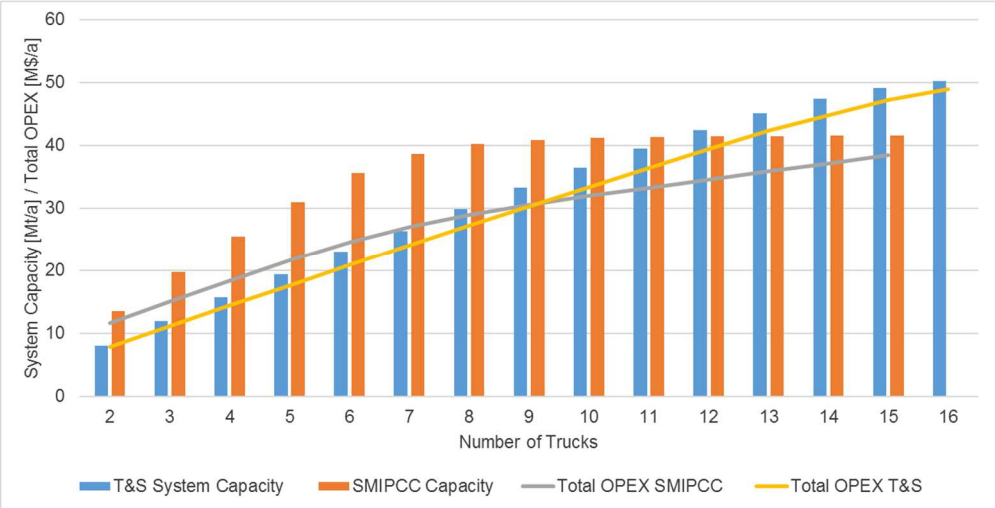
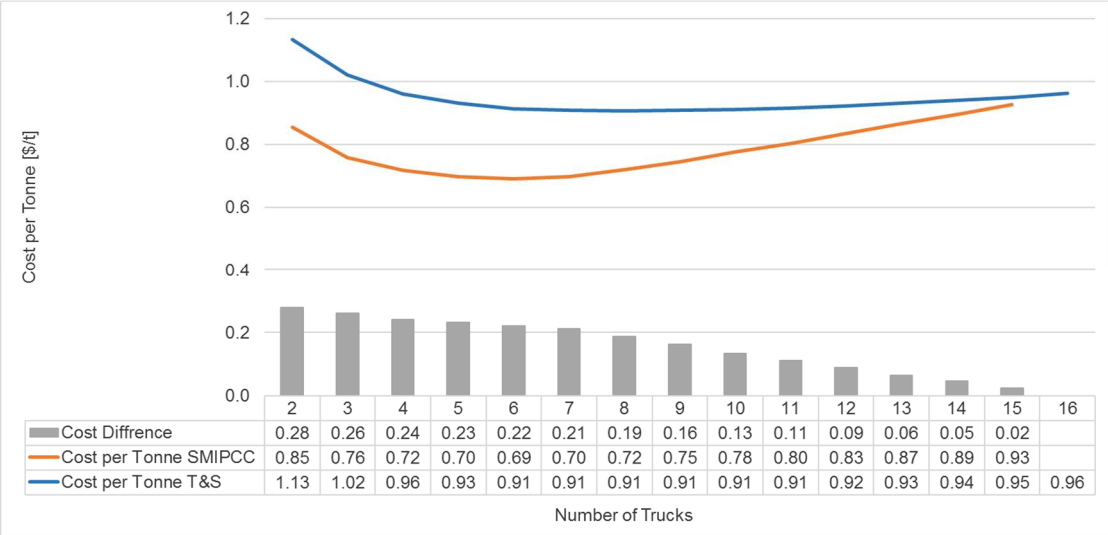



*Figure 6-13 Comparison of annual system capacity and total OPEX*

Figure 6-14 indicates the cost per tonne of the two competing systems. It can be seen that the cost per tonne of the truck and shovel system has a progression similar to the SMIPCC system. The cost per tonne of the truck and shovel system decrease by 0.20$/t between 2 and 5 trucks, and remain nearly constant at 0.91 $/t between 6 and 11 trucks before they increase slightly by 0.04 $/t between 12 and 16 trucks. The calculated minimum cost per tonne of the truck and shovel system occurs at 8 trucks and 0.906 $/t. The cost per tonne difference between the SMIPCC system and the truck and shovel system decreases gradually from 0.28 $/t to 0.02 $/t between 2 and 15 trucks.




| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cost Diffrence | 0.28 | 0.26 | 0.24 | 0.23 | 0.22 | 0.21 | 0.19 | 0.16 | 0.13 | 0.11 | 0.09 | 0.06 | 0.05 | 0.02 | |
| Cost per Tonne SMIPCC | 0.85 | 0.76 | 0.72 | 0.70 | 0.69 | 0.70 | 0.72 | 0.75 | 0.78 | 0.80 | 0.83 | 0.87 | 0.89 | 0.93 | |
| Cost per Tonne T&S | 1.13 | 1.02 | 0.96 | 0.93 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.92 | 0.93 | 0.94 | 0.95 | 0.96 |

*Figure 6-14 Comparison of cost per tonne*

Figure 6-15 visualises the effect of cost per tonne and annual system capacity of the two competing systems in more detail. In particular, it can be seen that between an annual capacity of 14 Mt/a to 41.5 Mt/a, the cost per tonne of the SMIPCC system is below the cost per tonne of the truck and shovel system. The cost per tonne difference between the two systems increases gradually from 0.14 $/t to 0.22 $/t for annual system capacities between 14M t/a and 38 Mt/a, and decrease significantly beyond 40M t/a.

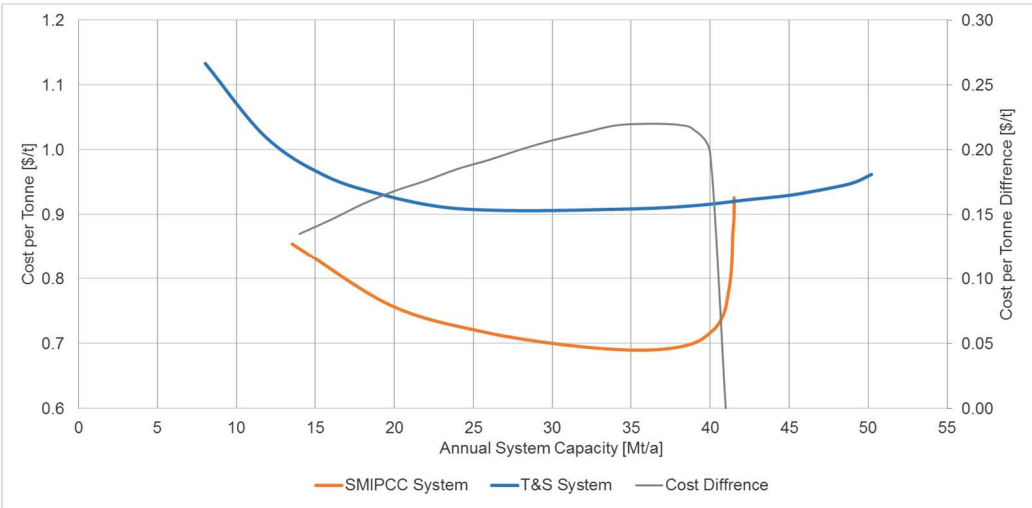



*Figure 6-15 Annual system capacity vs. cost per tonne*

Figure 6-16 indicated the required number of trucks for various annual system capacities for the competing systems. It can be seen that the more annual system capacity is required, the more trucks need to be introduced to each system. However, up to approximately 40 Mt/a required system capacity the SMIPCC system requires significantly fewer trucks. In this system capacity range the difference of the required truck quantity between the truck and shovel system and the SMIPCC system fluctuates between 1 and 4 trucks.

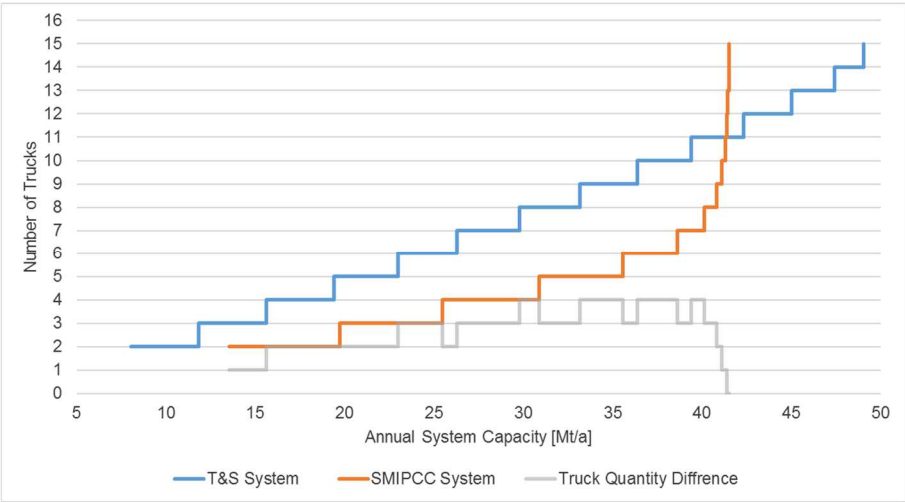



*Figure 6-16 Annual system capacity vs. truck quantity*

Although, Calculation 5 was purely based on the direct OPEX of the individual system elements (refer to Table 6-3), it can be assumed that the advantageous cost effect of SMIPCC systems compared to the truck and shovel system is further improved by the following aspects:

- haul road maintenance costs are likely to increase as trucks transport material along the entire distance of operating face and ex-pit dump,
- costs for diesel, diesel storage and carbon tax are likely to increase as long uphill hauls out of the pit consume considerably more diesel fuel then short horizontal hauls,
- infrastructure cost such as housing or workshops are likely to increase due to the higher number of trucks required and associated labour requirements.

In light of these aspects the robustness of the statements made throughout Calculation 5 are further strengthened.

## 6.3 CRITICAL DISCUSSION OF CASE STUDY RESULTS

All results of the case study are based on the simulation model as described in section 5.5.2. which uses the following simplifications:

1. **Work Time Distribution**
   As defined in section 4.5.3 the work time which describes the time period between two consecutive disturbances/repairs of system elements is assumed to be exponentially distributed. This assumption seems valid for system elements that are utilised reasonably and do not suffer from extensive periods in which they stand idle. However, within the conducted calculations, situations have been analysed in which the loader, the continuous part of the IPCC system and trucks indicate high system-induced downtimes. In particular, this occurs for the loader and the continuous part of the IPCC system at small truck quantities and for the trucks at high truck quantities (refer to Figure 6-6 and

Figure 6-11). For those situations when the system element is waiting, it can be expected that the work time of the element would increase substantially, as the working intensity is lower in comparison to periods of effective operating time. Thus, the amount of downtimes would decrease which would lead to an increase of effective operating time and annual system capacity. The results of the case study can be assumed to be valid for situations in which the system element is reasonably utilised.

2. **Alteration of Truck Allocation**
   Based on the simulation model trucks are required to wait in front of the crusher station whenever a failure or disturbance occurs at the continuous part of the IPCC system, regardless of the time it requires to be repaired. In reality trucks would be dispatched directly to the ex-pit dump whenever the identified failure is expected to take longer than a certain time period. For example, in the case of a conveyor belt rip the continuous part of the IPCC system can be down for 1 or 2 days. In those situations, trucks would be directly dispatched to the ex-pit dump which would further increase the effective operating time of the loader and therefore increase the annual system capacity of the SMIPCC system.

3. **Preventative Maintenance for Trucks**
   In the simulation model it is assumed that the occurrence and duration for preventative truck maintenance is identical to the preventative maintenance for other system elements. In reality preventative truck maintenance is based on regular service intervals determined by Service Meter Unit (or SMU) hours of the individual truck. This circumstance would lead to periods in which one or more trucks cannot be utilised which would decrease the result of the annual system capacity.

4. **Trucks in Reserve**
   The current simulation model does not account for any trucks in cold reserve. Hartmann [25] suggests that for every five to six production units (trucks), one spare unit should be provided in order to maintain production. The provision of spare truck units would further increase the results of the effective operating time of the loader and therefore increase the annual system capacity.

5. **Increasing Truck Travel Times**
   In the simulation model the truck travel time varies within a certain spread around the mean which remains constant over the entire observation period. However, in reality the truck travel time is likely to increase as the operating face develops further away from the SMIPCC crusher station or the ex-pit dump area. This circumstance would lead to a slight decrease of the annual system capacity.

# CHAPTER 7:
# SUMMARY AND RECOMMENDATIONS

*This chapter presents a brief summary of this research, the accomplishments, and directions for future research.*

## 7.1 SUMMARY

During the last decade, the mining industry has developed particular interest in SMIPCC systems for the transportation of waste rock materials. As the interest for IPCC systems increases so does the demand for investigative studies to analyse the applicability. The basis for such investigative studies is the knowledge of achievable effective operating hours of these systems and their corresponding annual capacity to meet assigned production schedules. Historically, deterministic calculations based on empirical data provided merely satisfactory estimates. However, disturbances and operational variations such as delays and hold-ups are inevitable in any earthmoving, quarrying and mining operation no matter how well the operation may be planned or managed. Thus, all too often such traditional calculation methods have proven to be inadequate in practice and outcomes have not met expectancy. Traditional calculation methods have four notable shortcomings; they

1. underestimate the influence of the random behaviour of system components and their interactions,
2. are time consuming when alteration is necessary to suit individual project requirements,
3. lack in terms of standardization throughout the industry, and
4. systematically carry hazards of human error and under or overestimate the achievable IPCC system capacities.

Therefore, the objective of this thesis was to develop a structured method to determine the annual capacity of SMIPCC systems under consideration of the random behaviour system elements and their interactions with one another. This objective was accomplished by achieving the following sub-ordinated targets:

1. Comprehensive analysis of in-pit crushing and conveying system (IPCC) and its applicability to the mining industry.
2. Literature review of available capacity determination methods for continuous mining systems and more particularly for SMIPCC systems.
3. Description and analysis of random SMIPCC system element behaviour.
4. Description and standardisation of a time usage model applicable to SMIPCC systems.
5. Development of a simulation model capable of determining system-induced operating delays.

The following findings of the research can be noted:

An analysis of IPCC systems which have been installed, are currently in erection/manufacturing process or on order since 1956 over the last seven decades revealed that in terms of quantity, fixed and fully-mobile systems, increasingly lose importance on account of semi-mobile and semi-fixed IPCC system. Within the last

decade 59% of all systems were of semi-mobile or semi-fixed type. Furthermore, it was found that the installed throughput capacity of all crusher station types increased during the last decades nevertheless they seem to reach their limits at around 12,000 t/h, 14,000 t/h and 9,000 t/h for fixed, semi-mobile or fully-mobile crusher stations. Additionally, it was found that with 32% in the last decade the transportation of overburden material by IPCC systems gains increasingly importance.

The random behaviour of SMIPCC system elements have a significant impact on the SMIPCC system capacity. They can be distinguished into capacity variation and disturbance variation. For each SMIPCC system element and their associated unit operations, adequate distributions have been defined based on available data from actual mining operations and literature in order to model their behaviour. As the capacity determining element, strong emphasis is given to the truck loading procedure of discontinuous loaders.
It was established that bucket payload and truck travel time can be sufficiently described by a normal distribution, while the bucket cycle time is better approximated by a gamma distribution. Additionally, it was shown that the truck payload and the truck loading time depend on the number of identically distributed bucket payloads, the truck payload policy and the loading methodology implemented at the mine. For both parameters distribution functions based on a single side loading method and full bucket policy were developed. Disturbance behaviour such as repair time and work time of SMIPCC system elements was found to be adequately represented by exponential distribution.

A time usage model specific for a simplified SMIPCC systems was developed based on TGL 32 - 778/01-15 which states all essential time components and structures the time components by their relation to each other. In this thesis, the factor system delay ratio is introduced, which enables accurate calculation of system-induced operating delays. Additionally, a simulation model was developed to quantify the system delay ratio while incorporating the complexity of the whole SMIPCC system, including the random behaviour of each system element and their interrelated dependencies.

The developed SMIPCC capacity calculation method is used in a case study to analyse the system behaviour based on a hypothetical mine with regards to time usage model components, system capacity and cost as a function of truck quantity and stockpile capacity. The major findings of the case study included the following:

- As expected, the annual capacity of a SMIPCC system increases as more trucks are introduced to the system. However, the increase of SMIPCC capacity shows diminishing marginal returns as the number of trucks in the system increases. Furthermore, the results indicate that annual SMIPCC capacity approaches a limit. In this particular case study, the limit of the annual SMIPCC system capacity was approximately 41.5 Mt/a.

- The progression of the cost per tonne curve of a SMIPCC system over an increasing number of trucks indicates two stages; one in which the cost per tonne decreases until they reach a minimum and one in which the cost per tonne increases. The positively sloped portion of the cost per tonne curve is directly attributable to the diminishing marginal returns of the annual SMIPCC system capacity. In this particular case study, the minimum cost per tonne of the SMIPCC system was found at 6 trucks and 0.69 $/t. The corresponding SMIPCC system capacity for that minimum was 35.6 Mt/a.
- As expected, the annual SMIPCC capacity increases as the mean repair time of the system elements decreases. However, in this particular case study for 6 trucks the reduction of the mean repair time of the continuous part of the SMIPCC system indicated the highest increase of SMIPCC system capacity. For example, by reducing the mean repair time of the continuous part of the SMIPCC system by 10% the annual capacity of the system increased by 3.6%, while for the same change of the mean repair time for the loader or the trucks the system capacity increases only by 1.4% and 1.1%, respectively.
- The introduction of a small stockpile in front of the crusher station increases the annual SMIPCC system capacity. The annual SMIPCC system capacity increases as the stockpile capacity increases. However, the SMIPCC system capacity shows diminishing marginal returns as the stockpile capacity increases. In this particular case study, an increase of the stockpile capacity from the base case (normal hopper capacity) of 725 t to 2,000 t indicated an increased SMIPCC system capacity of 4.0%, while an increase of the stockpile capacity from the base case capacity to a stockpile capacity of 18,000 t resulted in an increased system capacity of 14.3%.

  Correspondingly, the cost per tonne of the SMIPCC system decreases as the stockpile capacity increases. For example, by increasing the stockpile capacity from the base case capacity to a stockpile capacity of 18,000 t, the cost per tonne of the SMIPCC system is reduced by 0.046 $/t.
- The economic comparison of a conventional truck and shovel system compared to SMIPCC system revealed a significant cost difference between the two competing systems. In the annual system capacity range of 14 Mt/a to 38 Mt/a, the cost per tonne of the SMIPCC system was found to be 0.14 $/t to 0.22 $/t, lower than the truck and shovel system. The underlying assumption of the case study was that the truck travel time for the truck and shovel system increases by a factor of 2.5.

As an overall conclusion, it can be said that the accurate determination of annual SMIPCC system capacity is challenging due to the complexity of random system element behaviour and their associated interactions. However, the developed method provides an effective tool to account for these factors, and furthermore provides the option of directly comparing SMIPCC systems with conventional truck and shovel

systems. This method should certainly be applied for the projection of new SMIPCC systems, because the increased level of information provided can contribute valuable insight to the mining industry. A more precise estimation of achievable annual system capacity, an optimal number of trucks, and associated overall cost per tonne can be easily determined.

## 7.2 RECOMODATIONS FOR FURTHER REASEARCH

The presented work successfully fulfilled the research objective, which was to develop a structured method that allows the estimation of the annual capacity of SMIPCC systems under consideration of the random behaviour of system elements and their interaction. However, the boundaries of the developed method and the associated simulation model are focused on simplified SMIPCC systems. Therefore, an expansion of the method and associated simulation model, which incorporates heterogeneous truck fleets and multiple loaders, would pose an interesting challenge for future research and could be continued hereafter.

Additionally, future research can be focused on the further development of the current simulation model to incorporate the aspects highlighted in section 6.3.

Furthermore, an equivalent method could be developed that provides the same functions as the method presented in this thesis in order to cover the entire range of IPCC systems.

Finally, future research could be focused on the development of a model that includes the entire life of mine, in order to analyse the economic effects of investment costs when comparing SMIPCC systems to conventional truck and shovel systems.

# References


[1] H. Goergen, *Festgesteinstagebau*. Clausthal-Zellerfeld: Trans Tech Publ, 1987.

[2] M. Randolph, “Current Trends in Mining,” in *SME Mining Engineering Handbook*, 3rd ed., P. Darling, Ed. Society for Mining, Metallurgy, and Exploration, Inc. (SME), 2011, p. 15.

[3] C. Jamasmine, “Belaz launches world’s largest mining dump truck,” *Mining.com*, Oct-2013.

[4] G. Woodrow, “Benchmarks of performance for truck and loader fleets.,” in *Third Large Open Pit Mining Conference*, 1992.

[5] E. Bozorgebrahimi, “The Evaluation of Haulage Truck Size Effects on Open Pit Mining,” University of British Columbia, 2004.

[6] H. Lieberwirth, “Economic advantages of belt conveying in open-pit mining,” in *Mining Latin America / Minería Latinoamericana*, 1st ed., D. C. Bailey, Ed. Springer Netherlands, 1994, pp. 279–295.

[7] J. Fabian, “Cyclic mining systems in Czechoslovakian surface mines,” in *Proceedings of International symposium on Off-Highway Haulage in Surface Mines*, 1989, pp. 205–209.

[8] G. Mudd, “The Sustainability of Mining in Australia : Key Production Trends and Their Environmental Implications for the Future,” 2009.

[9] J. C. Lucio, C. T. Senra, and A. Souza, “Paving the future – a case study replacing truck-and shovels by shovel-and-conveyor continuous mining at Carajas open pit mines.,” in *Iron ore conference 2009*, 2009, no. July, pp. 269–276.

[10] R. M. Hays, “Mine Planning Considerations for In-Pit Crushing and Conveying Systems,” in *SME Mini Symposium*, 1983, pp. 33–41.

[11] E. M. Frizzell, “Mobile In-Pit Crushing - Product of Evolutionary Change,” *Trans. Am. Inst. Mining, Metall. Pet. Eng. Soc.*, vol. 278, no. June, pp. 578–580, 1985.

[12] B. H. Reupke, “Fully mobile in pit crushing and conveying system in ‘Werk Höver.’” Production manager Werk Höver, Holcim, Personal Communication, 2013.

[13] C. Drebenstedt and R. Ritter, “Cyclical and continuous method and in-put crushing operation,” *Gornyi Zhurnal*, no. 11, pp. 81–87, 2015.

[14] P. Darling, *SME mining engineering handbook*, vol. 2. Society for Mining, Metallurgy, and Exploration , 2011.

[15] E. Zimmermann and W. Kruse, “Mobile crushing and conveying in quarries-a chance for better and cheaper production!,” in *International Symposium Continuous Surface Mining 2006*, 2006, pp. 122–129.

[16] P. Moore, “In-Pit Crushing & Conveying – Insights from IPCC 2012,” *IM Int. Min.*, 2012.

[17] R. M. Hays, “Mine Planning Considerations for In-Pit Crushing and Conveying

Systems," 1983, pp. 33–41.

[18] D. Turnbull, "A Game Changer in Mining," *Bulk Solids Handling*, vol. 33, pp. 16–18, Nov-2013.

[19] J. Korak, "Technisch-wirtschaftliche Untersuchung der Transportbetriebsmittel unter besonderer Berücksichtigung der Transportmittelkombination Fahrbare Brechanlage-Gurtbandanlage für den transport der Haufwerke im engeren Festgesteins-Tagebau," TU Aachen, 1980.

[20] I. E. Hugo and R. Bunduwongese, "Mobile Crushing/Sizing Systems for Modern Open Cast Mining - A Case Study of Mae Moh Phase 5 Project, Thailand," in *Large Open Pit Conference*, 2007.

[21] D. Mac Phail, "The choice between in-pit crushing and conveying and conventional trucking at Valley Copper," in *The Planning and Operation of Open-Pit and Strip-Mines*, 1984.

[22] M. Johnson and J. Hoang, "Impacts of IPCC on Pit Shell Optimisation," in *International IPCC Conference*, 2014.

[23] D. G. Carmichael, *Engineering queues in construction and mining*. Ellis Horwood, 1987.

[24] J. Elbrond, "Calculation Of An Open Pit Operation's Capacity," in *SME Fall Meeting and Exhibit*, 1977.

[25] H. L. Hartman, Ed., *SME Mining Engineering Handbook*, no. Bd. 1. Colorado USA: Society for Mining, Metallurgy, and Exploration, 1992.

[26] J. G. Londono, P. Knights, and M. Kizil, "Review of In-pit Crusher Conveyor (IPCC) application," in *2012 Australian Mining Technology Conference*, 2012, pp. 63–82.

[27] R. A. Beatty and A. A. Bustos-Ramirez, "Dragline Modifications and Hopper Design Associated with the DHCC Method of Open Cut Stripping," in *Third International Conference on Bulk Materials, Storage, Handling and Transportation: Preprints of Papers*, 1989, p. 154.

[28] J. G. Londoño, P. F. Knights, and M. S. Kizil, "Modelling of In-Pit Crusher Conveyor alternatives," *Min. Technol.*, vol. 122, no. 4, pp. 193–199, Dec. 2013.

[29] Fortescue Metals Group, "Chichester Hub," 2015. [Online]. Available: http://www.fmgl.com.au/Our_Business/Chichester_Hub. [Accessed: 20-Feb-2015].

[30] Sandvik, "Fully-mobile crusher stations for mining operation right for quarry operation." 2013.

[31] KruppRobins, "Large Capacity Mobile Crushing Plants," 2014. [Online]. Available: http://www.krupprobins.com/images/Crushers/MobCrush-05.jpg.

[32] Joy Global, "Case Study How In-Pit Crusher Conveyor System Helps PRB Wyodak Coal Mine Sustain Efficient Power Generation," 2011.

[33] R. W. Utley, "In-Pit Crushing," in *SME Mining Engineering Handbook*, 3rd ed., P. Darling, Ed. Society for Mining, Metallurgy, and Exploration, 2011, pp. 941–957.

[34] R. D. Stoll, C. Niemann-Delius, C. Drebenstedt, and K. Müllensiefen, *Der Braunkohlentagebau: Bedeutung, Planung, Betrieb, Technik, Umwelt*. Springer, 2008.

[35] J. Plattner, “History and design of mobile in-pit crushers for open pit mines,” *Large Open Pit Mining Conference*. Australasian Institute of Mining & Metallurgy, Newman, Australia, pp. 17–21, 1986.

[36] S. J. Kirk, *Western Surface Coal Mining*. Gillette, 1989.

[37] P. Plattner, “Hopper size.” Lead Engineer, Sandvik, Personal Communication, 2012.

[38] Sandvik, “CR800 series hybrid,” 2014. [Online]. Available: http://mining.sandvik.com/sandvik//S003713.nsf/Alldocs/Products*5CCrushers*and*screens*5CRoll*crushers*2ACR810/$file/CR800_hybrid_low_res.pdf.

[39] FLSmidth, “EV hammer impact crusher,” 2014. [Online]. Available: http://www.flsmidth.com/~/media/Brochures/Brochures for crushers and raw material stores/EVHammerImpactCrusherlowres.ashx.

[40] FLSmidth, “Gyratory crushers,” 2014. [Online]. Available: http://www.flsmidth.com/~/media/PDF Files/Crushing/Gyratory Crusher/GyratoryCrusher_brochure.ashx.

[41] ThyssenKrupp, “Gyratory Crusher,” 2014. [Online]. Available: http://www.thyssenkrupp-industrial-solutions.com/fileadmin/documents/brochures/kreiselbrecher_en.pdf.

[42] Pennsylvania and Crusher, “Handbook of Crushing,” 2003. [Online]. Available: https://eva.fing.edu.uy/pluginfile.php/64897/mod_folder/content/0/handbook_of_crushing.pdf?forcedownload=1.

[43] MMD, “MMD SIZERS,” 2014. [Online]. Available: http://www.mmdsizers.com/downloads/MMD_P_A_3_English.pdf.

[44] FLSmidth, “TST jaw crusher,” 2014. [Online]. Available: http://www.flsmidth.com/~/media/PDF Files/Crushing/FLSmidth_TST_JawCrusher_brochure.ashx.

[45] K. Boyd and R. W. Utley, *Mineral Processing Plant Design, Practice, and Control Proceedings*, no. Bd. 1. Society for Mining, Metallurgy, and Exploration, 2002.

[46] F. Habashi, “A short history of mineral processing,” *Proc. XXIII Int. Miner. Process. …*, 2006.

[47] M. Harcus, “Crusher Time,” *Mining Magazine*, London, pp. 48–57, Apr-2011.

[48] Scheuerle, “Self-Propelled Modular Transporters,” 2013. [Online]. Available: http://www.scheuerle.de/en/home/press/article/print.html.

[49] F. Foti, “TII ,” *IPCC 2013*. Cologne, 2013.

[50] K. Strzodka, *Tagebautechnik. 2*, vol. 2. Dt. Verlag für Grundstoffindustrie, 1980.

[51] A. Kesimal, “Different Types of Belt Conveyors and Their Applications in Surface Mines,” *Miner. Resour. Eng.*, vol. 6, no. 04, pp. 195–219, 1997.

[52] K. J. Benecke and R. S. Shehata, “Application criteria for conveyors in hard rock mining: the system crusher—conveyor—spreader (November 7–8, 1985) Mining Equipment Selection Symp,” *Krupp Ind. GmbH, West Ger. CANMET, UK*, pp. 1–25, 1985.

[53] E. Bahke, “New developments of belt conveyor systems,” *ZKG Int.*, vol. 45, no. 3, pp. 121–130, 1992.

[54] FAM, “Belt wagons,” 2014. [Online]. Available: http://www2.fam.de/english/Products/Opencast mining systems/Belt wagons/index.html.

[55] TNT, “Convetional horizontal conveyor,” 2014. [Online]. Available: http://www.tntinc.com/grasshopperhorizontalconveyor.html.

[56] Takraf, “Mobile transfer Conveyors,” 2014. [Online]. Available: http://www.takraf.com/en/Products/Mining_Equipments/mobiletransferconveyor.htm.

[57] Sandvik, “Sandvik offering guide 2013-14.” Sandvik, 2014.

[58] J. Kempas, “Application of mobile primary crushing and belt conveying systems for Iron Ore mining,” *Australas. Inst. Min. Metall. Publ. Ser.*, no. August, pp. 311–317, 2007.

[59] G. Grant M., “ADVANCEMENT OF MOBILE CONVEYING SOLUTIONS FOR IPCC AND WASTE HANDLING OPERATIONS ,” *IPCC 2013*. Cologne, 2013.

[60] Metso, “Nordberg mobile conveyors,” 2014. [Online]. Available: http://www.metso.com/miningandconstruction/mm_conv.nsf. [Accessed: 12-Feb-2014].

[61] Maats, “Trackshifting Dozer.” [Online]. Available: http://www.maats.com/various/liebherr-conveyor-shifters/liebherr-rl-64-conveyor-belt-shifter. [Accessed: 24-Apr-2014].

[62] FAM, “Drive Station,” 2014. [Online]. Available: http://www.fam.de/www.fam.de/english/Products/Conveying/html. [Accessed: 12-Feb-2014].

[63] KruppRobins, “Shiftable Conveyors.” [Online]. Available: http://www.krupprobins.com/Products/Mining Equipment/shiftableconveyors.html. [Accessed: 21-Mar-2014].

[64] J. A. Dos Santos, “Sandwich Belt High Angle Conveyor Applications in Open-Pit Mining,” no. October 1983, 1985.

[65] J. Dos Santos, “High Angle Conveyors-HAC’s from Mine to Prep Plant and Beyond,” *Bulk Solids Handl.*, vol. 13, p. 303, 1993.

[66] E. Sheshko and A. Kutenkov, “Substantiation of parameters high angle conveyor with boards and partitions at large productivity in open cast mines,” *Transp. i logistika*, 2001.

[67] T. Ziller and P. Hartlieb, *Fördergurte in der Praxis: Know How und Know Why ; Fördergurt Herstellung, Montage und Verbindungstechnik, Inspektion, Wartung und Instandsetzung, Maschinen, Hilfs- und Prüfmittel, Wirtschaftlichkeit und Kostenkontrolle, Ressourcenschonung und Umweltschut*. VGE-Verlag, 2010.

[68] J. Weissflog, “Shiftable Belt Conveyor Systems in Open Pit Mining,” *SME-AIME Fall Meeting and Exhibit*. SME, Utah, USA, 1983.

[69] K. Strzodka, *Tagebautechnik. 2*, vol. 2. Dt. Verlag für Grundstoffindustrie, 1980.

[70] B. Küsel, “St 10,000 – a new development in high-tension conveyor belt design,” *Aust. Bulk Handl. Rev.*, 2012.

[71] R. Summerford, “Mechanical Splicing vs Vulcanisating,” *World Coal*, 2009.

[72] G. N. Kunze, H. G. Hring, and K. Jacob, *Baumaschinen: Erdbau- Und Tagebaumaschinen*, no. Bd. 10. Vieweg+Teubner Verlag, 2002.

[73] P. Plattner, “Spreader Design.” Lead Engineer, Sandvik, Personal Communication, 2014.

[74] Takraf, “Bandabsetzer,” 2014. [Online]. Available: http://www.takraf.com/de/produkte/Tagebauanlagen/Bandabsetzer.htm. [Accessed: 12-Feb-2014].

[75] FAM, “Absetzer auf Raupen,” 2014. [Online]. Available: http://www.fam.de/deutsch/Produkte/Tagebautechnik/Absetzer%2520auf%2520Raupen/index.html. [Accessed: 12-Feb-2014].

[76] ThyssenKrupp, “Spreader References.” ThyssenKrupp Fördertechnik GmbH, 2012.

[77] J. F. Rodenberg, S. . R. Winzer, and D. J. Nordin, “Direct dumping mining systems – Application and economics,” *Int. J. Surf. Mining, Reclam. Environ.*, vol. 2, no. 4, pp. 193–208, Jan. 1988.

[78] FLSmidth, “Mobile Stacking Conveyor,” 2014. [Online]. Available: http://www.flsmidth.com/en-us/Industries/Categories/Products/Material+Handling/Belt+Conveying/MobileConveyorSystems/MobileStackingConveyors. [Accessed: 12-Feb-2014].

[79] FAM, “Stacker,” 2014. [Online]. Available: http://www.fam.de/english/Products/Stockyard%2520systems/Stackers/index.html. [Accessed: 12-Feb-2014].

[80] ThyssenKrupp, “ThyssenKrupp Robins - References,” 2013. [Online]. Available: http://www.thyssenkrupprobins.com/References/Stackers/stackers.html. [Accessed: 12-Feb-2014].

[81] TNT, “Mobile stacking systems,” 2014. [Online]. Available: http://www.tntinc.com/mobilestackingsystemsvideo.html. [Accessed: 12-Feb-2014].

[82] FLSmidth, “Mobile Bridge Boom Stacker,” 2014. [Online]. Available: http://www.flsmidth.com/en-US/Industries/Categories/Products/Material+Handling/Tailings+Waste+Stacking+Systems/MobileBridgeBoomStacker. [Accessed: 12-Feb-2014].

[83] FAM, “Stacker reclaimers,” 2014. [Online]. Available: http://stacker-reclaimer.fam.de/. [Accessed: 12-Feb-2014].

[84] TAKRAF, “Stacker/Reclaimer,” 2014. [Online]. Available: http://www.takraf.com/en/products/yardequipment/stacker_reclaimer.htm.

[Accessed: 12-Feb-2014].

[85] Liebherr, “Stacker / Reclaimer machines,” 2014. [Online]. Available: http://www.liebherr.com/CP/en-GB/products_cp.wfw/id-18224-0. [Accessed: 12-Feb-2014].

[86] TAKRAF, “Stacker / Reclaimers,” 2014. [Online]. Available: http://www.tenovagroup.com/stacker_reclaimers.php. [Accessed: 12-Feb-2014].

[87] H. G. Kok, “Use of Mobile Crushers in the Minerals Industry,” *T 272, ME Nov*, vol. 1584, 1982.

[88] D. Wood, W. H. Bryan, and S. of E. Geologists, “Crucial Challenges to Discovery and Mining – Tomorrow’s Deeper Ore Bodies ,” 2012.

[89] G. J. Klir, *Trends in general systems theory*. John Wiley & Sons Canada, Limited, 1972.

[90] D. König, J. Sajkiewicz, and D. Stoyan, *Leistungsberechnung für Fördersysteme*. Leipzig: Deutscher Verlag für Grundstoffindustrie, 1985.

[91] J. Sajkiewicz, “Application of numerical symbols for determination of technically possible work states for machinery system,” *Exploit. Probl. Mach.*, vol. 10, no. 22, pp. 219–236, 1975.

[92] G. Gruschka and H. Stoyan, “Planungsmodelle für ein Grubenbetrieb mit Bandförderung und Parallelabbau,” *Neue Bergbautechnik*, vol. 3, no. 5, pp. 174–177, 1975.

[93] Y. Xi and T. Yegulalp, “Reliability-based capacity determination of a bucket wheel excavator system in Yuabaoshan Surface Coal Mine,” *Soc. Min. Eng. AIME*, vol. 294, pp. 1953–1959, 1994.

[94] P. Ryder, “Developments in the design, planning and operation of underground conveyor coal belt clearance,” *Oper. Res. und Datenverarbeitung im Bergbau*, no. 4, p. Y–I1–YI14, 1975.

[95] K. Talbot, “Simulation of conveyor belt networks in coal mines,” in *15th International Symposium APCOM*, 1977, pp. 297–304.

[96] J. M. Czaplicki, *Shovel-Truck Systems: Modelling, Analysis and Calculations*. Taylor & Francis, 2008.

[97] S. Deshmukh, *Sizing of Fleets in Open Pits*, XXII. American Institute of Mining, Metallurgical and petroleum Engineers, 1970.

[98] E. Koenigsberg, “Cyclic Queues,” *Oper. Res.*, vol. 9, no. 1, pp. pp. 22–35, 1958.

[99] M. J. Maher and J. G. Cabrera, “The transident behavior of cyclic queue,” *Oper. Reasearch Q.*, vol. 24, no. 4, pp. 32–41, 1973.

[100] M. J. Maher and J. G. Cabrera, “A multi-stage cyclic queueing model,” *Int. J. Prod. Res.*, vol. 13, no. 3^603–613, 1975.

[101] P. K. Muduli, “Modeling truck-shovel systems as multiple-chain closed queuing networks,” Columbia University, 1997.

[102] J. M. Czaplicki, “The analysis and calculation procedure for shovel-truck systems with crusher and conveyor,” *Gospod. Surowcami Miner.*, vol. 24, no. 4/3, 2008.

[103] P. Morriss, “Key Production Drivers in In-Pit Crushing and Conveying (IPCC) Studies,” *South. African Inst. Min. Metall.*, p. 33, 2008.

[104] S. Peng, D. Zhang, and Y. Xi, “Computer simulation of a semi-continuous open-pit mine haulage system,” *Int. J. Min. Geol. Eng. Int. J. Min. Geol. Eng.*, vol. 6, no. 3, pp. 267–271, Oct. 1988.

[105] B. Kolonja, R. Stanić, and J. Hamović, “Simulation of mine material handling systems using AutoMod,” *Transp. i logistika*, 2001.

[106] M. C. Albrecht, “Equipment sizing of a material handling system using discrete event simulation,” in *Application of Computers and Operations Research in the Mineral Industry*, Taylor & Francis, 2005, pp. 449–455.

[107] J. Zhang and Q. Wang, “A Queuing Network Model for Shovel-Truck-Crusher Systems in Open-pit Mining,” in *Proceedings of Application of Computers and Operations Research in the Mineral Industry Conference 2009*, 2009.

[108] R. Todt, “Analyse von Zugmangelzeiten, die durch gegenseitige Beeinflussung der Betriebsabschnitte Gewinnung, Förderung und Verkippung in Abraumabteilungen von Tagebauen mit Zugförderung entstehen,” Dissertation, Technische Universität Bergakademie Freiberg, 1964.

[109] B. Kahn, “Untersuchung zur Anwendung der Technologie der kombinierten Zug-Band-Förderung in Abraumbetrieben von Braunkohlentagebauen Unter bes. Berücks. d. stationären Kippgrabens als Massenspeicher,” [s.n.], Freiberg, 1966.

[110] R. J. Barnes, M. S. King, and T. B. Johnson, “Probability Techniques For Analyzing Open Pit Production Systems,” in *Proceedings of the 16th APCOM*, 1979, pp. 462–476.

[111] N. R. Billette, “Haulage System Capacity: Analytical and Simulation Models Revisited,” in *19th International Symposium 1986 - Application of Computers and Operations Research*, 1986, pp. 355–364.

[112] D. C. Montgomery, *Applied Statistics and Probability for Engineers 6th edition:* 2013.

[113] C. Burt and L. Caccetta, “Equipment Selection for Surface Mining: A Review,” *Interfaces (Providence).*, vol. 44, no. 2, pp. 143–162, 2014.

[114] R. J. Hardy, “Selection Criteria For Loading and Hauling Equipment - Open Pit Mining Applications,” Western Australian School of Mines, 2007.

[115] G. Kühn, “Über die Ausnutzung der Universalbagger,” *Fördern und Heb.*, vol. 1, no. 5, pp. 16–21, 1955.

[116] M. Osanloo, “Prediction of Shovel Productivity in the Gol-e-Gohar Iron Mine,” *J. Min. Sci.*, vol. 41, no. 2, pp. 177–184, 2005.

[117] S. P. Singh and R. Narendrula, “Factors affecting the productivity of loaders in surface mines,” *Int. J. Mining, Reclam. Environ.*, vol. 20, no. 1, pp. 20–32, Mar. 2006.

[118] J. Walenzyk, “Application Engineer, Komatsu Mining Germany GmbH - Excavator productivity.” Düsseldorf, 2014.

[119] H. Härtig, R. Ciesielski, K. Strzodka, and R. Steinmetz, *Grundlagen für die Berechnung von Tagebauen. Braunkohle, Kiessand, Ton, Naturstein*, 3.Edition ed. Leipzig: Deutscher Verlag für Grundstoffindustrie, 1982.

[120] Harnischfeger, “Peak Performance Practices.” P&H Mining Equipment, Milwaukee, Wisconsin USA, 2003.

[121] W. Schwate, “Beitrag zur optimalen gestalltung der Gewinnung in Festgesteinstagebauen unter besonderer Berücksichtigung der gleislosen diskontinuierlichen Förderung,” TU Freiberg, 1976.

[122] K. Awuah-Offei, B. Osei, and H. Askari-Nasab, “Modeling Truck-Shovel Energy Efficiency under Uncertainty,” in *Transactions for the Society for Mining, Metallurgy, and Exploration, Inc. Volume 330*, 2011, pp. 573–585.

[123] C. Rowlands and G. D. Just, “Performance Characteristics of Dragline Buckets,” in *Third Large Open Pit Mintng Conference*, 1992, no. September, pp. 89–92.

[124] E. K. Chanda and R. J. Hardy, “Selection Criteria for Open Pit Production Equipment – Payload Distributions and the ‘10/10/20’ Policy,” in *35th APCOM Symposium 2011*, 2011, no. September, pp. 24–30.

[125] P. Knights and S. Paton, “Payload variance effects on truck bunching,” in *Seventh Large Open Pit Mining Conference*, 2010, no. July, pp. 27–28.

[126] Caterpillar, “Caterpillar Quarry and Construction Truck 10/10/20 Payload Managment Guidelines,” Peoria, USA, 2008.

[127] P&H, “Electric Mining Shovels - Product Overview,” 2014. [Online]. Available: http://www.phmining.com/MinePro/Literature/Brochures/EN-EMS01_brochure.pdf. [Accessed: 23-Oct-2014].

[128] Komatsu, “960E-1K,” 2014. [Online]. Available: http://www.komatsu.com/ce/products/pdfs/KAC_960E-1K.pdf. [Accessed: 23-Oct-2014].

[129] R. W. Barbaro, “Evaluating the productivity of a shovel-truck materials haulage system using a cyclic queueing model,” in *AIME Transactions Volume*, 1988, vol. 44, no. 2.

[130] J. Maran and E. Topuz, “Simulation of truck haulage systems in surface mines,” *Int. J. Surf. Mining, Reclam. Environ.*, vol. 2, no. 1, pp. 43–49, Jan. 1988.

[131] W. C. Morgan and L. Peterson, “Determining shovel-truck productivity,” *Min. Eng.*, vol. 20, no. 12, pp. 76–80, 1968.

[132] N. K. Nanda, “Optimizing of mine production system through operation research techniques,” in *19th Mining Congress*, 2003, pp. 583–596.

[133] G. N. Panagiotou, “Optimizing the shovel-truck operation using simulation and queueing models,” in *Proceedings of the Second International Symposium on Mine Mechanization and Automation, Lulea, Sweden*, 1993.

[134] Y. Lizotte, E. Bonates, and A. Leclerc, “Analysis of truck dispatching with dynamic heuristic procedures,” in *International Symposium on Off-highway*

*haulage in surface mines*, 1989, pp. 47–55.

[135] J. Szymanski, R. Suglo, S. Planeta, and J. Paraszczak, “Simulation analysis model of mining methods,” in *Thirteenth International Symposium on Mine Planning and Equipment Selection*, 2004, pp. 613–618.

[136] Y. Lizotte and E. Bonates, “Truck and shovel dispatching rules assessment using simulation,” *Min. Sci. Technol.*, vol. 5, no. 1, pp. 45–58, May 1987.

[137] G. Griffin, “Permutation theory applied to truck-shovel system simulation,” in *Off-Highway Haulage in Surface Mines*, 1989, pp. 83–87.

[138] L. Zhongzhou, L. Qining, and R. Singhal, “Erlangian cyclic queueing model for shovel-truck haulage systems,” in *Mine Planning and Equipment Selection*, 1988, pp. 423–428.

[139] B. Knights, M. Kizil, and W. Seib, “Truck-shovel fleet cycle optimisation using GPS collision avoidance system,” in *12th Coal Operators’ Conference*, 2012, pp. 361–370.

[140] D. Scheffler and W. Kunze, “Beitrag zur Kapazitätseinschätzung des Kalksteintagebaus Karsdorf,” *Neue Bergbautechnik*, vol. 2, no. 7, pp. 486–492, 1972.

[141] G. Lumley, “Reducing the Variability in Dragline Operator Performance,” in *Coal Operators’ Conference*, 2005, pp. 97–106.

[142] D. Stoyan, “Truck loading time modeled as inverse Gaussian distribution.” Freiberg, 2014.

[143] Q. Wang, Y. Zhang, C. Chen, and W. Xu, “Probability distribution of key time parameters in open-pit mine truck dispatching,” *J. China Coal Soc.*, vol. 31, no. 6, pp. 761–764, 2006.

[144] R. A. Carter, “Cat Refines, Expands Rope Shovel Feature Lineup,” *Engineering and Mining Journal*, 2014.

[145] Tasman Asia Pacific, “Benchmarking the productivity of Australia’s black coal industry,” 1998. .

[146] V. I. Rotar, *Probability and Stochastic Modeling*. Taylor & Francis, 2012.

[147] D. Stoyan and H. Stoyan, *Mathematische Methoden in der Operationsforschung: Fördertechnik, Bergbau, Transportwesen*. Deutscher Verlag für Grundstoffindustrie, 1971.

[148] K. Awuah-Offei, B. A. Osei, and H. Askari-Nasab, “Improving Truck-Shovel Energy Efficiency Through Discrete Event Modeling,” in *SME Annual Meeting*, 2012, p. Preprint 12–069.

[149] D. Gove and W. Morgan, “Optimizing truck-loader matching,” *Int. J. Rock Mech. Min. Sci. Geomech.*, vol. 32, no. 3, 1995.

[150] R. M. Hays, *Surface Mining*. Littleton CO USA: Society for Mining, Metallurgy, and Exploration, 1990.

[151] Caterpillar, *Caterpillar Performance Handbook 42*, 42nd ed. Peoria, USA: Caterpillar Inc., 2012.

[152] S. Gladysz, “Störprozesse in technologischen Systemen der Tagebaue,” *Wegiel brunatny*, no. 1, pp. S.62–74, 1964.

[153] A. Bovas and L. Johannes, *Statistical Methods for Forecasting*. New York: Wiley, 1983.

[154] R. a. Hall and L. K. Daneshmend, “Reliability Modelling of Surface Mining Equipment: Data Gathering and Analysis Methodologies,” *Int. J. Surf. Mining, Reclam. Environ.*, vol. 17, no. 3, pp. 139–155, Sep. 2003.

[155] V. A. Temeng, “Probabilistic analysis of reliability and effectiveness of elementary shovel-truck system at Nchanga Open-pit,” University of Zambia, 1988.

[156] G. Sharma, T. Haukaas, R. a. Hall, and S. Priyadarshini, “Bayesian statistics and production reliability assessments for mining operations,” *Int. J. Mining, Reclam. Environ.*, vol. 23, no. 3, pp. 180–205, Sep. 2009.

[157] S. Elevli, N. Uzgoren, and M. Taksuk, “Maintainability analysis of mechanical systems of electric cable shovels,” *J. Sci. …*, 2008.

[158] R. Hall, “Analysis of Mobile Equipment Maintenance Data In an Underground Mine,” 1997.

[159] F. Simon, B. Javad, and B. Abbas, “Availability analysis of the main conveyor in the Svea Coal Mine in Norway,” *Int. J. Min. Sci. Technol.*, vol. 24, no. 5, pp. 587–591, Sep. 2014.

[160] J. Barabady and U. Kumar, “Reliability analysis of mining equipment: A case study of a crushing plant at Jajarm Bauxite Mine in Iran,” *Reliab. Eng. Syst. Saf.*, vol. 93, no. 4, pp. 647–653, Apr. 2008.

[161] E. Bozorgebrahimi, “The evaluation of haulage truck size effects on open pit mining,” University of British Columbia, 2004.

[162] R. Pascual, R. Madariaga, G. Santelices, D. Godoy, and E. L. Droguett, “A structured methodology to optimise throughput of production lines,” *Int. J. Mining, Reclam. Environ.*, pp. 1–12, Sep. 2014.

[163] J. G. Londono, “Systems modelling of parallel conveyors in IPCC systems,” The University of Queensland, 2012.

[164] J. M. Czaplicki, *Statistics for Mining Engineering*. Leiden: CRC Press/Balkema, 2014.

[165] J. Sajkiewicz, “Theory der Fördersysteme,” Wrocław, 1980.

[166] CIM, “CIM Mining Standards and Guidelines Committee,” 2012.

[167] Z. Lukacs, “Standard definitions for the benchmarking of availability and utilization of equipment,” 2014.

[168] P. Morriss, “Key Production Drivers in in-Pit Crushing and Conveying (Ipcc) Studies,” *South. African Inst. Min. Metall.*, p. 33, 2008.

[169] P. F. Knights and P. Oyanader, “Best-in-class maintenance benchmarks in Chilean open pit mines,” *CIM Bull.*, vol. 98, no. 1088, p. 93, 2005.

[170] Xstrata, “XCN BD GDL 0027 TIME MODEL – NOMENCLATURE AND KEY PERFORMANCE INDICATORS.” Xstrata Coal, p. 28, 2014.

[171] M. Dalryple, “Personal Comunication: Time usage model Rio Tinto.” 2014.

[172] TGL 32 - 778/01-15, *Begriffe für den Tagebau. Gliederung der Kalenderzeit für Tagebaugeräte*. GDR, 1983.

[173] Z. Pan, “Personal Comunication with maintenance manager: Downtime due to bad weather at Zhahanaoer Mine - Houlinhe coal mine company.” 2013.

[174] C. Hu, “Personal Comunication with maintenance manager: Downtimes at Yiminhe Coal Mine -Huaneng Yimin Coal Electricity Corp.” 2013.

[175] P. D. Tomlingson, *Mine Maintenance Management Reader*. Society for Mining, Metallurgy, and Exploration, 2007.

[176] B. S. Dhillon, *Mining Equipment Reliability, Maintainability, and Safety*, vol. null. 2008.

[177] P. D. Tomlingson, *Equipment Management: Key to Equipment Reliability and Productivity in Mining*. Society for Minig, Metallurgy, and Exploration, 2009.

[178] M. Gellrich, “Personal Comunication: Maintenance intervalls BWE system at Vattenfall.” 2014.

[179] D. P. Tripathy, “Effective maintenance Practices for Mining Equipments,” 2011.

[180] R. Ritter, A. Herzog, and C. Drebenstedt, “Automated Dozer Concept Aims to Cut IPCC Downtime,” *Engineering & Mining Journal*, Jacksonville, pp. 56–59, Nov-2016.

[181] R. Ritter, “Reliability and Capacity Planning of Fully Mobile IPCC Systems,” in *International IPCC Conference*, 2014.

[182] C. H. Ta, A. Ingolfsson, and J. Doucette, “A linear model for surface mining haul truck allocation incorporating shovel idle probabilities,” *Eur. J. Oper. Res.*, vol. 231, no. 3, pp. 770–778, 2013.

[183] B. V. Gnedenko, Y. K. Belayev, and A. D. Solovyev, *Mathematical methods of reliability theory*. New York: Academic Press, 1969.

[184] H. Daduna, R. Krenzler, R. Ritter, and D. Stoyan, “Heuristic Approximations for Closed Networks : A Case Study in Open-pit Mining,” *Vor. auf arXiv.org*, pp. 1–41, 2016.

[185] F. Soumis, J. Ethier, and J. Elbrond, “Truck dispatching in an open pit mine,” *Int. J. Surf. Mining, Reclam. Environ.*, vol. 3, no. 2, pp. 115–119, 1989.

[186] D. Elizandro and H. Taha, *Performance Evaluation of Industrial Systems: Discrete Event Simulation in Using Excel/VBA, Second Edition*. Taylor & Francis, 2012.

[187] *Mine and Mill Equipment Costs*. Washington: InfoMine USA, Inc., 2015.

[188] S. N. Chiu, D. Stoyan, W. S. Kendall, and J. Mecke, *Stochastic Geometry and Its Applications*. Wiley, 2013.

# Appendices

## List of Appendices

# Appendix I - List of IPCC Systems

*Table A-I Global list of IPCC systems*

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sentinel Mine (No.3) | Kalumbila Minerals Ldt. (First Quantum Minerals) | Zambia | Africa | Copper | Copper | Gyratory crusher | Direct feeding' | - | n.a. | Semi-mobile / Semi fix | - | 2014 | 3,600 | Thyssen Krupp | - |
| - | TPI Cement | Thailand | Central Asia | Limestone | Industrial/mass commodities | Impact crusher | - | - | - | Fully-mobile | - | 2014 | 600 | Metso | - |
| MLMR (No.1) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2013 | 14,000 | Thyssen Krupp | - |
| MLMR (No.2) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2013 | 14,000 | Thyssen Krupp | - |
| S11D (No.1) | Vale | Brazil | South America | Iron | Overburden | Hybrid crusher | Apron feeder | Crawler- tracks | - | Fully-mobile | -- | 2013 | 11,500 | Sandvik | - |
| S11D (No.2) | Vale | Brazil | South America | Iron | Overburden | Hybrid crusher | Apron feeder | Crawler tracks | - | Fully-mobile | -- | 2013 | 11,500 | Sandvik | - |
| S11D (No.3) | Vale | Brazil | South America | Iron | Overburden | Hybrid crusher | Apron feeder | Crawler tracks | - | Fully-mobile | -- | 2013 | 11,500 | Sandvik | - |
| S11D (No.4) | Vale | Brazil | South America | Iron | Overburden | Hybrid crusher | Apron feeder | Crawler tracks | - | Fully-mobile | -- | 2013 | 11,500 | Sandvik | - |
| Cape Preston Mine (No.3) | Sino Iron CITIC Pacific | Australia | Australasia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2013 | 4,250 | Thyssen Krupp | - |
| Cape Preston Mine (No.4) | Sino Iron CITIC Pacific | Australia | Australasia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2013 | 4,250 | Thyssen Krupp | - |
| Sentinel Mine (No.1) | Kalumbila Minerals Ldt. (First Quantum Minerals) | Zambia | Africa | Copper | Copper | Gyratory crusher | Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2013 | 3,600 | Thyssen Krupp | - |
| Sentinel Mine (No.2) | Kalumbila Minerals Ldt. (First Quantum Minerals) | Zambia | Africa | Copper | Copper | Gyratory crusher | Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2013 | 3,600 | Thyssen Krupp | - |
| Mina Ministro Hales Plant | Corporacion Nacional del Cobre de Chile | Chile | South America | Copper | Copper | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2013 | 4,500 | Thyssen Krupp | - |
| Datang Mine (No.1) | Antofagasta | China | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2013 | 9,000 | Thyssen Krupp | - |
| Datang Mine (No.2) | and | China | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2013 | 9,000 | Thyssen Krupp | - |
| Datang Mine (No.3) | Pan Pacific Copper | China | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2013 | 9,000 | Thyssen Krupp | - |
| Baiyinhua No.2 Coal Mine (No.3) | China Power Complete Equipment Co. Ltd. | China | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2013 | 6,000 | Thyssen Krupp | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baiyinhua No.2 Coal Mine (No.2) | China Power Complete Equipment Co. Ltd. | China | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2013 | 6,000 | Thyssen Krupp | - |
| Angren -I | UsbekCoal | Uzbekistan | CIS | Coal | Overburden | Double roll crusher | Apron feeder | Crawler tracks | - | Fully-mobile | -- | 2013 | 5,250 | FAM | - |
| Angren -II | UsbekCoal | Uzbekistan | CIS | Coal | Overburden | Double roll crusher | Apron feeder | Crawler tracks | - | Fully-mobile | - | 2013 | 5,250 | FAM | - |
| - | TBEA | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | - | 2013 | 3,000 | Hazemag | 730 |
| Datang | Inner Mongolia Datang International Xilinhot Mining Co. | China | Central Asia | Coal | Overburden | Hybrid crusher | apron feeder | - | - | Semi-mobile / Semi fix | - | 2013 | 4,500 | Sandvik | - |
| Baiyinhua No.2 Coal Mine (No.4) | China Power Complete Equipment Co. Ltd. | China | Central Asia | Coal | Coal | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2013 | 3,000 | Thyssen Krupp | - |
| - | Altai Polymet | Kazakstan | CIS | Copper | Copper | Jaw crusher | - | - | - | Fully-mobile | - | 2013 | 2,500 | Metso | - |
| - | Boral | Australia | Australasia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2013 | 1,150 | Metso | - |
| Samarco 3 | Vale/BHP | Brazil | South America | Iron | Iron ore | Jaw crusher | - | Crawler tracks | - | Fully-mobile | - | 2013 | 800 | Metso | - |
| Samarco 4 | Vale/BHP | Brazil | South America | Iron | Iron ore | Jaw crusher | - | Crawler tracks | - | Fully-mobile | - | 2013 | 800 | Metso | - |
| Angren -III | UsbekCoal | Uzbekistan | CIS | Coal | Coal | Double roll crusher | Apron feeder | Crawler tracks | - | Fully-mobile | -- | 2013 | 800 | FAM | - |
| - | TPI Cement | Thailand | Central Asia | Limestone | Industrial/mass commodities | Impact crusher | - | - | - | Fully-mobile | - | 2013 | 600 | Metso | - |
| Baiyinhua No.2 Coal Mine (No.1) | China Power Complete Equipment Co. Ltd. | China | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2012 | 6,000 | Thyssen Krupp | - |
| Lomas Bayas | | Chile | South America | Copper | Copper | Gyratory crusher | - | - | - | Fix | - | 2012 | 3,000 | TAKRAF | - |
| Kearl (No.1) | Imperial Oil | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2012 | 14,000 | Thyssen Krupp | - |
| Cemento Apodi | Companiha Industrial De Cimento Apodi | Brazil | South America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2012 | 850 | Thyssen Krupp | - |
| Bunge Pant | Nordkalk | Sweden | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2012 | 1,200 | Thyssen Krupp | - |
| Roy Hill | Roy Hill mine | Australia | Australasia | Iron | Iron ore | Jaw crusher | | - | - | Semi-mobile / Semi fix | - | 2012 | 5,600 | TAKRAF | - |
| Carajas N4E (No.2) | Vale | Brazil | South America | Iron | Overburden | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2012 | 3,900 | Thyssen Krupp | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cape Preston Mine (No.2) | Sino Iron CITIC Pacific | Australia | Australasia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2012 | 4,250 | Thyssen Krupp | - |
| TATA Steel DSO Timmins | TATA Steel Minerals Canada Ltd. | Canada | North America | Iron | Iron ore | Hybrid crusher | apron feeder | - | - | Semi-mobile / Semi fix | - | 2012 | 1,200 | Sandvik | - |
| Tanggang Sijiaying Iron Ore Mine (No.3) | Sinotrans Tangshan International Trade Co. Ltd. | China | Central Asia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2012 | 2,000 | Thyssen Krupp | - |
| Tanggang Sijiaying Iron Ore Mine (No.4) | Sinotrans Tangshan International Trade Co. Ltd. | China | Central Asia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | | 2012 | 2,000 | Thyssen Krupp | - |
| Yuanjiacun Iron Ore Mine | Taigang Group International Trade Co. (TISCO) | China | Central Asia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | | 2012 | 4,500 | Thyssen Krupp | - |
| Jianshan Iron Ore Mine | Codelco | China | Central Asia | Iron | Overburden | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | | 2012 | 6,000 | Thyssen Krupp | - |
| Carajas N4E (No.1) | Vale | Brazil | South America | Iron | Overburden | Double roll crusher | Apron feeder | - | -- | Fully-mobile | | 2012 | 3,900 | Thyssen Krupp | - |
| - | Gacko Abraum | Bosnia-Herzegovina | Europe | Coal | Overburden | Feeder breaker | - | - | - | Semi-mobile / Semi fix | | 2012 | 2,000 | Hazemag | 730 |
| | Ugljevik | Bosnia-Herzegovina | Europe | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | | 2012 | 800 | Hazemag | 315 |
| Carajas Mine N4E (No.1) | Vale | Brazil | South America | Iron | Iron ore | Hybrid crusher | Apron feeder | Crawler tracks | - | Fully-mobile | - | 2012 | 3,000 | Sandvik | - |
| Carajas Mine N4E (No.2) | Vale | Brazil | South America | Iron | Iron ore | Hybrid crusher | Apron feeder | Crawler tracks | - | Fully-mobile | - | 2012 | 3,000 | Sandvik | - |
| - | Freeport TFM Mine | Congo Republic | Africa | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | | 2012 | 800 | Metso | - |
| - | Marocca | Italy | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | | 2012 | 800 | Metso | - |
| - | Lafarge | Poland | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | | 2012 | 800 | Metso | - |
| - | TPI Cement | Thailand | Central Asia | Limestone | Industrial/mass commodities | Impact crusher | - | - | - | Fully-mobile | | 2012 | 600 | Metso | - |
| BSM-V Carajas | Vale | Brazil | South America | Iron | Iron ore | Jaw crusher | apron feeder | - | - | Fully-mobile | | 2011 | 10,400 | Sandvik | - |
| Brocemi Works | Cemex | Latvia | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | | 2011 | 600 | Thyssen Krupp | - |
| Ras Baridi Works | Yanubu Cement Co. | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | | 2011 | 1,600 | Thyssen Krupp | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Khao Wong Plant | Siam Cement Co. | Thailand | Central Asia | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | | 2011 | 2,500 | Thyssen Krupp | - |
| Shurovo Works | Shurovko Cement OJSC | Russia | CIS | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | | 2011 | 1,400 | Thyssen Krupp | - |
| Bloom Lake (No2) | Cliffs Natural Resources | Canada | North America | Iron | Iron ore | Gyratory crusher | | - | - | Semi-mobile / Semi fix | | 2011 | 3,900 | TAKRAF | - |
| Cape Preston Mine (No.1) | Sino Iron CITIC Pacific | Australia | Australasia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | | 2011 | 4,250 | Thyssen Krupp | - |
| Simando Plant | Rio Tinto and Chinalco | Guinea | Africa | Iron | Iron ore | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | | 2011 | 2,500 | Thyssen Krupp | - |
| Tonkolili - I | African Minierals | Sierra Leone | Africa | Iron | Iron ore | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2011 | 3,500 | FAM | - |
| Tonkolili - II | African Minierals | Sierra Leone | Africa | Iron | Iron ore | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2011 | 3,500 | FAM | - |
| Tanggang Sijiaying Iron Ore Mine (No.1) | Sinotrans Tangshan International Trade Co. Ltd./ Hebei Iron and Steel Mining Company | China | Central Asia | Iron | Overburden | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | | 2011 | 6,100 | Thyssen Krupp | - |
| Tanggang Sijiaying Iron Ore Mine (No.2) | Sinotrans Tangshan International Trade Co. Ltd. | China | Central Asia | Iron | Overburden | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | | 2011 | 6,100 | Thyssen Krupp | - |
| - | Hebei Hengye - Wulantuga II | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | | 2011 | 1,200 | Hazemag | 315 |
| - | Hebei Hengye - Dayan | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | | 2011 | 2,000 | Hazemag | 500 |
| Isla Riesco | Empresas Copec/Ultramar | Chile | South America | Coal | Coal | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2011 | 1,500 | FAM | - |
| - | Datang International | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | | 2011 | 3,000 | Hazemag | 730 |
| Baoqing | Baoqing Coal Power Chemistry Development | China | Central Asia | Coal | Coal | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | | 2011 | 3,000 | Sandvik | - |
| Penasquito | Penasquito | Mexico | North America | Gold | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | | 2011 | 12,500 | FLSmidth | - |
| PT Adaro | PT Adaro | Indonesia | Australasia | Coal | Overburden | Sizer | - | | - | Semi-mobile / Semi fix | - | 2011 | 6,000 | FLSmidth | - |
| PT Adaro | PT Adaro | Indonesia | Australasia | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2011 | 6,000 | FLSmidth | - |
| Wankinskij | Mordovcement | Russia | CIS | Chalk | Overburden | Impact crusher | Apron feeder | Crawler tracks | - | Fully-mobile | -- | 2011 | 1,900 | FAM | - |
| BSM-IV Carajas | Vale | Brazil | South America | Iron | Iron ore | Jaw crusher | apron feeder | - | - | Fully-mobile | - | 2010 | 10,400 | Sandvik | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radomiro Tomic Copper Mine | Codelco | Chile | South America | Copper | Copper | Gyratory crusher | - | - | - | Fix | - | 2010 | 7,700 | TAKRAF | - |
| Muzahimiyan Works (No.2) | Riyadh Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2010 | 1,000 | Thyssen Krupp | - |
| Aitik (surface crusher) | Aitik Mine | Sweden | Europe | Copper | Copper | Gyratory crusher | apron feeder | - | - | Semi-mobile / Semi fix | - | 2010 | 8,000 | Sandvik | - |
| Assarel Copper Mine | Assarel Medet J.V. | Bulgaria | Europe | Copper | Overburden | Gyratory crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2010 | 5,000 | Thyssen Krupp | - |
| Ray Mine (No.2) | Asarco LLC | USA | North America | Copper | Copper | Gyratory crusher | Apron feeder | - | 1250 | Semi-mobile / Semi fix | 3 | 2010 | 4,500 | Thyssen Krupp | - |
| - | Gacko II | Bosnia-Herzegovina | Europe | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | - | 2010 | 500 | Hazemag | 250 |
| Mina El Hatillo | Vale | Colombia | South America | Coal | Overburden | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | -- | 2010 | 1,500 | FAM | - |
| Elbistan, Cöllolar Coal Field (No.4) | Park Teknik Elektrik Madencilik Turizm Sanayi ve Ticaret A.S. | Turkey | Europe | Coal | Overburden | Sizer | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2010 | 7,600 | Thyssen Krupp | - |
| Elbistan, Cöllolar Coal Field (No.3) | Park Teknik Elektrik Madencilik Turizm Sanayi ve Ticaret A.S. | Turkey | Europe | Coal | Overburden | Sizer | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2010 | 7,600 | Thyssen Krupp | - |
| Baorixile | Baorixile | China | Central Asia | Coal | Coal | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2010 | 3,000 | Sandvik | - |
| - | Singleton Birch | UK | Europe | Chalk | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 2010 | 800 | MMD | 225 |
| - | Boral | Australia | Australasia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2010 | 800 | Metso | - |
| Clermont | Rio Tinto | Australia | Australasia | Coal | Overburden | Sizer | - | - | - | Fully-mobile | - | 2009 | 12,000 | TAKRAF | - |
| Fort McMurray Kanada | Suncor Energy Cooperation | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2009 | 7,500 | Thyssen Krupp | - |
| AOSP Expansion (No.1) | Albian Sands Energy | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 11,000 | Thyssen Krupp | - |
| AOSP Expansion (No.2) | Albian Sands Energy | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 11,000 | Thyssen Krupp | - |
| Horizon (No.3) | CNRL | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 11,000 | Thyssen Krupp | - |
| Merida Works | Cemex | Mexico | North America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 600 | Thyssen Krupp | - |
| Tepeaca Works (No.1) | Cemex | Mexico | North America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 2,000 | Thyssen Krupp | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tepeaca Works (No.2) | Cemex | Mexico | North America | Limestone | Industrial/mass commodities | Sizer | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 500 | Thyssen Krupp | - |
| Yaqui Works | Cemex | Mexico | North America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 500 | Thyssen Krupp | - |
| Tepeaca Works (No.3) | Cemex | Mexico | North America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 500 | Thyssen Krupp | - |
| Bloom Lake | Cliffs Natural Resources | Canada | North America | Iron | Iron ore | Gyratory crusher | | - | - | Semi-mobile / Semi fix | - | 2009 | 3,900 | TAKRAF | - |
| Jelsa Quarry | Norsk Stein AS | Norway | Europe | Granite | Industrial/mass commodities | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2009 | 2,600 | Thyssen Krupp | - |
| Aitik (in-pit crusher) | Aitik Mine | Sweden | Europe | Copper | Copper | Gyratory crusher | apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 8,000 | Sandvik | - |
| Spinifex Ridge Mine | Moly Mines Ltd. | Australia | Australasia | Copper | Copper | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2009 | 3,980 | Thyssen Krupp | - |
| - | Huahai Machinery - Sandaoling | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | - | 2009 | 800 | Hazemag | 250 |
| - | Xialongtan - Yunnan III | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | - | 2009 | 1,800 | Hazemag | 500 |
| Vostotschnyj | JSC Eurasian Energy Corporation | Kazakhstan | CIS | Coal | Overburden | Double roll crusher | - | - | - | Semi-mobile / Semi fix | - | 2009 | 4,250 | TAKRAF | - |
| Vostotschnyj | | Kazakhstan | CIS | Coal | Overburden | Double roll crusher | - | - | - | Semi-mobile / Semi fix | - | 2009 | 4,251 | TAKRAF | - |
| Elbistan, Cöllolar Coal Field (No.1) | Park Teknik Elektrik Madencilik Turizm Sanayi ve Ticaret A.S. | Turkey | Europe | Coal | Overburden | Sizer | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2009 | 7,600 | Thyssen Krupp | - |
| Elbistan, Cöllolar Coal Field (No.2) | Park Teknik Elektrik Madencilik Turizm Sanayi ve Ticaret A.S. | Turkey | Europe | Coal | Overburden | Sizer | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2009 | 7,600 | Thyssen Krupp | - |
| Baiyinhua 4 (No.2) | Inner Mongolia Xilingoule Bai Yin Hua | China | Central Asia | Coal | Coal | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 2,200 | Sandvik | - |
| Baiyinhua 4 (No.1) | Inner Mongolia Xilingoule Bai Yin Hua | China | Central Asia | Coal | Coal | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 2,200 | Sandvik | - |
| Orissa Panchpatmali Bauxite Mine | National Aluminium Co. Ltd.(NALCO) | India | Central Asia | Bauxite | Bauxit | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2009 | 1,200 | Thyssen Krupp | - |
| - | Hansen Brick | UK | Europe | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 2009 | 420 | MMD | 110 |
| Cananea | - | Mexico | North America | Copper | Copper | Gyratory crusher | - | - | - | Fix | - | 2008 | 3,200 | TAKRAF | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizon (No.1) | CNRL | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2008 | 11,000 | Thyssen Krupp | - |
| Horizon (No.2) | CNRL | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2008 | 11,000 | Thyssen Krupp | - |
| Citeureup Works (No.2) | PT Indocement | Indonesia | Australasia | Limestone | Industrial/mass commodities | Sizer | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2008 | 500 | Thyssen Krupp | - |
| Citeureup Works (No.2) | PT Indocement | Indonesia | Australasia | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2008 | 1,200 | Thyssen Krupp | - |
| Gibraltar | Taseko | Canada | North America | Copper | Copper | Gyratory crusher | - | - | - | Semi-mobile / Semi fix | - | 2008 | 4,000 | TAKRAF | - |
| Los Pelambres | Antofagasta and Pan Pacific Copper | Chile | South America | Copper | Copper | Gyratory crusher | - | - | - | Semi-mobile / Semi fix | - | 2008 | 7,550 | TAKRAF | - |
| - | Hebei Hengye - Wulantuga I | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | - | 2008 | 800 | Hazemag | 250 |
| Baiyinhua 2 | Inner Mongolia Xilingoule Bai Yin Hua | China | Central Asia | Coal | Coal | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2008 | 2,000 | Sandvik | - |
| Southern Peru Copper Tia Maria | Southern Peru Copper Tia Maria | Peru | South America | Copper | Copper | Gyratory crusher | - | - | - | Fix | - | 2008 | 9,000 | FLSmidth | - |
| Baja Mining El Boleo | Baja Mining El Boleo | Mexico | North America | Copper | Copper | Sizer | - | - | - | Fix | - | 2008 | 600 | FLSmidth | - |
| Wankinskij | Mordovcement | Russia | CIS | Chalk | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | - | Fully-mobile | - | 2008 | 1,700 | FAM | - |
| Wankinskij | Mordovcement | Russia | CIS | Chalk | Overburden | Impact crusher | Apron feeder | Crawler tracks | - | Fully-mobile | - | 2008 | 1,380 | FAM | - |
| Steinbruch Karsdorf | Lafarge Zement | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder |  | - | Fully-mobile | -- | 2008 | 1,000 | FAM | - |
| Cloud Break iron-ore mine | Fortescue Metals Group | Australia | Australasia | Iron Ore | Overburden | Sizer | - | Crawler tracks | - | Fully-mobile | - | 2007 | 4,000 | FLSmidth | - |
| Cloud Break iron-ore mine | Fortescue Metals Group | Australia | Australasia | Iron Ore | Overburden | Sizer | - | Crawler tracks | - | Fully-mobile | - | 2007 | 4,000 | FLSmidth | - |
| Cloud Break iron-ore mine | Fortescue Metals Group | Australia | Australasia | Iron Ore | Overburden | Sizer | - | Crawler tracks | - | Fully-mobile | - | 2007 | 4,000 | FLSmidth | - |
| Cloud Break iron-ore mine | Fortescue Metals Group | Australia | Australasia | Iron Ore | Overburden | Sizer | - | Crawler tracks | - | Fully-mobile | - | 2007 | 4,000 | FLSmidth | - |
| Open Pit Yimin | Huaneng Yimin Coal &Electricity Co. Ltd. | China | Central Asia | Coal | Coal | Double roll crusher | Apron feeder | - | - | Fully-mobile | - | 2007 | 3,000 | Thyssen Krupp | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | Vulcan Materials | Mexico | North America | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fix | - | 2007 | 3,250 | MMD | 335 |
| Poltava Mine (No.2) | Poltavskij GOK | Ukraine | CIS | Iron | Iron ore | Jaw crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2007 | 1,250 | Thyssen Krupp | - |
| - | Xialongtan - Yunnan I+II | China | Central Asia | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | - | 2007 | 1,800 | Hazemag | 500 |
| Cetenario Franke | Cetenario Franke | Chile | South America | Copper | Copper | Jaw crusher | - | - | - | Fix | - | 2007 | 1,000 | FLSmidth | - |
| Argos Cement | Argos Cement | Columbia | South America | Limestone | Industrial/mass commodities | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2007 | 2,500 | FLSmidth | - |
| - | Samarco 2 | Brazil | South America | Iron | Iron ore | Jaw crusher | - | - | - | Fully-mobile | - | 2007 | 800 | Metso | - |
| - | Samarco 1 | Brazil | South America | Iron | Iron ore | Jaw crusher | - | - | - | Fully-mobile | - | 2007 | 800 | Metso | - |
| - | Alumbera | Argentina | South America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2007 | 800 | Metso | - |
| - | BAG | Germany | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2007 | 800 | Metso | - |
| - | BG Stone | Norway | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2007 | 800 | Metso | - |
| - | Tarmac Barrasford | UK | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2007 | 800 | Metso | - |
| - | GCC | USA | North America | Limestone | Industrial/mass commodities | Impact crusher | - | - | - | Fully-mobile | - | 2007 | 600 | Metso | - |
| Muzahimiyan Works (No.1) | Riyadh Cement | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron -feeder | - | - | Fully-mobile | - | 2006 | 1,300 | Thyssen Krupp | - |
| Olavarria Works | Cementos Avellaneda S.A. | Argentina | South America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2006 | 1,200 | Thyssen Krupp | - |
| Fumane Works | Industria Cementi Giovanni Rossi S.P.A. | Italy | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2006 | 900 | Thyssen Krupp | - |
| Maraat Works | City Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2006 | 1,000 | Thyssen Krupp | - |
| Alcoa Juruti Plant | Alcoa Juruti Plant | Brazil | South America | Bauxite | Bauxit | Sizer | - | - | - | Fix | - | 2006 | 1,100 | FLSmidth | - |
| - | Echeverria | Spain | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2006 | 800 | Metso | - |
| - | Suncor Energy | Canada | North America | Oilsand | Oil sand | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2005 | 6,000 | MMD | 522 |
| Aurora Mine (AMS) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2005 | 11,000 | Thyssen Krupp | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North Mine (NMAPS) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2005 | 9,000 | Thyssen Krupp | - |
| Steepbank Mine (No.1) | Suncor Energy | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2005 | 12,000 | Thyssen Krupp | - |
| Steepbank Mine (No.2) | Suncor Energy | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2005 | 12,000 | Thyssen Krupp | - |
| Qian´an Mine (No.2), Shougang | China Shougang International Trade & Engineering Corp. | China | Central Asia | Iron | Iron ore | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2005 | 4,400 | Thyssen Krupp | - |
| Qian´an Mine (No.1), Shougang | China Shougang International Trade & Engineering Corp. | China | Central Asia | Iron | Overburden | Gyratory crusher | 'Direct feeding' | - | - | Semi-mobile / Semi fix | - | 2005 | 5,400 | Thyssen Krupp | - |
| Escondida | BHP Billiton (57.5%), Rio Tinto (10%) and Pan Pacific Copper (12.5%) | Chile | South America | Copper | Copper | Jaw crusher | - | - | - | Semi-mobile / Semi fix | - | 2005 | 8,800 | TAKRAF | - |
| La Loma mine | Drummond Coal x 4 | Colombia | South America | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2005 | 5,000 | MMD | 750 |
| Lignitos de Meirama | Lignitos de Meirama | Spain | Europe | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2005 | 1,000 | MMD | 315 |
| Mae Moh | Ital Thai Development Plc x 4 | Thailand | Central Asia | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2005 | 6,500 | MMD | 375 |
| Titan Cement Roanoke Plant | Titan Cement Roanoke Plant | USA | North America | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fix | - | 2005 | 980 | FLSmidth | - |
| Hatch/Goldfields Corona | Hatch/Goldfields Corona | Peru | South America | Gold Ore | Gold Ore | Sizer | - | - | - | Fix | - | 2005 | 775 | FLSmidth | - |
| Hatch/Goldfields Corona | Hatch/Goldfields Corona | Peru | South America | Gold Ore | Gold Ore | Sizer | - | - | - | Fix | - | 2005 | 775 | FLSmidth | - |
| Holcim St. Genevieve Cement | Holcim St. Genevieve Cement | USA | North America | Limestone | Industrial/mass commodities | Gyratory crusher | - | - | - | Fix | - | 2005 | 2,600 | FLSmidth | - |
| - | Bernegger | Austria | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2005 | 1,000 | Metso | - |
| Riyadh Works (No.3) | Yamama Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Fully-mobile | - | 2004 | 1,500 | Thyssen Krupp | - |
| Werk Harburg (No.2) | Märker Kalk GmbH | Germany | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Transport crawler | - | Semi-mobile / Semi fix | - | 2004 | 1,450 | Thyssen Krupp | - |
| Wildegg Works (No.2) | Jura Cement Fabriken | Switzerland | Europe | Limestone | Industrial/mass commodities | Impact crusher | Chain conveyor | - | - | Semi-mobile / Semi fix | - | 2004 | 700 | Thyssen Krupp | - |
| Carajas | Vale | Brazil | South America | Iron | Iron ore | Jaw crusher | - | - | - | Semi-mobile / Semi fix | - | 2004 | 750 | TAKRAF | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Old Cliffe Hill Quarry | | U.K. | Europe | Granite | Industrial/mass commodities | Gyratory crusher | - | - | - | Semi-mobile / Semi fix | - | 2004 | 2,500 | TAKRAF | - |
| Vedanta Alumina Lanjigarh | Vedanta Alumina Lanjigarh | India | Central Asia | Bauxite | Bauxit | Sizer | - | - | - | Fix | - | 2004 | 2,000 | FLSmidth | - |
| Buraydah Works (No.2) | Qassim Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Fully-mobile | - | 2004 | 900 | Thyssen Krupp | - |
| - | Holcim | Belgium | Europe | Chalk | Industrial/mass commodities | Sizer | - | - | - | Fix | - | 2003 | 600 | MMD | 260 |
| Collahuasi Ujina Mine | Compania Minera Dona Ines de Collahuasi Xstrata, Anglo American and Pan Pacific Copper. | Chile | South America | Copper | Copper | Gyratory crusher | - | - | - | Fix | - | 2003 | 8,500 | TAKRAF | - |
| Aurora Mine (No.2) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | Transport crawler | - | Semi-mobile / Semi fix | - | 2003 | 11,000 | Thyssen Krupp | - |
| Wössingen | Lafarge Zement | Germany | Europe | Chalk | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2003 | 1,000 | FAM | - |
| Tata Iron & Steel Bokaro Plant | Tata Iron & Steel Bokaro Plant | India | Central Asia | Coal | Coal | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2003 | 1,000 | FLSmidth | - |
| - | Longtan Dam | China | Central Asia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2003 | 800 | Metso | - |
| - | Longtan Dam | China | Central Asia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2003 | 800 | Metso | - |
| - | Kraemer | USA | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2003 | 800 | Metso | - |
| - | Luck Stone | USA | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2003 | 800 | Metso | - |
| Muskeg River Mine (No.1) | Albian Sands Energy Inc. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | Transport crawler | - | Semi-mobile / Semi fix | - | 2002 | 14,000 | Thyssen Krupp | - |
| Muskeg River Mine (No.2) | Albian Sands Energy Inc. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | Transport crawler | - | Semi-mobile / Semi fix | - | 2002 | 14,000 | Thyssen Krupp | - |
| Escondida | BHP Billiton (57.5%), Rio Tinto (10%) and Pan Pacific Copper (12.5%) | Chile | South America | Copper | Copper | Gyratory crusher | - | - | - | Semi-mobile / Semi fix | - | 2002 | 8,800 | TAKRAF | - |
| Grasberg | Freeport Mining | Indonesia | Australasia | Copper | Copper | Gyratory crusher | - | - | - | Semi-mobile / Semi fix | - | 2002 | 5,600 | TAKRAF | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mae Moh V (NO.1) | Italian-Thai Development Public Company Ltd (ITD) | Thailand | Central Asia | Coal | Overburden | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2002 | 5,500 | Sandvik | - |
| Mae Moh V (NO.2) | Italian-Thai Development Public Company Ltd (ITD) | Thailand | Central Asia | Coal | Overburden | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2002 | 5,500 | Sandvik | - |
| Mae Moh V (NO.3) | Italian-Thai Development Public Company Ltd (ITD) | Thailand | Central Asia | Coal | Overburden | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2002 | 5,500 | Sandvik | - |
| Mae Moh V (NO.4) | Italian-Thai Development Public Company Ltd (ITD) | Thailand | Central Asia | Coal | Overburden | Sizer | apron feeder | - | - | Semi-mobile / Semi fix | - | 2002 | 5,500 | Sandvik | - |
| - | Ofitas | Spain | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2002 | 800 | Metso | - |
| - | Zemer | USA | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2002 | 800 | Metso | - |
| BHP Goonyella | BHP | Australia | Australasia | Coal | Overburden | Sizer | - | - | - | Fully-mobile | - | 2001 | 10,000 | MMD | 430 |
| - | Yatela Gold | Mali | Africa | Gold Ore | Gold Ore | Sizer | - | - | - | Fix | - | 2001 | 600 | MMD | - |
| - | Gravas y Derivados | Spain | Europe | Limestone | Industrial/mass commodities | Sizer | - | - | - | Semi-mobile / Semi fix | - | 2001 | 1,000 | MMD | 315 |
| - | DJL | Canada | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2001 | 800 | Metso | - |
| - | Tarmac Swinden | UK | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2000 | 1,150 | Metso | - |
| Aurora Mine (No.1) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | Transport crawler | - | Semi-mobile / Semi fix | 2 | 2000 | 11,000 | Thyssen Krupp | 140 |
| Millenium Mine - III | Suncor Energy Cooperation | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2000 | 12,000 | FAM | - |
| Millenium Mine - I | Suncor Energy Cooperation | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2000 | 12,000 | FAM | - |
| Millenium Mine - II | Suncor Energy Cooperation | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 2000 | 12,000 | FAM | - |
| Dürnbach Quarry | WOPFINGER BAUSTOFFE GMBH | Austria | Europe | Limestone | Industrial/mass commodities | Jaw crusher | Reciprocating plate feeder | - | 300 | Semi-mobile / Semi fix | 1 | 2000 | 1,200 | Thyssen Krupp | 200 |
| Killaskilln Works | LAGAN CEMENT LTD, | Ireland | Europe | Limestone | Industrial/mass commodities | Impact crusher | Chain Conveyor | Transport crawler | 140 | Semi-mobile / Semi fix | 2 | 2000 | 520 | Thyssen Krupp | 500 |
| | Gacko I | Bosnia-Herzegovina | Europe | Coal | Coal | Feeder breaker | - | - | - | Semi-mobile / Semi fix | - | 2000 | 1,000 | Hazemag | 250 |
| SNIM | SNIM | Mauritania | Africa | Iron Ore | Iron ore | Gyratory crusher | - | - | - | Fix | - | 2000 | 8,400 | FLSmidth | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | Zemer | USA | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2000 | 800 | Metso | - |
| - | Lemminkäinen | Finland | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2000 | 550 | Metso | - |
| - | REP | France | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 2000 | 550 | Metso | - |
| Krasna Okterbrski Bauxite Mine | Aluminium of Kazakhstan | Kazakhstan | CIS | Bauxite | Bauxit | Impact crusher | Chain conveyor | Crawler tracks | 265 | Fully-mobile | - | 2000 | 400 | Thyssen Krupp | 630 |
| Ain Dar Works (No.2) | Saudi Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 725 | Fully-mobile | - | 1999 | 1,000 | Thyssen Krupp | 1700 |
| Martha mine | WAIHI GOLD | NEW ZEALAND | Australasia | GOLD ORE | Gold Ore | Feeder breaker | - | - | - | Fix | - | 1999 | 4,600 | Joy Global | - |
| Olavarria Works | Loma Negra S.A. | Argentina | South America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Transport crawler | 690 | Semi-mobile / Semi fix | 2 | 1999 | 2,200 | Thyssen Krupp | 2200 |
| Pljevlja Mine | JP. Rudnik Uglja Pljevlja | Montenegro | Europe | Limestone | Overburden | Double roll crusher | Apron feeder | Transport crawler | 500 | Semi-mobile / Semi fix | 2 | 1999 | 3,000 | Thyssen Krupp | 700 |
| Panagyureshte Mine | Assarel Copper | Bulgaria | Europe | Copper | Overburden | Gyratory crusher | Apron feeder | Transport crawler | 1000 | Semi-mobile / Semi fix | 2 | 1999 | 3,000 | Thyssen Krupp | 380 |
| - | Bögel | Germany | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1999 | 800 | Metso | - |
| - | Pirna Land | Germany | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1999 | 800 | Metso | - |
| - | Bau Meier | Germany | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1999 | 800 | Metso | - |
| - | Camas | USA | North America | Limestone | Industrial/mass commodities | Impact crusher | - | - | - | Fully-mobile | - | 1999 | 600 | Metso | - |
| - | Skipiol | Germany | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1999 | 550 | Metso | - |
| - | PT Semen Padang 'A' | Indonesia | Australasia | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fix | - | 1998 | 2,000 | MMD | - |
| - | PT Semen Padang 'B' | Indonesia | Australasia | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fix | - | 1998 | 2,000 | MMD | - |
| Steepback Mine - I | Suncor Energy Cooperation | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 1998 | 12,000 | FAM | - |
| Steepback Mine - II | Suncor Energy Cooperation | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | - | - | Semi-mobile / Semi fix | - | 1998 | 12,000 | FAM | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Werk Burglengenfeld | Heidelberger Zement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Transport crawler | 770 | Semi-mobile / Semi fix | 2 | 1998 | 1,600 | Thyssen Krupp | 2500 |
| Serra dos Carajás (No.1) | Companhia Vale do Rio Doce (CVRD) | Brazil | South America | Iron | Iron ore | Jaw crusher | Apron feeder | Tire piggy back transporter | 880 | Semi-mobile / Semi fix | 1 | 1998 | 8,700 | Thyssen Krupp | 160 |
| Serra dos Carajás (No.2) | Companhia Vale do Rio Doce (CVRD) | Brazil | South America | Iron | Iron ore | Jaw crusher | Apron feeder | Tire piggy back transporter | 880 | Semi-mobile / Semi fix | 3 | 1998 | 8,700 | Thyssen Krupp | 160 |
| Grasberg Mine (No.3) | Freeport Mining | Indonesia | Australasia | Copper | Overburden | Gyratory crusher | 'Direct feeding' | Transport crawler | 1600 | Semi-mobile / Semi fix | 1 | 1998 | 8,200 | Thyssen Krupp | 950 |
| Taldinski | Kuzbassrazrezugol | Russia | CIS | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1998 | 3,601 | TAKRAF | - |
| Taldinski | Kuzbassrazrezugol | Russia | CIS | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1998 | 3,600 | TAKRAF | - |
| Mae Moh Mine (No.4) | Chieng Mai Construction Co. | Thailand | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 560 | Semi-mobile / Semi fix | 2 | 1998 | 4,500 | Thyssen Krupp | 900 |
| Mae Moh Mine (No.5) | Chieng Mai Construction Co. | Thailand | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 560 | Semi-mobile / Semi fix | 2 | 1998 | 4,500 | Thyssen Krupp | 900 |
| Mae Moh Mine (No.6) | Chieng Mai Construction Co. | Thailand | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 560 | Semi-mobile / Semi fix | 2 | 1998 | 4,500 | Thyssen Krupp | 900 |
| Mae Moh Mine (No.7) | Chieng Mai Construction Co. | Thailand | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 560 | Semi-mobile / Semi fix | 2 | 1998 | 4,500 | Thyssen Krupp | 900 |
| - | Boden Frakt | Sweden | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1998 | 550 | Metso | - |
| - | Perak Hanjung | Malaysia | Australasia | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 1997 | 1,200 | MMD | - |
| Collahuasi Ujina Mine (No.2) | Compania Minera Dona Ines de Collahuasi Xstrata, Anglo American and Pan Pacific Copper. | Chile | South America | Copper Ore | Copper | Gyratory crusher | 'Direct feeding' | Tire piggy back transporter | 1145 | Fix | 1 | 1997 | 5,900 | Thyssen Krupp | 600 |
| Collahuasi Ujina Mine (No.1) | Compania Minera Dona Ines de Collahuasi Xstrata, Anglo American and Pan Pacific Copper. | Chile | South America | Copper Ore | Copper | Gyratory crusher | 'Direct feeding' | Tire piggy back transporter | 1146 | Fix | 1 | 1997 | 5,900 | Thyssen Krupp | 600 |
| Fort McMurray Mine (No.4) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | Transport crawler | 1055 | Semi-mobile / Semi fix | 1 | 1997 | 7,500 | Thyssen Krupp | 1500 |
| Fort McMurray Mine (No.5) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | Transport crawler | 1055 | Semi-mobile / Semi fix | 1 | 1997 | 7,500 | Thyssen Krupp | 1500 |
| Wülfrath Werk Rohdenhaus (No.2) | Rheinkalk | Germany | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | Apron feeder | Transport crawler | 1400 | Semi-mobile / Semi fix | 3 | 1997 | 1,800 | Thyssen Krupp | 400 |
| Wülfrath Werk Rohdenhaus (No.1) | Rheinkalk | Germany | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | Apron feeder | Transport crawler | 1400 | Semi-mobile / Semi fix | 3 | 1997 | 1,800 | Thyssen Krupp | 400 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | Zuari Agro Chemicals | India | Central Asia | Limestone | Industrial/mass commodities | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1997 | 750 | MMD | - |
| Grasberg Mine (No.2) | Freeport Mining | Indonesia | Australasia | Copper | Copper | Gyratory crusher | 'Direct feeding' | Transport crawler | 1600 | Semi-mobile / Semi fix | 1 | 1997 | 6,500 | Thyssen Krupp | 950 |
| Cananea | - | Mexico | North America | Copper | Copper | Gyratory crusher | | - | - | Semi-mobile / Semi fix | - | 1997 | 3,600 | TAKRAF | |
| Bachatsky x 2 | Kuzbassrazrezugol | Russia | CIS | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1997 | 3,500 | MMD | 225 |
| Taldinsky x 1 | Kuzbassrazrezugol | Russia | CIS | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1997 | 3,500 | MMD | 224 |
| Taldinsky x 2 | Kuzbassrazrezugol | Russia | CIS | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1997 | 3,500 | MMD | 225 |
| Banpu | Banpu Public Company Limited | Thailand | Central Asia | Coal | Overburden | Double roll crusher | apron feeder | - | - | Semi-mobile / Semi fix | - | 1997 | 1,500 | Sandvik | - |
| - | Robust Rock | Philippines | Australasia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1997 | 800 | Metso | - |
| - | REP | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | - | - | - | Fully-mobile | - | 1997 | 450 | Metso | - |
| Chuquicamata | Codelco | Chile | South America | Copper | Copper | Gyratory crusher | - | - | - | Semi-mobile / Semi fix | - | 1996 | 5,750 | TAKRAF | - |
| Porto Trombetas mine | MRN x 2 | Brazil | South America | Bauxite | Bauxit | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1996 | 3,000 | MMD | 373 |
| Paranam Mine (No.2) | and | Suriname | Africa | Bauxite | Bauxit | Double roll crusher | Chain conveyor | Transport crawler | 165 | Semi-mobile / Semi fix | 1 | 1996 | 450 | Thyssen Krupp | 368 |
| Paranam Mine (No.1) | Chinalco | Suriname | Africa | Bauxite | Bauxit | Double roll crusher | Chain conveyor | Transport crawler | 165 | Semi-mobile / Semi fix | 1 | 1996 | 450 | Thyssen Krupp | 368 |
| PT Semen Bosowa | PT Semen Bosowa | Indonesia | Australasia | Limestone | Industrial/mass commodities | Gyratory crusher | - | - | - | Fix | - | 1996 | 1,215 | FLSmidth | - |
| - | Tohoku Saiseki | Japan | Central Asia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1996 | 550 | Metso | - |
| - | Newmont Mining | Uzbekistan | CIS | Gold | Gold Ore | Jaw crusher | - | - | - | Fully-mobile | - | 1995 | 2,000 | Metso | - |
| Werk Harburg (No.1) | Märker Kalkwerk GmbH, | Germany | Europe | Limestone | Industrial/mass commodities | Feeder breaker | Chain conveyor | Crawler tracks | 220 | Fully-mobile | - | 1995 | 1,000 | Thyssen Krupp | 500 |
| Davao Works | Davao Union Cement Corp. | Philippines | Australasia | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 465 | Fully-mobile | - | 1995 | 1,000 | Thyssen Krupp | 950 |
| Mesa J | Robe River | Australia | Australasia | Iron Ore | Iron ore | Sizer | - | - | - | Fix | - | 1995 | 5,500 | MMD | 400 |
| Lengfurt Works | HEIDELBERGER ZEMENT AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | 960 | Semi-mobile / Semi fix | 1 | 1995 | 1,500 | Thyssen Krupp | 1600 |
| Escondida | BHP Billiton (57.5%), Rio Tinto (10%) and Pan Pacific Copper (12.5%) | Chile | South America | Copper | Copper | Gyratory crusher | - | - | - | Semi-mobile / Semi fix | - | 1995 | 5,750 | TAKRAF | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mae Moh Mine | Mae Moh Coal Mine | Thailand | Central Asia | Coal | Coal | Double roll crusher | apron feeder | - | - | Semi-mobile / Semi fix | - | 1995 | 1,750 | Sandvik | - |
| - | Dragages | Hong Kong | Central Asia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1995 | 800 | Metso | - |
| - | Dragages | Hong Kong | Central Asia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1995 | 800 | Metso | - |
| - | CBPO Oderbrecht | USA | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1995 | 800 | Metso | - |
| - | CBPO Oderbrecht | USA | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1995 | 800 | Metso | - |
| - | REP | France | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1995 | 550 | Metso | - |
| Wyodak coal mine | Gillette Energy Complex | USA | North America | Coal | Coal | Feeder breaker | - | Crawler tracks | - | Fully-mobile | - | 1994 | 2,150 | Joy Global | - |
| Bishah Works | SOUTHERN PROVINCE CEMENT CO, | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 635 | Fully-mobile | 1 | 1994 | 1,000 | Thyssen Krupp | 1500 |
| - | Material Services | USA | North America | Limestone | Industrial/mass commodities | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1994 | 2,000 | MMD | 224 |
| Poltava Mine (No.1) | Poltavskij GOK | Ukraine | CIS | Iron | Iron ore | Gyratory crusher | Apron feeder | Transport crawler | 1200 | Semi-mobile / Semi fix | 3 | 1994 | 2,500 | Thyssen Krupp | 450 |
| Grasberg Mine (No.1) | Freeport Mining | Indonesia | Australasia | Copper | Copper | Gyratory crusher | 'Direct feeding' | Transport crawler | 1150 | Semi-mobile / Semi fix | 1 | 1994 | 6,000 | Thyssen Krupp | 440 |
| Wyodak coal mine | Gillette Energy Complex | USA | North America | Coal | Coal | Feeder breaker | - | Skid | - | Semi-mobile / Semi fix | - | 1994 | 2,150 | Joy Global | - |
| - | Sumikin Kogyo | Japan | Central Asia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1994 | 800 | Metso | - |
| - | Guthrie | Malaysia | Australasia | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1994 | 800 | Metso | - |
| - | Longwood Quarries | UK | Europe | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 1994 | 500 | MMD | 110 |
| - | Longwood Quarries | UK | Europe | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 1994 | 100 | MMD | 110 |
| Werk Deuna | Dyckerhoff Zementwerke AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 975 | Fully-mobile | - | 1993 | 2,000 | Thyssen Krupp | 2800 |
| Anshan Mine (No.2) | Anshan Iron and Steel | China | Central Asia | Iron | Iron ore | Gyratory crusher | Apron feeder | Transport crawler | 1730 | Semi-mobile / Semi fix | 3 | 1993 | 4,900 | Thyssen Krupp | 600 |
| Anshan Mine (No.1) | Anshan Iron and Steel | China | Central Asia | Iron | Iron ore | Gyratory crusher | Apron feeder | Transport crawler | 1730 | Semi-mobile / Semi fix | 3 | 1993 | 7,300 | Thyssen Krupp | 600 |
| - | Banpu Coal Co. x 4 | Thailand | Central Asia | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1993 | 4,500 | MMD | 375 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | BAG | Germany | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1993 | 800 | Metso | - |
| - | SQW | Germany | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1993 | 800 | Metso | - |
| - | Tribasa | Mexico | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | | Fully-mobile | - | 1993 | 550 | Metso | - |
| Ferques Quarry | Carrieres du Boulonnais | France | Europe | Limestone | Industrial/mass commodities | Jaw crusher | Vibrating feeder/pan with two screens | Transport crawler | 700 | Semi-mobile / Semi fix | 3 | 1992 | 1,800 | Thyssen Krupp | 280 |
| Ramagundam Mine (No.1) | Singareni Collieries | India | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 430 | Semi-mobile / Semi fix | 4 | 1992 | 3,500 | Thyssen Krupp | 800 |
| Ramagundam Mine (No.2) | Singareni Collieries | India | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 430 | Semi-mobile / Semi fix | 4 | 1992 | 3,500 | Thyssen Krupp | 800 |
| Ramagundam Mine (No.3) | Singareni Collieries | India | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 430 | Semi-mobile / Semi fix | 4 | 1992 | 3,500 | Thyssen Krupp | 800 |
| Ramagundam Mine (No.4) | Singareni Collieries | India | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 430 | Semi-mobile / Semi fix | 4 | 1992 | 3,500 | Thyssen Krupp | 800 |
| - | Tarmac Pant | UK | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1992 | 800 | Metso | - |
| Werk Sölhde | Vereinigte Kreidewerke Dammann KG | Germany | Europe | Chalk | Industrial/mass commodities | Impact crusher | Chain conveyor | Tyre system | 254 | Fully-mobile | - | 1992 | 350 | Thyssen Krupp | 560 |
| Söhlde Plant | VEREINIGTE KREIDEWERKE DAMMANN KG | Germany | Europe | Chalk | Industrial/mass commodities | Impact crusher | Chain conveyor | Tyre system | 254 | Fully-mobile | 1 | 1992 | 350 | Thyssen Krupp | 560 |
| Piparwar Mine | White Industries-Piparwar | India | Central Asia | Coal | Coal | Double roll crusher | Apron feeder | Tyre system | 745 | Fully-mobile | - | 1991 | 2,800 | Thyssen Krupp | 500 |
| Werk Bernburg | E. Schwenk Zementwerke KG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 975 | Fully-mobile | - | 1991 | 2,000 | Thyssen Krupp | 2800 |
| Fort McMurray Mine (No.3) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Double roll crusher | Apron feeder | Transport crawler | 650 | Semi-mobile / Semi fix | 1 | 1991 | 5,500 | Thyssen Krupp | 900 |
| Cornaux Cornaux Works | Juracime S.A. | Switzerland | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Transport crawler | 510 | Semi-mobile / Semi fix | 1 | 1991 | 500 | Thyssen Krupp | 750 |
| Tabubil Mine | OK TEDI Mining Ltd. | Papua New Guinea | Australasia | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1765 | Semi-mobile / Semi fix | 3 | 1991 | 6,300 | Thyssen Krupp | 662 |
| Kinshasa Kolwezi Mine (No.1) | Gecamines | Zaire | Africa | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1991 | 4,600 | Thyssen Krupp | 380 |
| Kinshasa Kolwezi Mine (No.2) | Gecamines | Zaire | Africa | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1991 | 4,600 | Thyssen Krupp | 300 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | Tribasa | Mexico | North America | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1991 | 550 | Metso | - |
| Dexin | Dexin Copper | China | Central Asia | Copper | Overburden | Gyratory crusher | - | - | - | Fix | - | 1990 | 5,500 | Metso | - |
| Brush Creek Mine | SF INDUSTRIES | USA | North America | Phosphate | Phosphate | Feeder breaker | Apron feeder | - | - | Semi-mobile / Semi fix | - | 1990 | 1,850 | Joy Global | - |
| Werk Weisenau (No.2) | Heidelberger Zement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Transport crawler | 659 | Semi-mobile / Semi fix | 1 | 1990 | 1,400 | Thyssen Krupp | 2400 |
| - | Blue Circle Dunbar | UK | Europe | Limestone | Industrial/mass commodities | Sizer | - | - | - | Semi-mobile / Semi fix | - | 1990 | 1,000 | MMD | 375 |
| Escondida 2 | BHP Billiton (57.5%), Rio Tinto (10%) and Pan Pacific Copper (12.5%) | Chile | South America | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1200 | Semi-mobile / Semi fix | 1 | 1990 | 5,000 | Thyssen Krupp | 400 |
| Ray Mine (No.1) | Asarco LLC | USA | North America | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1250 | Semi-mobile / Semi fix | 3 | 1990 | 4,500 | Thyssen Krupp | 515 |
| - | Lignitos de Meirama | Spain | Europe | Coal | Overburden | Sizer | - | - | - | Semi-mobile / Semi fix | | 1990 | 3,000 | MMD | 250 |
| Mae Moh Mine | Mae Moh Coal Mine | Thailand | Central Asia | Coal | Coal | Double roll crusher | apron feeder | - | - | Semi-mobile / Semi fix | - | 1990 | 1,725 | Sandvik | - |
| Al Barh Works | Mafraq Cement Co. | Yemen | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 370 | Fully-mobile | - | 1990 | 500 | Thyssen Krupp | 570 |
| - | Longwood Quarries | UK | Europe | Limestone | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 1990 | 500 | MMD | 300 |
| Antequera Quarry | ARICOSA | Spain | Europe | Limestone | Industrial/mass commodities | Jaw crusher | Vibrating feeder/pan | Transport crawler | 125 | Semi-mobile / Semi fix | 1 | 1989 | 320 | Thyssen Krupp | 132 |
| Nimingara Mine | Goldworthy Mining Limited | Australia | Australasia | Iron | Iron ore | Gyratory crusher | Apron feeder | Transport crawler | 780 | Semi-mobile / Semi fix | 2 | 1989 | 3,330 | Thyssen Krupp | 375 |
| Chuquicamata Mine | Codelco | Chile | South America | Copper | Copper | Gyratory crusher | 2 Apron feeders | Transport crawler | 2500 | Semi-mobile / Semi fix | 4 | 1989 | 9,600 | Thyssen Krupp | 900 |
| Moengo Mine | Alcoa-Suriname Aluminium Co. | Suriname | Africa | Bauxite | Bauxit | Double roll crusher | Chain conveyor | Transport crawler | 264 | Semi-mobile / Semi fix | 1 | 1989 | 600 | Thyssen Krupp | 320 |
| Aubema/Mae Moh | Aubema/Mae Moh | Thailand | Central Asia | Coal | Overburden | Double roll crusher | - | - | - | Semi-mobile / Semi fix | - | 1989 | 1,400 | FLSmidth | - |
| O&K/Suralco | O&K/Suralco | Suriname | Africa | Bauxite | Bauxit | Double roll crusher | - | - | - | Semi-mobile / Semi fix | - | 1989 | 800 | FLSmidth | - |
| - | Perasso | France | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1989 | 550 | Metso | - |
| Antelope Mine | | USA | North America | Coal | Coal | Feeder breaker | - | - | - | Fully-mobile | - | 1988 | 1,135 | Joy Global | - |
| Vikram Nagar Post Khov Works | Vikram Cement Ltd. | India | Central Asia | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system "exchangable" | 450 | Semi-mobile / Semi fix | 2 | 1988 | 850 | Thyssen Krupp | 1060 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hualien Plant | Asia Cement Corporation | Taiwan | Central Asia | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Tyre system | 460 | Semi-mobile / Semi fix | 1 | 1988 | 2,000 | Thyssen Krupp | 800 |
| Smoky Valley Mine | Round Mountain Gold | USA | North America | Gold | Gold Ore | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1988 | 4,500 | Thyssen Krupp | 515 |
| Denver Carlin Mine (No.2) | Newmont Gold | USA | North America | Gold | Gold Ore | Gyratory crusher | Apron feeder | Transport crawler | 550 | Semi-mobile / Semi fix | 3 | 1988 | 1,100 | Thyssen Krupp | 260 |
| Denver Carlin Mine (No.1) | Newmont Gold | USA | North America | Gold | Gold Ore | Gyratory crusher | Apron feeder | Transport crawler | 551 | Semi-mobile / Semi fix | 3 | 1988 | 1,100 | Thyssen Krupp | 260 |
| Lake County Mine | Homestake Mining Company | USA | North America | Gold | Gold Ore | Gyratory crusher | Apron feeder | Transport crawler | 570 | Semi-mobile / Semi fix | 3 | 1988 | 1,000 | Thyssen Krupp | 300 |
| Panguna Mine | Bougainville Copper Ltd. | Papua New Guinea | Australasia | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1988 | 6,000 | Thyssen Krupp | 515 |
| Morenzi Mine (No.1) | Phelps Dodge Corporation | USA | North America | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1988 | 6,750 | Thyssen Krupp | 515 |
| Morenzi Mine (No.2) | Phelps Dodge Corporation | USA | North America | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1988 | 6,750 | Thyssen Krupp | 515 |
| Reuchenette Works | Vigier Cement AG | Switzerland | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 591 | Fully-mobile | - | 1988 | 750 | Thyssen Krupp | 1120 |
| - | ARC Silverdale | UK | Europe | Aggregartes | Industrial/mass commodities | Jaw crusher | - | - | - | Fully-mobile | - | 1988 | 550 | Metso | - |
| Highland Valley Copper-Molybdenum Mine | Teck | Canada | North America | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1987 | 6,600 | Thyssen Krupp | 515 |
| Logan Lake Mine (No.2) | Lornex Highland Valley Copper | Canada | North America | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 1450 | Semi-mobile / Semi fix | 3 | 1987 | 6,600 | Thyssen Krupp | 515 |
| St. Barbara Mine | Enel Compartimento di Firenze | Italy | Europe | Coal | Coal | Feeder breaker | Chain conveyor | Crawler tracks | 135 | Fully-mobile | - | 1987 | 800 | Thyssen Krupp | 200 |
| - | Singleton Birch | UK | Europe | Chalk | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 1987 | 600 | MMD | 225 |
| - | Singleton Birch | UK | Europe | Chalk | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 1987 | 400 | MMD | 150 |
| Boddignton Gold Mine | Alcoa Western Aluminium | Australia | Australasia | Gold | Gold Ore | Feeder breaker | Chain conveyor | Crawler tracks | 75 | Fully-mobile | - | 1986 | 1,350 | Thyssen Krupp | 150 |
| Dallas Midlothian Works | Box Crow Cement | USA | North America | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Tyre system | 400 | Fully-mobile | - | 1986 | 1,200 | Thyssen Krupp | 370 |
| St. Varent Quarry | Carrieres de la Noubleau | France | Europe | Diorite | Industrial/mass commodities | Jaw crusher | Apron feeder | Crawler tracks | 520 | Fully-mobile | - | 1986 | 1,000 | Thyssen Krupp | 160 |
| Werk Harburg | Märker Zementwerke GmbH | Germany | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Transport crawler | 430 | Semi-mobile / Semi fix | 1 | 1986 | 1,000 | Thyssen Krupp | 500 |
| Mount Whaleback Mine | Mt. Newman Mining Co. | Australia | Australasia | Iron | Iron ore | Jaw crusher | Apron feeder | Transport crawler | 1100 | Semi-mobile / Semi fix | 3 | 1986 | 6,000 | Thyssen Krupp | 300 |
| Bingham Canyon Mine | Kennecott Company | USA | North America | Copper | Copper | Gyratory crusher | 'Direct feeding' | Transport crawler | 1250 | Semi-mobile / Semi fix | 1 | 1986 | 9,000 | Thyssen Krupp | 735 |
| Huolinhe Mine | Huolinhe Coal Mine | China | Central Asia | Coal | Coal | Double roll crusher | chain conveyor | - | - | Semi-mobile / Semi fix | - | 1986 | 2,000 | Sandvik | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mannersdorf Works | Perlmooser Zementwerke AG | Austria | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 540 | Fully-mobile | - | 1986 | 750 | Thyssen Krupp | 1120 |
| - | Singleton Birch | UK | Europe | Chalk | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | | 1986 | 400 | MMD | 150 |
| Werk Dotternhausen | Rohrbach Zement, | Germany | Europe | Oil sand | Oil sand | Impact crusher | Chain conveyor | Tyre system | 195 | Fully-mobile | - | 1986 | 300 | Thyssen Krupp | 350 |
| Buraydah Works (No.1) | Qassim Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 730 | Fully-mobile | - | 1985 | 1,250 | Thyssen Krupp | 1930 |
| Umm Araj Works | Southern Province Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 830 | Fully-mobile | - | 1985 | 1,000 | Thyssen Krupp | 370 |
| Naubastae Works | Jaypee Rewa Cement Ltd. | India | Central Asia | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 375 | Fully-mobile | - | 1985 | 800 | Thyssen Krupp | 650 |
| Riyadh Works (No.2) | Yamama Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 592 | Fully-mobile | - | 1985 | 800 | Thyssen Krupp | 1400 |
| Fort McMurray Mine (No.2) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Feeder breaker | Chain conveyor | Transport crawler | 230 | Semi-mobile / Semi fix | 2 | 1985 | 2,800 | Thyssen Krupp | 360 |
| Fort McMurray Mine (No.2) | Syncrude Canada Ltd. | Canada | North America | Oil sand | Oil sand | Feeder breaker | Chain conveyor | Transport crawler | 230 | Semi-mobile / Semi fix | 2 | 1985 | 2,800 | Thyssen Krupp | 360 |
| Ragland Works | National Cement Co. - Ciment Vicat | USA | North America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 300 | Fully-mobile | - | 1985 | 720 | Thyssen Krupp | 750 |
| El-Hammam Quarry | Alexandria Portland Cement Co. | Egypt | Africa | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 400 | Fully-mobile | - | 1985 | 600 | Thyssen Krupp | 1260 |
| Abu Sier Quarry | Alexandria Portland Cement Co. | Egypt | Africa | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 360 | Fully-mobile | - | 1985 | 600 | Thyssen Krupp | 630 |
| Hofuf Works (No.2) | Saudi Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 500 | Fully-mobile | - | 1985 | 500 | Thyssen Krupp | 850 |
| Pawlodar -I | Eurasian Natural Resources | Kazakhstan | CIS | Bauxite | Bauxit | Impact crusher | ? | Crawler tracks | - | Fully-mobile | - | 1985 | 450 | FAM | - |
| Pawlodar -II | Eurasian Natural Resources | Kazakhstan | CIS | Bauxite | Bauxit | Impact crusher | ? | Crawler tracks | - | Fully-mobile | - | 1985 | 450 | FAM | - |
| San Antonio Quarry | Redland Worth Corporation | USA | North America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 1150 | Fully-mobile | - | 1984 | 4,500 | Thyssen Krupp | 2200 |
| Watsonville Logan Quarry | Graniterock Co | USA | North America | Granite | Industrial/mass commodities | Gyratory crusher | Apron feeder | Tyre system | 600 | Fully-mobile | - | 1984 | 2,500 | Thyssen Krupp | 300 |
| Usine La Grave de Peille | Ciments Vicat | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Transport crawler | 526 | Semi-mobile / Semi fix | 1 | 1984 | 850 | Thyssen Krupp | 1200 |
| Vancouver Island Mine | Island Copper Mine BHP | Canada | North America | Copper | Copper | Gyratory crusher | Apron feeder | Transport crawler | 900 | Semi-mobile / Semi fix | 1 | 1984 | 3,600 | Thyssen Krupp | 370 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mae Moh Mine (No.1) | Bangkok Motor Equipment Co. Ltd. | Thailand | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 431 | Semi-mobile / Semi fix | 2 | 1984 | 3,600 | Thyssen Krupp | 800 |
| Mae Moh Mine (No.2) | Bangkok Motor Equipment Co. Ltd. | Thailand | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 430 | Semi-mobile / Semi fix | 2 | 1984 | 3,600 | Thyssen Krupp | 800 |
| Mae Moh Mine (No.3) | Bangkok Motor Equipment Co. Ltd. | Thailand | Central Asia | Coal | Overburden | Double roll crusher | Apron feeder | Transport crawler | 430 | Semi-mobile / Semi fix | 2 | 1984 | 3,600 | Thyssen Krupp | 800 |
| - | Singleton Birch | UK | Europe | Chalk | Industrial/mass commodities | Sizer | - | - | - | Fully-mobile | - | 1984 | 600 | MMD | 225 |
| Werk Höver (No.5) | Nordcement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 350 | Fully-mobile | - | 1984 | 500 | Thyssen Krupp | 560 |
| Torr Works Quarry | Foster Yeoman Ltd. | Great Britain | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | Apron feeder | Hydraulic walking mechansim | 1150 | Fully-mobile | - | 1983 | 3,900 | Thyssen Krupp | 400 |
| New Brunswick Mine | Brunswick Mining & Smelting | Canada | North America | Basalt | Industrial/mass commodities | Gyratory crusher | Apron feeder | Hydraulic walking mechansim | 630 | Fully-mobile | - | 1983 | 1,500 | Thyssen Krupp | 285 |
| Omarska Jezero Mine | RMK ZENICA RO PROMET | Bosnia and Herzegovina | Europe | Iron | Iron ore | Double roll crusher | Apron feeder | Crawler tracks | 375 | Fully-mobile | - | 1983 | 1,000 | Thyssen Krupp | 330 |
| Zoutkloof Works | Cape Portland Cement | South Africa | Africa | Limestone | Industrial/mass commodities | Gyratory crusher | Apron feeder | Transport crawler | 860 | Semi-mobile / Semi fix | 1 | 1983 | 1,100 | Thyssen Krupp | 400 |
| Ulan Mine | White Industries-Ulan Coal | Australia | Australasia | Coal | Coal | Double roll crusher | Apron feeder | Tyre system | 540 | Fully-mobile | - | 1982 | 2,300 | Thyssen Krupp | 400 |
| Boddington Mine | Worsley Aluminium | Australia | Australasia | Bauxite | Bauxit | Jaw crusher | Apron feeder | Hydraulic walking mechansim | 850 | Fully-mobile | - | 1982 | 2,000 | Thyssen Krupp | 350 |
| Phalaborwa Mine | Foskor | South Africa | Africa | Phoscorite (Copper, Magnetit, Silver, Apatit) | Copper | Gyratory crusher | Apron feeder | Hydraulic walking mechansim | 825 | Fully-mobile | - | 1981 | 2,000 | Thyssen Krupp | 450 |
| Wagerup Willowdale Mine | Alcoa Western Aluminium | Australia | Australasia | Bauxite | Bauxit | Jaw crusher | Apron feeder | Hydraulic walking mechansim | 850 | Fully-mobile | - | 1981 | 2,000 | Thyssen Krupp | 350 |
| Sishen Mine | Rio Tinto | South Africa | Africa | Iron | Iron ore | Gyratory crusher | Direct feeding' / Apron feeder | Transport crawler | 2390 | Semi-mobile / Semi fix | 3 | 1981 | 6,000 | Thyssen Krupp | 900 |
| Grootegeluk Mine | ISCOR Ltd. | South Africa | Africa | Coal | Overburden | Gyratory crusher | Apron feeder | Hydraulic walking mechansim | 1100 | Fully-mobile | - | 1980 | 3,000 | Thyssen Krupp | 400 |
| Steinbruch Deuna | DYCKERHOFF ZEMENTWERKE AG | Germany | Europe | Chalk | Industrial/mass commodities | Impact crusher | - | Crawler tracks | - | Fully-mobile | - | 1980 | 800 | FAM | - |
| Steinbruch Müchehof | - | Germany | Europe | Chalk | Industrial/mass commodities | Gyratory crusher | - | Crawler tracks | - | Fully-mobile | - | 1980 | 800 | FAM | - |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Steinbruch Rübeland | - | Germany | Europe | Chalk | Industrial/mass commodities | Gyratory crusher | ? | Crawler tracks | - | Fully-mobile | - | 1980 | 800 | FAM | - |
| SteinbruchElbingerrode | - | Germany | Europe | Chalk | Industrial/mass commodities | Gyratory crusher | ? | Crawler tracks | - | Fully-mobile | - | 1980 | 700 | FAM | - |
| Hidalgo Jasso Works | Cemento Portland La Cruz Azul | Mexico | North America | Limestone | Industrial/mass commodities | Gyratory crusher | 'Direct feeding' | Tyre system | 417 | Semi-mobile / Semi fix | 1 | 1980 | 600 | Thyssen Krupp | 250 |
| Lagunas Works | Cemento Portland La Cruz Azul | Mexico | North America | Limestone | Industrial/mass commodities | Gyratory crusher | 'Direct feeding' | Tyre system | 417 | Semi-mobile / Semi fix | 1 | 1980 | 600 | Thyssen Krupp | 250 |
| Shagamu Works (No.2) | The West African Portland Cement Co | Nigeria | Africa | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Tyre system | 450 | Fully-mobile | - | 1980 | 500 | Thyssen Krupp | 180 |
| Ain Dar Works (No.1) | Saudi Bahraini Cement Co. | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Gyratory crusher | Apron feeder | Hydraulic walking mechansim | 750 | Fully-mobile | - | 1979 | 1,250 | Thyssen Krupp | 430 |
| Dunbar Works | Blue Circle Cements, | Great Britain | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Drag type tyre traveling mechanism | 670 | Fully-mobile | - | 1979 | 1,000 | Thyssen Krupp | 900 |
| Lomé Works | Cimao Togo Cement, | Togo | Africa | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Tyre system "exchangeable" | 790 | Semi-mobile / Semi fix | 4 | 1978 | 900 | Thyssen Krupp | - |
| Meirama Works | Lignitos de Meirama S.A. | Spain | Europe | Granite | Industrial/mass commodities | Gyratory crusher | Reciprocating plate feeder | Transport crawler | 485 | Semi-mobile / Semi fix | 1 | 1978 | 600 | Thyssen Krupp | 250 |
| Brunnen Works | K. Hürlimann Söhne AG | Switzerland | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | 'Direct feeding' | Tyre system | 245 | Fully-mobile | - | 1978 | 500 | Thyssen Krupp | 250 |
| Ashaka Works | Ashaka Cement Co. Ltd. | Nigeria | Africa | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | - | - | Fully-mobile | - | 1977 | 800 | Thyssen Krupp | 1100 |
| Bussac Quarry | Ciments Francais | France | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Tyre piggy back transporter | 455 | Semi-mobile / Semi fix | 2 | 1977 | 900 | Thyssen Krupp | 720 |
| Dudfield Works | Anglo Alpha Cement Ltd. | South Africa | Africa | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 520 | Fully-mobile | - | 1976 | 1,100 | Thyssen Krupp | 730 |
| Werk Lengfurt | Heidelberger Zement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 920 | Fully-mobile | - | 1976 | 1,000 | Thyssen Krupp | 1600 |
| Monselice Works | Italcementi SPA | Italy | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 600 | Fully-mobile | - | 1976 | 1,000 | Thyssen Krupp | 1600 |
| Riyadh Works (No.1) | Yamama Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 600 | Fully-mobile | - | 1976 | 800 | Thyssen Krupp | 1300 |
| Shagamu Works (No.1) | The West African Portland Cement Co | Nigeria | Africa | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Tyre system | 405 | Fully-mobile | - | 1976 | 500 | Thyssen Krupp | 180 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Huntly Mine (No.2) | Alcoa Western Aluminium | Australia | Australasia | Bauxite | Bauxit | Jaw crusher | Apron feeder | Hydraulic walking mechansim | 560 | Fully-mobile | - | 1975 | 1,700 | Thyssen Krupp | 230 |
| Rumelange Works | Intermoselle Sarl | Luxembourg | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Hydraulic walking mechansim | 600 | Fully-mobile | - | 1975 | 1,500 | Thyssen Krupp | 400 |
| Halkis Works | Halkis Cement Company | Greece | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 1250 | Fully-mobile | - | 1975 | 1,000 | Thyssen Krupp | 1600 |
| Hofuf Works (No.1) | Saudi Cement Company | Saudi Arabia | Middle East | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 615 | Fully-mobile | - | 1975 | 1,000 | Thyssen Krupp | 1520 |
| Vallcarca Works | Cementos Uniland | Spain | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 374 | Fully-mobile | - | 1975 | 600 | Thyssen Krupp | 920 |
| Monjos Works | Cementos Uniland | Spain | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 374 | Fully-mobile | - | 1975 | 600 | Thyssen Krupp | 920 |
| Taranto Works (No.2) | ITALSIDER | Italy | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | 'Direct feeding' | Transport crawler | 480 | Semi-mobile / Semi fix | 1 | 1975 | 1,000 | Thyssen Krupp | 250 |
| Le Havre Quarry | Ciments Lafarge | France | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Tyre system | 420 | Fully-mobile | - | 1974 | 1,200 | Thyssen Krupp | 360 |
| Apaxco Centro Works | Cementos Apasco SA | Mexico | North America | Limestone | Industrial/mass commodities | Gyratory crusher | Apron feeder | Hydraulic walking mechansim | 650 | Fully-mobile | - | 1974 | 1,000 | Thyssen Krupp | 370 |
| Rekingen Works | Cementfabrik Holderbank | Switzerland | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 610 | Fully-mobile | - | 1974 | 770 | Thyssen Krupp | 1250 |
| Boussens Quarry | Ciments Lafarge | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 280 | Fully-mobile | - | 1974 | 600 | Thyssen Krupp | 400 |
| Brunnen Works | K. Hürlimann Söhne AG | Switzerland | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Tyre system | 240 | Fully-mobile | - | 1974 | 500 | Thyssen Krupp | 480 |
| Altkirch Quarry | S.A. Des Chaux et Ciments Portland du Haut Rhin | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 660 | Fully-mobile | - | 1973 | 850 | Thyssen Krupp | 1300 |
| Werk Hardegsen | Nordcement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 580 | Fully-mobile | - | 1973 | 600 | Thyssen Krupp | 990 |
| Maddaloni/Caserta Works | Cementerie del Tirreno SPA | Italy | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 450 | Fully-mobile | - | 1973 | 500 | Thyssen Krupp | 500 |
| Werk Karlstadt | E. Schwenk Zementwerke KG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 600 | Fully-mobile | - | 1972 | 1,000 | Thyssen Krupp | 1600 |
| Taranto Works (No.1) | Italsider | Italy | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 550 | Fully-mobile | - | 1972 | 1,000 | Thyssen Krupp | 700 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Werk Rottenburg | C. Baresel AG | Germany | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | 'Direct feeding' | Hydraulic walking mechansim | 290 | Fully-mobile | - | 1972 | 700 | Thyssen Krupp | 200 |
| Bath Works | Canada Cement Lafarge Ltd. | Canada | North America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 500 | Fully-mobile | - | 1972 | 650 | Thyssen Krupp | 1320 |
| Werk Höver (No.4) | Nordcement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 345 | Fully-mobile | - | 1972 | 500 | Thyssen Krupp | 560 |
| Beeste Kroal Works | Pretoria Portland Cement Co. | South Africa | Africa | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 300 | Fully-mobile | - | 1972 | 420 | Thyssen Krupp | 800 |
| Huntly Mine (No.1) | Alcoa Western Aluminium | Australia | Australasia | Bauxite | Bauxit | Jaw crusher | Apron feeder | Hydraulic walking mechansim | 420 | Fully-mobile | - | 1971 | 1,500 | Thyssen Krupp | 230 |
| Werk Höver (No.3) | Nordcement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 345 | Fully-mobile | - | 1971 | 500 | Thyssen Krupp | 560 |
| Rochefort Quarry | Ciments de Champagnole S.A. | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 450 | Fully-mobile | - | 1971 | 500 | Thyssen Krupp | 750 |
| Werk Misburg (No.3) | Hannoversche Portland-Zementwerke | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 225 | Fully-mobile | - | 1971 | 450 | Thyssen Krupp | 400 |
| Castrovillari Works | Italcementi | Italy | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 395 | Fully-mobile | - | 1971 | 400 | Thyssen Krupp | 600 |
| Matera Works | Italcementi | Italy | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 385 | Fully-mobile | - | 1971 | 400 | Thyssen Krupp | 600 |
| Spoleto Works | Cementerie del Tirreno SPA | Italy | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 235 | Fully-mobile | - | 1971 | 400 | Thyssen Krupp | 380 |
| Abouo Works | Cementi del Cantabrico | Spain | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 325 | Fully-mobile | - | 1971 | 325 | Thyssen Krupp | 680 |
| Northfleet Works (No.2) | Blue Circle Cements | Great Britain | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 520 | Fully-mobile | - | 1970 | 1,000 | Thyssen Krupp | 1000 |
| Oviedo Works | S.A. Tudela-Lafarge, | Spain | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | 'Direct feeding' | Hydraulic walking mechansim | 280 | Fully-mobile | - | 1970 | 700 | Thyssen Krupp | 200 |
| Merone Works | Cementeria di Merone | Italy | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Apron feeder | Hydraulic walking mechansim | 420 | Fully-mobile | - | 1970 | 600 | Thyssen Krupp | 220 |
| Port-La-Nouvelle Quarry | Ciments Lafarge | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 345 | Fully-mobile | - | 1970 | 400 | Thyssen Krupp | 600 |
| Cassis Quarry | Ciments Lafarge | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Drag type tyre traveling mechanism | 52 | Fully-mobile | - | 1970 | 190 | Thyssen Krupp | 160 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northfleet Works (No.1) | Blue Circle Cements | Great Britain | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 520 | Fully-mobile | - | 1969 | 1,000 | Thyssen Krupp | 1000 |
| Werk Amöneburg/Flörsheim | Dyckerhoff Zementwerke AG | Germany | Europe | Limestone | Industrial/mass commodities | Double roll crusher | Belt conveyor | Hydraulic walking mechansim | 520 | Fully-mobile | - | 1969 | 800 | Thyssen Krupp | 330 |
| Werk Weisenau | Heidelberger Zement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 385 | Fully-mobile | - | 1969 | 600 | Thyssen Krupp | 1080 |
| Wildegg Works | Jura Cement Fabriken | Switzerland | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 320 | Fully-mobile | - | 1969 | 500 | Thyssen Krupp | 800 |
| FrangeyQuarry | Ciments Lafarge | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 320 | Fully-mobile | - | 1969 | 325 | Thyssen Krupp | 570 |
| Ranteil Quarry | Ciments du Sud-Quest (Lafarge) | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Hydraulic walking mechansim | 250 | Fully-mobile | - | 1968 | 350 | Thyssen Krupp | 440 |
| João Pessoa Works | Cia. Paraiba de CimentoPortland | Brazil | South America | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 285 | Fully-mobile | - | 1968 | 260 | Thyssen Krupp | 500 |
| Balangero Works | Amiantifera S.P.A. | Italy | Europe | Aggregartes | Industrial/mass commodities | Gyratory crusher | Belt conveyor | Hydraulic walking mechansim | 400 | Fully-mobile | - | 1967 | 700 | Thyssen Krupp | 160 |
| Vaujours Quarry | Lambert | France | Europe | Gypsum rock | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 285 | Fully-mobile | - | 1967 | 400 | Thyssen Krupp | 500 |
| Fradera Works | Cementos Frader S.A. | Spain | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 192 | Fully-mobile | - | 1967 | 200 | Thyssen Krupp | 220 |
| St. Pierre la Cour Quarry | Ciments Lafarge | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 425 | Fully-mobile | - | 1966 | 750 | Thyssen Krupp | 750 |
| Gargenville Quarry | Poliet et Chausson | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 425 | Fully-mobile | - | 1966 | 700 | Thyssen Krupp | 810 |
| Kirchdorf Works | Portland-Cementwerke Hofmann & Co. | Austria | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Drag type tyre traveling mechanism | 225 | Fully-mobile | - | 1966 | 335 | Thyssen Krupp | 500 |
| Werk Hemkenrode | Elmkalkwerke Schnuch KG | Germany | Europe | Limestone | Industrial/mass commodities | Gyratory crusher | Belt conveyor | Hydraulic walking mechansim | 300 | Fully-mobile | - | 1966 | 300 | Thyssen Krupp | 90 |
| Werk Helen | Kalk, Mergel & Steinwerke Hehlen | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Shovel-feeder | Drag type tyre traveling mechanism | 65 | Fully-mobile | - | 1966 | 100 | Thyssen Krupp | 96 |
| Werk Misburg (No.2) | Hannoversche Portland Zementwerke | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 226 | Fully-mobile | - | 1965 | 450 | Thyssen Krupp | 360 |
| La Malle Quarry | Ciments Lafarge | France | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 340 | Fully-mobile | - | 1964 | 400 | Thyssen Krupp | 440 |

| Mine Name | Company Name | Country | Region | Commodity | Transported material | Type of crusher | Type of Feeder | Transport system | Station service weight [t] | Mobility | Number Modules | Year of commissioning | Systems Capacity [t/h] | Manufacturer of System | Crusher Power [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Werk Wunstorf | Nordcement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 206 | Fully-mobile | - | 1964 | 200 | Thyssen Krupp | 290 |
| Werk Höver (No.2) | Nordcement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 143 | Fully-mobile | - | 1962 | 300 | Thyssen Krupp | 145 |
| Werk Misburg (No.1) | Hannoversche Portland-Zement werke | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 128 | Fully-mobile | - | 1961 | 250 | Thyssen Krupp | 96 |
| Werk Höver (No.1) | Nordcement AG | Germany | Europe | Limestone | Industrial/mass commodities | Impact crusher | Apron feeder | Crawler tracks | 145 | Fully-mobile | - | 1956 | 250 | Thyssen Krupp | 96 |

## Appendix II - Mathematical Proof of Equation (4-11)

When considering a sequence of truck loading times while ignoring potential truck deficiency times as only effective operating time is used as a reference. The basic principle of marked point processes can be used [188].

The starting points $t_i$ of the loading process create a stationary point process. It´s intensity (mean point density) equals

$$\lambda = \frac{1}{\overline{t_{Lo}}}$$

The points $t_i$ are marked by the truck payloads $c_T$ of their respective trucks which were loaded. Consequently, this process can be explained by a marked point process. Which mean mark is equal to $\overline{c_T}$, the mean truck payload.

Of interest is the mean loaded mass $C_L$ per unit time, loader capacity. Within a time interval $[\tau_1, \tau_2]$ the mean loader capacity equals

$$C_L(\tau_1, \tau_2) = \sum_{i:\tau_1 < t_i < \tau_2} c_T$$

The associated mean, according to equation (4.34) in [188] is equal to

$$E(C_L) = \lambda c_T(\tau_2 - \tau_1)$$

Thus the relation

$$C_L = \lambda c_T$$

or

$$C_L = \frac{\overline{c_T}}{\overline{t_{Lo}}}$$

holds.

## Appendix III - Bucket Cycle Times Data

Appendix III can be found within the attached CD-ROM.

## Appendix IV - Repair Time Data

Appendix IV can be found within the attached CD-ROM.