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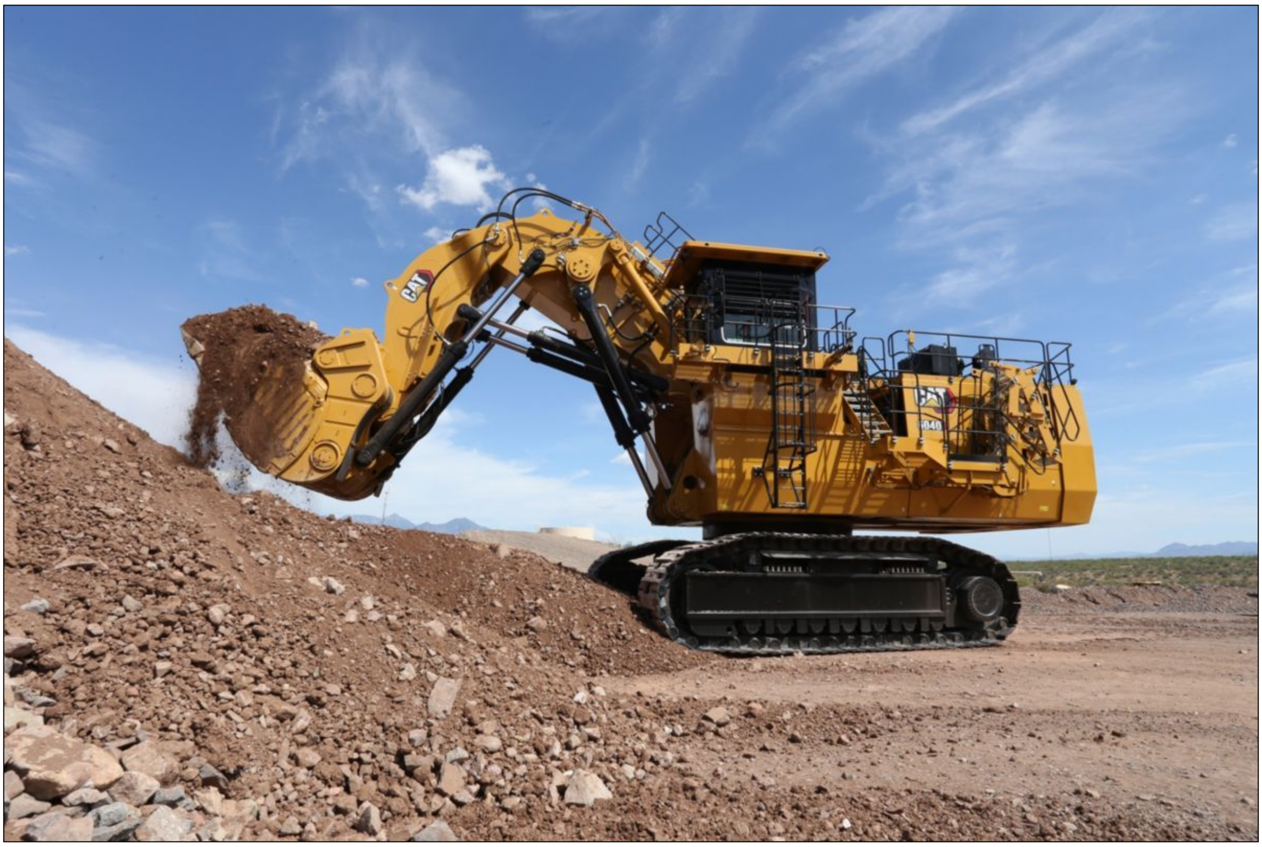

An assessment of the underlying causes for the difference between theoretical and real-world production rates of mining shovels.

by

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Abstract

The goal of a mining operation is to extract the maximum value from exploiting the orebody. The equipment used by these mining operations has a nominally rated performance to achieve needed annual production. However, this nominally rated performance is not achieved during operations. This study assesses the underlying causes of reduced shovel production in a mining operation.

The following research questions will be answered in this study: What factors contribute to deviations from the predicted performance? What factors are the most significant? What is the effect of automated trucks on shovel productivity? Can a data-driven model be developed to predict the actual productivity of the shovel in the real world?

The underlying causes of reduced shovel production are assessed through a literature review and five case studies. The case studies consisted of three data analytical desk studies, interviews with industry professionals, and a mine visit to north Africa.

The literature review shows that the mining industry uses formulas to determine the theoretical production rates. The factors in the shovel production formula should be predicted with frequency distributions. Also, truck automation will increase trucking hours, impacting shovel productivity through truck exchange time. The first case study shows a sensitivity analysis of the shovel formula. This sensitivity analysis shows that the swell factor, density, bucket fill, efficiency, and cycle time have a more significant impact than truck exchange time, dumping of the first bucket, and the number of cycles. The second case study shows the underperformance of different electric rope shovel models in different mining operations. The third case study compares the theoretical shovel capacity with the total material moved for 16 years. This shovel capacity and total material ratio should be between 1-2.5 for a mining operation to be classified as above-average-in-class. The fourth case study shows the different factors influencing shovel productivity based on the interviewees' responses. The last case study shows the effects of operational decisions on a mining operation. The literature review and case studies are used to develop a flowchart regarding the factors influencing shovel productivity.

This flowchart was used to synthesise the results. The difference between theoretical and real-world production rates can be decreased when the frequency distributions are known for all the shovel production formula factors. This shovel production formula for annual production rate can be divided into three main pillars. These three pillars are the hourly production rate, use of availability, and mechanical availability. The pillars allow OEMs or mining companies to implement the correct improvement measures to improve shovel productivity. However, one solution for every mining operation will be impossible due to the uncertainty in the data and variability of each mining operation.

To conclude, the factors that contribute to deviations from the predicted performance are categorised as uncontrollable (weather and geographical location), direct (density and cycle time), and indirect (fragmentation and face dimensions), which all impact shovel productivity. The most significant factors are not found during the study, but solving underperformance in the direct factors will solve most of the problems. The effect of automated trucks on shovel productivity will result in additional trucking capacity, which will need to be absorbed by the shovel. Lastly, a data-driven model can be developed with access to all the data from a mining operation. However, this data is often not available to an OEM. Therefore, it is not advisable to develop such a model.

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1 Introduction

Mining companies are trying to find improvements without needing significant capital investment due to stagnation of workforce efficiency, increasing fuel costs, and pressure from investors. The two main drivers for the improvement focus of mining companies were the end of the super-cycle of mining and the arrival of the Global Financial Crisis in which the marginal costs grew faster than the marginal increase in production (Botin and Vergara, 2015).

The typical workflow for hard rock mining consists of drill, blast, load, and haul. For loading and hauling, a combination of shovels and trucks are used in the mining industry. The cost of loading and hauling operations represents approximately 50 to 60 % of the total cost of material handling (Burt and Caccetta, 2018, Alarie and Gamache, 2002, etc.). The trucks have been the focus of improvements for the last decade because the potential gains were much higher than the shovels. However, the improvements are becoming less impacted through past innovations, leading to a shift in focus on other parts of the mining cycle. The part that works together with the hauling is the loading part of the mining cycle. According to Tapia et al. (2021), a loading and haulage system's productivity is determined by the equipment's characteristics, associated times, and the material's loading and transporting characteristics. Therefore, the loading of the trucks with different sizes of shovels will be used for optimised performance. Currently, shovel production is calculated using a formula used throughout the industry. This way of calculating shovel production is often not a realistic representation of real-world shovel production that can be achieved in day-to-day operations. Mining companies will receive production rates that cannot be met with shovels sold to the mining operations. Since loading and hauling are directly related, the new development regarding truck automation can significantly impact the shovel's usage and productivity.

Therefore, this study will find the underlying causes for the reduced shovel production and a model will be developed to improve the shovel production rate estimation. It was hypothesised that several factors would influence shovel productivity, which will all have a different impact. However, it is very likely that a couple of factors significantly impact shovel productivity. These factors will solve the majority of the underperformance. Furthermore, the effect of truck automation on shovel productivity will be investigated in this study. It was hypothesised that the increase in efficiency of the automation of the trucks would lead to increased productivity of the shovel.

This study will first review the literature needed to understand the current procedures used in the mining industry. Then different case studies will be executed to find the underlying causes for underperformance in shovel productivity. The literature and case studies will be used to develop a flow chart diagram, which can be used to improve the performance of the shovel. Furthermore, the literature and a case study will be used to show the effect of automated trucks on shovel productivity.

2 Objective & Scope

2.1 Hypothesis

Shovel productivity can be negatively influenced in many different ways. The factors that influence shovel productivity are external factors because, in a controlled environment, the equipment can achieve theoretical production rates. Therefore, the negative contribution could result from the shovel's non-optimum utilisation. The factors could be one or more of the following factors: geographical location, seasonality, shovel age, operator experience, operator training, mine planning, mechanical availability, commodity, operational procedures, and shovel and truck matching. Furthermore, the increase in efficiency of the automation of the trucks will lead to increased productivity of the shovel.

2.2 Objective

This study aims to find the underlying causes for the underperformance of mining shovels, which will be investigated by finding differences between the theoretical and real-world production rates of a mining shovel. Furthermore, the effect of automated trucks on shovel productivity is a secondary aim of this study.

2.3 Research questions

The hypothesis and objective of this study have led to the following research questions, which will form the basis of this study.

1. What are the factors that contribute to deviations from the predicted performance?
2. What factors are the most significant?
3. Can a data-driven model be developed to predict the actual productivity of the shovel in the real world?
4. What is the effect of automated trucks on shovel productivity?

2.4 Methodology

A literature review and multiple small-scale case studies were conducted to understand better the influences on shovel productivity. Reviewing the literature provides information on factors that have already been shown to influence shovel productivity. The case studies develop an understanding of all the different aspects that may influence shovel productivity. These case studies range from a sensitivity analysis of the shovel productivity formula, interviews with varying people working in the mining industry, and a site visit to see an actual mining operation. All these case studies will be used to develop a flow chart of all factors influencing shovel productivity. A fleet size diagnostic guide is developed, which can assist Caterpillar employees in improving fleet size selection for a project or improve the performance of the shovel operating in a mine. The fleet size diagnostic guide will increase the likelihood that the theoretical production rates will be achieved in the real world.

2.5 Scope

The study covers the underlying causes of the difference between theoretical and real-world production rates. Background information related to the basics of mining shovels and calculating production rates for shovels is shown in the literature review. The literature develops the understanding of the topic for the reader. Furthermore, the scope of this study comprises the following topics:

- Hydraulic shovels and electric rope shovels
- All the steps within a mining operation range from reserve estimation to the finished commodity.
- Gold, iron, and copper ore operations are included.
- Four pass shovel and truck match is only used during this study

- automation of trucks

Due to the limited time available for this study, the following subjects will be outside the scope of the study.

- Wheel loaders and drag lines
- Development of a quantitative model with the use of data from an existing mine
- Operations that use an in-pit crusher (anything other than a classic truck and shovel operation)
- Underground mining operations
- All other commodities that are mined
- A detailed analysis of the efficiency factor
- Detailed analysis of the time usage model and the effect on the efficiency factor

2.6 Outline of the study

The introduction and objective of this study have been discussed in the previous and current chapters. The literature review is given in chapter 3. The literature review will give the reader the necessary information to understand this study regarding the mining process and shovels. Furthermore, information regarding the shovel production formula, the factors in this formula, and automation will be explained.

In chapter 4, different case studies will be executed, which are the central part of this study. Five different case studies will be done with the following topics: Sensitivity analysis of theoretical production rate, Analysis of Copper Mines in South America, Annual production versus theoretical fleet production, Interviews with industry experts, and Visit to a mine site in north Africa.

The information of all these case studies is synthesised (chapter 5), which brings together all the information from the literature review and case studies. Chapter 5 consists of a flowchart of all the factors influencing shovel productivity.

Chapter 6 is a fleet size diagnostic guide, which Caterpillar employees can use to improve fleet size selection for a project. This fleet diagnostic guide can also be used to improve underperforming shovels.

This study ends with discussion, conclusion, and recommendations in chapters 7, 8, and 9.

3 Literature review

Before finding the root cause for the underperformance of shovels, background information regarding the mining process and a general introduction to shovels is needed. Furthermore, the following subjects will also be introduced: key performance indicators (KPIs), pass match between shovels and trucks, time usage model, loading cycle, and loading method. After this, the shovel productivity formula is introduced. Here, all the different factors and the effect of skewness in a frequency distribution will be explained.

3.1 The mining process flow

First, the general workflow and data flow within a mine are explained, including the reconciliation methods used to verify the actual data and improve the assumptions.

Before a mine can be developed, the amount of resources will need to be estimated by drilling in a zone with potential valuable ore (Lowrie, 2002). In the drilled zone, interpolation will be done between the drilled holes. The interpolation will tell the estimated amount of resources within the exploration and drilled location, which is the first step shown in figure 1 (Soofastaei, 2022). The next step is to transform the resources into reserves, which is done by implementing an economic model. The reserves are the part of the resource that is economically and profitable to exploit. When reserves are available, mine planning is made to extract the resources in the most efficient way (Lowrie, 2002). During all these processes, the assumed data is reconciled, which includes eight different data flows (see numbered arrows in figure 1) (Morley and Thompson, 2006). The next step is the production of the mine, which includes the dispatch of all the drills, shovels, trucks, and auxiliary machines. The shovel loads the material on the trucks. These loaded trucks will move the material to the crusher, processing plant, or waste dump. The processing plant delivers an end product that is sold to customers. The end product can vary for each operation and commodity. The end product for gold or silver is a bar, while iron ore can be sold as pellets.

The mine production process flow is shown in figure 1. The drill and blast team will create broken stocks that will be available for the shovel to load onto trucks. When the shovel has moved all the material, the walls will have to be cleared of loose rocks that can be a safety hazard. After the wall is cleared, the bench will be prepared for drilling. Furthermore, the loading machines will also have to move oversized material, which will need to be reduced in size and re-handled. The hauling fleet can dump the material at different locations. These locations include the dumping of the waste, the hauling of the ore to the crusher, the rehandling of the ore to the crusher, or the stockpiling of the ore.

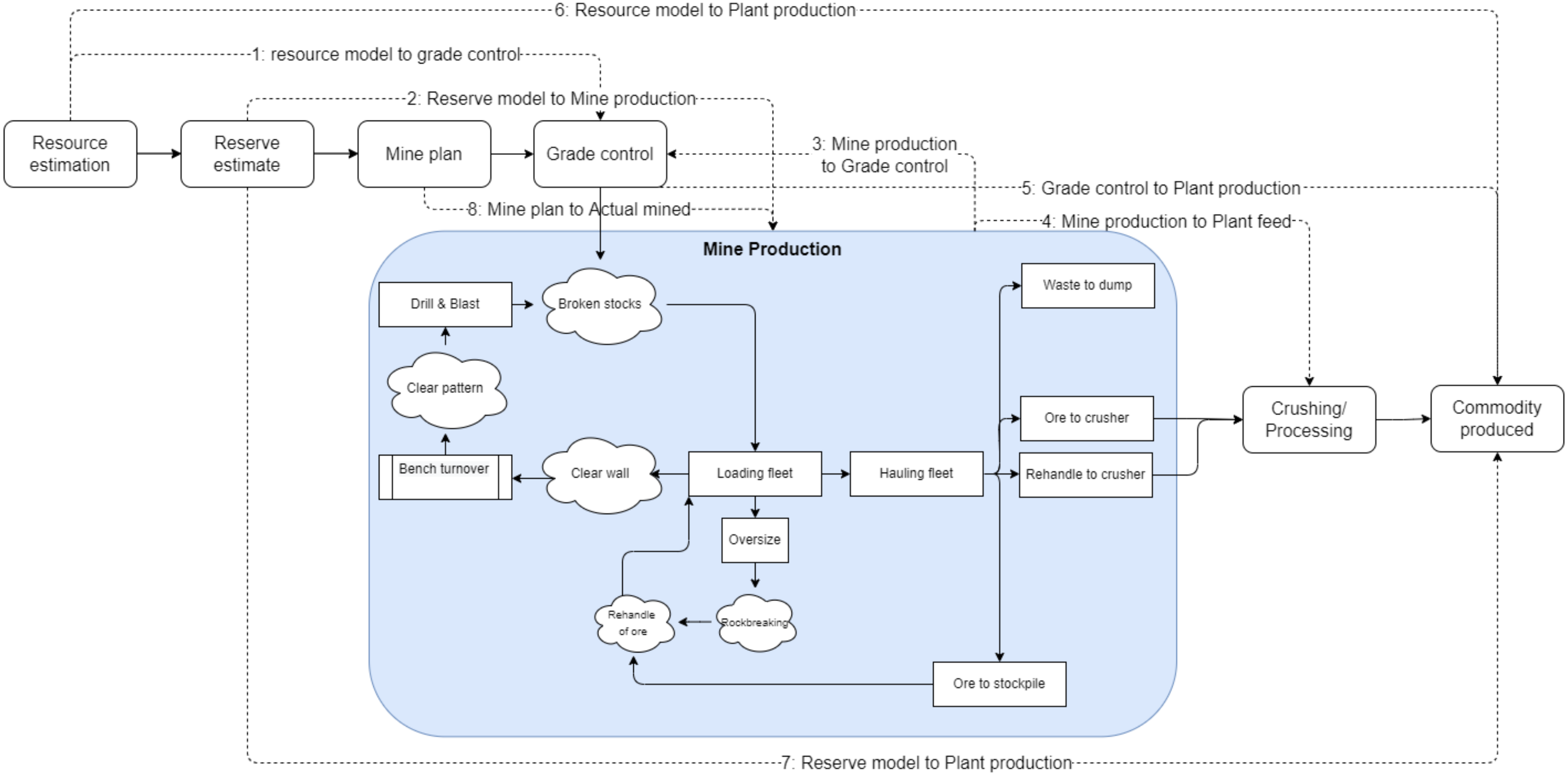


Figure 1: Generalised mining process map showing eight common reconciliation points (Morley and Thompson, 2006) with additional details on mine production

Reconciliation in mining is about comparing an estimate with a measurement (Morley and Thompson, 2006). Estimates are made in the following processes: the resource model, the ore reserve model, the grade control information, and the mining production plan. Measurements of real-world data are performed during the following processes: survey information, material movement records, or official production from the processing plant. The purpose of the reconciliation is as follows, according to Morley and Thompson (2006):

- Measure the performance of the operation against targets
- Confirm grade and tonnage estimation accuracy
- Ensure valuation of mineral assets is accurate
- Provide key performance indicators

According to Morley and Thompson (2006), eight key relationships should be used for reconciliation within the mine. These eight key relationships have been highlighted with numbered arrows in figure 1. The key reconciliations that any mining operation should monitor on an ongoing basis. In table 1, the numbered arrows from figure 1 are explained.

Table 1: Key reconciliation relationships in a mining operation (Morley and Thompson, 2006)

	Reconciliation	**Data sources**	**Time frame**	**Purpose**
1.	Resource model to grade control	Resource model Grade control mining block designs	Monthly data showing annual trends	Used to validate resource model estimation and tonnage calculation assumptions. Long-term view with the objective of improving the quality of resource model estimates.
2.	Reserve model to mine production	Reserve model Survey pickups Plant feed tonnes and grade	Monthly data showing annual trends	Used to validate reserve and design assumptions against actual mining practices. Long-term view with the objective of improving the quality of mine design parameters.
3.	Mine production to grade control	Survey pickups Grade control model	Based on survey frequency, which should be at least monthly, but could be weekly or fortnightly	Used to compare what grade control was designed to be mined and what was actually mined. Also allows tacking of truck factors. Short-term view to assist in improving grade control block design.
4.	Mine production to plant feed	Dispatch tonnes Control Grades Plant feed tonnes Plant head grade samples	Daily data showing monthly trends and annual compilation	Used to validate grade control grade and tonnage predictions on a short-term basis. Assists in guiding daily mining activities.
5.	Grade control model to plant production	Grade control model Survey pickups Plant commodity produced	Based on survey frequency, which should be at least monthly, but could be weekly or fortnightly	Used to validate grade control total contained commodity predictions to plant actual commodity produced. Medium-term view with the objective of improving grade control estimation techniques.
6.	Resource model to plant production	Resource model Survey pickups Plant commodity produced	Normally monthly with annual trends	Used to validate Resource model total contained commodity predictions to plant actual commodity produced. Long-term view with the objective of improving resource model estimation.
7.	Reserve model to plant production	Resource model Survey pickups Plant commodity produced	Normally monthly with annual trends	Used to validate Reserve model total contained commodity predictions to plant actual commodity produced. Long-term view with the objective of improving design and scheduling parameters and assumptions.
8.	Mine plan to actual mined	Budget/forecast/ schedules Dispatch Grade control grades	Daily data showing monthly trends and annual compilation	Used to show variance to plan. This can be achieved in a number of different ways – but the authors recommend using Dispatch so that variances can be tracked on a daily basis. Short- to medium-term view with the objective of improving mine planning.

3.2 The general design of an open pit mine

According to Wetherelt and van der Wielen (2011), a literature survey shows that more than 52% of industrial-scale mining operations worldwide are open-pit metal mines. Therefore, this section focuses on the geometry of an open-pit operation.

Open-pit mining is the process of mining near-surface deposits using horizontal benches (Wetherelt and van der Wielen, 2011). Open-pit mining has two main differences compared to strip mining and quarrying (Soofastaei, 2022). First, in open-pit mining, the overburden must be moved out of the pit and disposed of in an external disposal area. With strip mining, the overburden can be disposed of inside the mined area after the valuable material is extracted. Second, the open-pit mining method selectively mines the ore compared to quarrying. In contrast, an aggregate or a dimensional stone is produced with quarrying (Soofastaei, 2022).

All open-pit mines have at least three main infrastructures: benches, haul road networks, and dumps. Material is excavated on a series of layers with a uniform thickness called a bench (Hustrulid et al., 2013, Soofastaei, 2020). Three different benches are found in an open pit mine (see figure 2). Active (working) benches are benches where shovels are mining material. Inactive benches where no production activity is taking place at the moment. However, inactive benches have the potential to be activated in the future. Furthermore, catch benches ensure that falling material from the top benches is caught and stopped from falling onto the active areas (Soofastaei, 2022). The haul road network is a series of haul roads connecting different loading points to different dumping points. Furthermore, the haul road network also connects other service areas inside and outside the open pit (Soofastaei, 2022). A haul road in an open-pit mine consists of a travel lane, safety berm, and drainage ditch (Soofastaei, 2022). The width of two-way traffic, the most common road in open-pit mines, must be greater than four times the largest truck width (Hustrulid et al., 2013, Soofastaei et al., 2016). The last major infrastructure of an open-pit mine is the waste dump. The waste dump refers to the dump of mined material with no to little economic value at its placement (Orman et al., 2011). The mining production fleet (drills, shovels, trucks, and ancillary equipment) works within the three infrastructures mentioned above to produce economic value for shareholders.

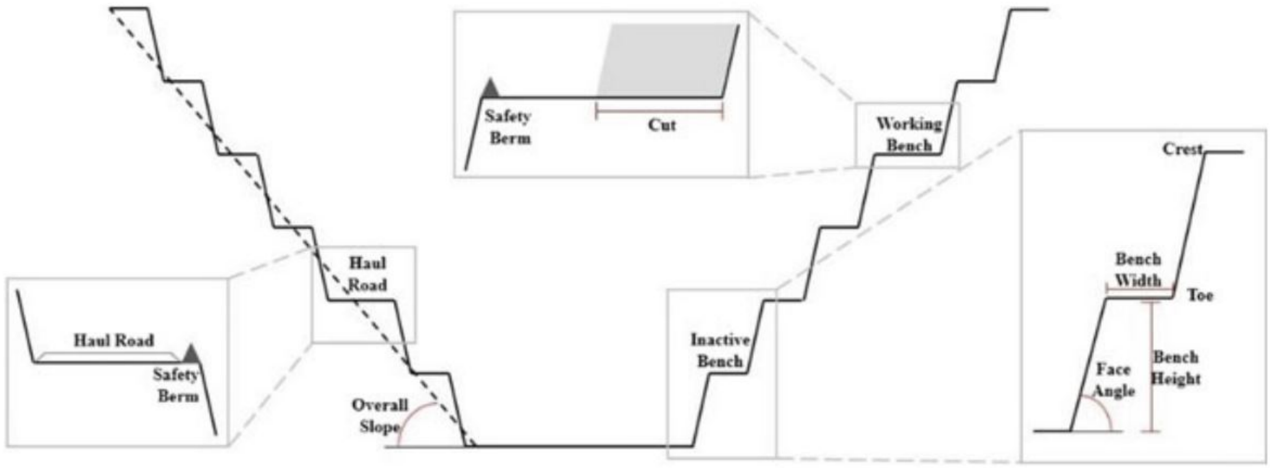


Figure 2: open-pit geometry (retrieved from Orman et al. (2011))

3.3 Shovel

In the previous section, the whole mining process was introduced. However, this study focuses on the production part of the mine with an emphasis on shovels. The term 'shovel' has been an overarching title for all loading equipment. The overarching title of 'shovel' refers to the moment when the electric rope shovels were most commonly used in all open-pit mines (Noaks and Landz, 1993). Since then, the industry has developed hydraulic excavators with buckets larger than 40 m^3 that are widely used. Therefore, the mining industry has many loading unit options. These options include rope shovels, hydraulic excavators, draglines, and wheel loaders. Regardless of the type of loading unit chosen, selecting the correct specifications concerning the bucket size of the loading unit will impact productivity.

The following three types of shovels are included in this study: backhoe excavator, front shovel, and electric rope shovel. All shovels have different specifications and various sizes. The shovels shown in figures 3, 4, and 5 are a schematic representation of the shovels. The schematic representation of the shovel improves the explanation. However, in the appendix, the three shovel types are shown in a mining environment (see figures A1, A2, and A3).

Figure 3 shows a backhoe configuration of a hydraulic shovel. A hydraulic shovel excavates using a bucket fitted to an arm, which is attached to the machine with a boom and is powered by hydraulic motors (Noaks and Landz, 1993). The lines in figure 3 show the digging envelope of a backhoe shovel. The bucket, arm, and boom can all be moved to achieve the positions withing the lines. The bucket is emptied by moving the bucket.

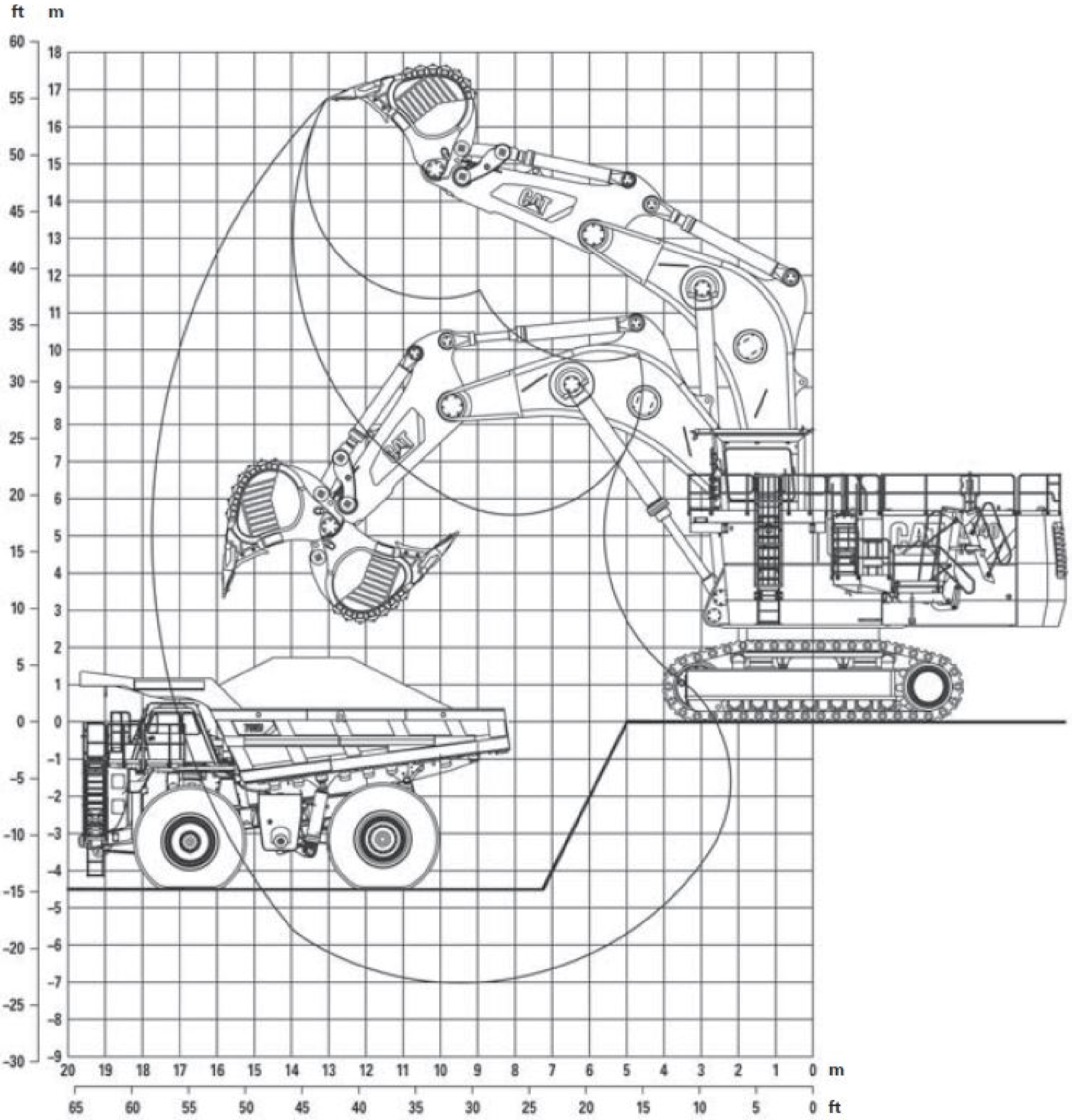


Figure 3: Backhoe hydraulic shovel (retrieved from Caterpillar (2019))

The backhoe configuration is not only standard in the mining industry but also in construction. Therefore, a backhoe configuration hydraulic shovel will be easier to find experienced operators who can switch from construction. The switched operators will need to be trained to optimise their skills to the needs of the mining operation. Furthermore, the backhoe shovel is the only machine that needs to be put on a bench to load the trucks, as shown in figure 3. The backhoe configuration is typical in mining operations that require a high degree of selectivity (Noaks and Landz, 1993). Lastly, the machine life of a large-size hydraulic shovel can be 50000 hours or more (Noaks and Landz, 1993).

Figure 4 shows a front shovel configuration of a hydraulic shovel. In figure 4, the line indicates the maximum reach of the front shovel. Furthermore, figure 4 shows four buckets at different locations, indicating the bucket's position at that moment. The bucket is emptied by lifting the front of the bucket while the bottom of the bucket stays stationary. A front shovel configuration will work on the same level as the truck (see figure 4). A front shovel configuration produces high digging forces in the lower part of the bench. However, the breakout force is lower at the end of the movement (Dzakpata et al., 2011). The machine life of a front shovel can be 50000 hours or more (Noaks and Landz, 1993).

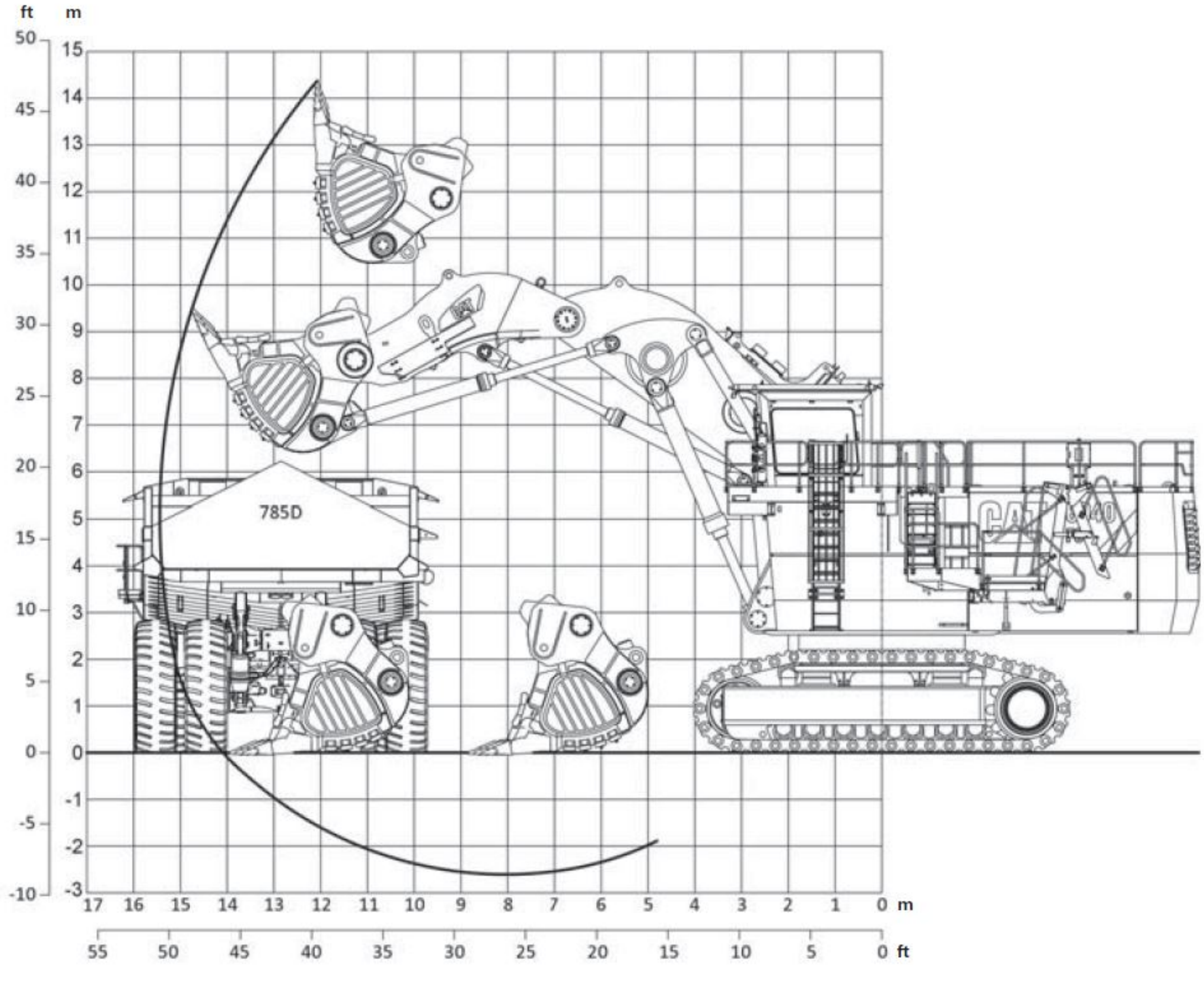


Figure 4: Front shovel (retrieved from Caterpillar (2019))

Figure 5 shows an electric rope shovel. An electric rope shovel uses wire ropes to pull a bucket on the end of a dipper stick through the muckpile (Noaks and Landz, 1993). Furthermore, electric rope shovels dump the material in the truck by releasing the dipper door at the bottom of the bucket (see the A in figure 5). Since the dipper door opens at the bottom, the clearance between the truck and rope shovel must be sufficient. The line in figure 5 indicates the maximum reach of the machine (B is the maximum cutting height, C is the maximum cutting radius, and D is the maximum radius at floor level). Lastly, the tail swing radius of the revolving frame is marked with E in figure 5.

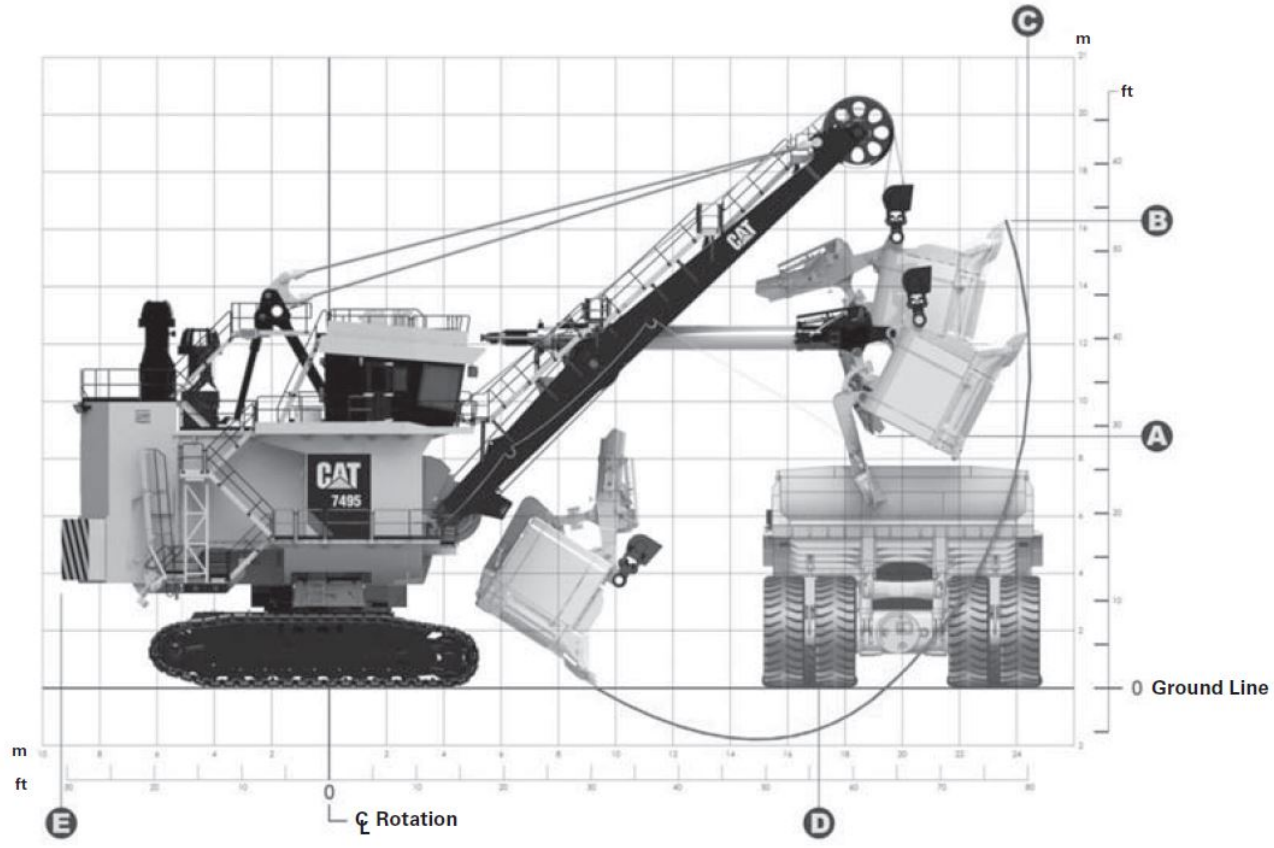


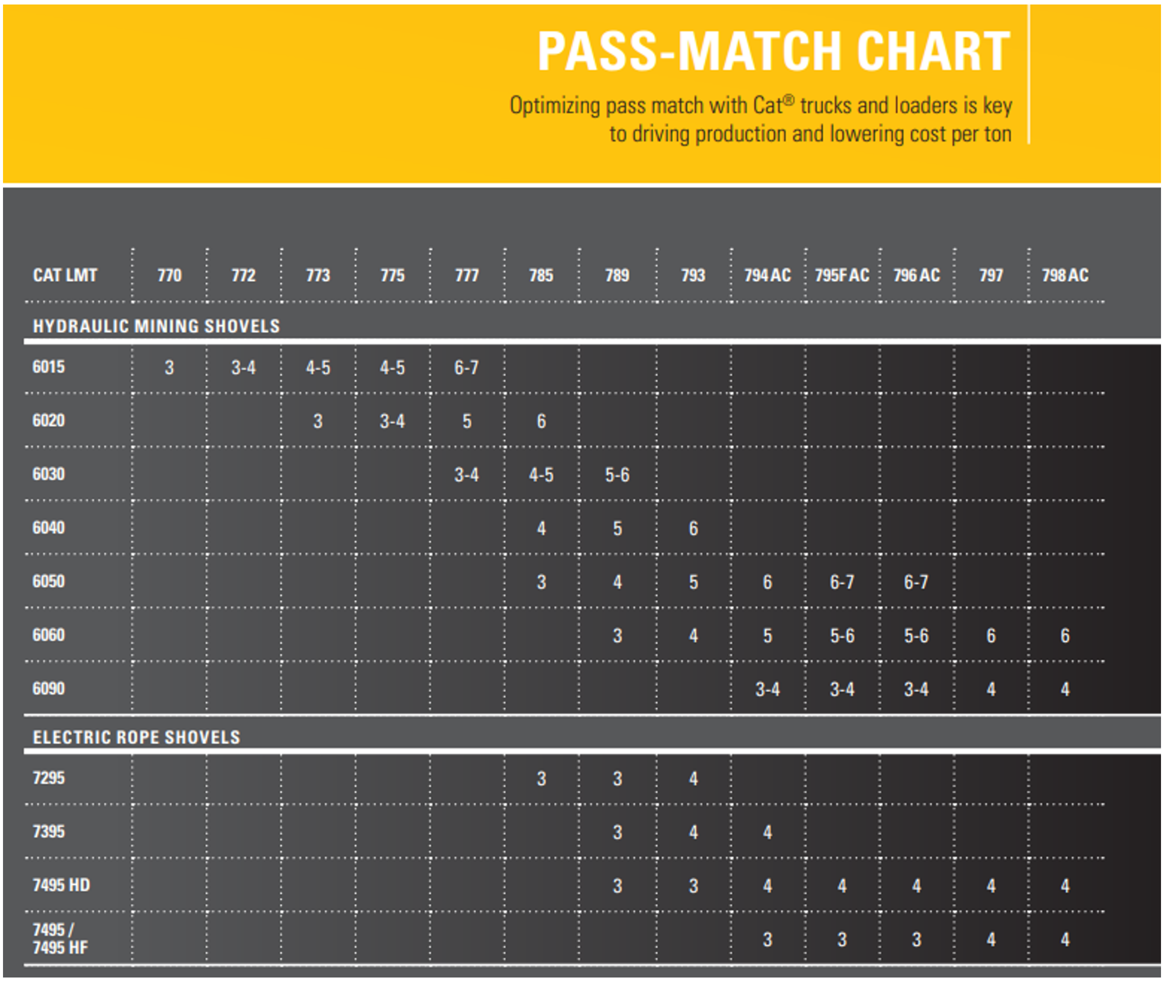
Figure 5: Electric rope shovel (retrieved from Caterpillar (2019))

An electric rope shovel will produce a constant high digging force throughout the bench, resulting from the hoisting force produced by the wire ropes (Dzakpata et al., 2011). Furthermore, an electric rope shovel can be characterised by its heavy-duty construction (Noaks and Landz, 1993). Lastly, the projected lifetime of an electric rope shovel is 100000 hours or more, which can be extended with a large-scale rebuild of the machine (Noaks and Landz, 1993).

3.3.1 Shovel and truck size

Several determining factors are considered to find a good match between the shovel and the truck. All these determining factors are related to the physical specifications of the shovel and the truck. The shovel and the truck have a defined payload that can be moved during a cycle.

In figure 6, different combinations of shovels and trucks are shown with the number representing the number of passes the shovel needs to fill a truck. Combinations will lead to maximum use of both the shovel and the truck payload and result in high production rates in the most cost-effective way. The pass match ranges between three and seven passes (see figure 6), which depend on the payloads of the shovel and truck. For example, a mining operation has a 6060 shovel (see the left column in figure 6), which they want to match with a new fleet of trucks. The mining operation can select the following trucks: 789, 793, 794 AC, 795F AC, 796 AC, 797, or 798 AC. All these trucks have an ideal pass match with a 6060 shovel. Furthermore, when a mining operation expands its existing fleet with new machines. The pass-match standards can be used to select equipment that works together with the existing fleet. For example, the existing fleet of a mining operation consists of a 7395 electric rope shovel matched with a 793 truck. The mining operation wants to expand the number of shovels without changing the trucks. The mining operation can select the following shovels: 7495 HD, 7295, 6060, 6050, and 6040. The final selection of the shovel will depend on the needs of the mining operation.



PASS-MATCH CHART

Optimizing pass match with Cat® trucks and loaders is key to driving production and lowering cost per ton

CAT LMT	770	772	773	775	777	785	789	793	794 AC	795F AC	796 AC	797	798 AC
HYDRAULIC MINING SHOVELS													
6015	3	3-4	4-5	4-5	6-7								
6020			3	3-4	5	6							
6030					3-4	4-5	5-6						
6040						4	5	6					
6050						3	4	5	6	6-7	6-7		
6060							3	4	5	5-6	5-6	6	6
6090									3-4	3-4	3-4	4	4
ELECTRIC ROPE SHOVELS													
7295						3	3	4					
7395							3	4	4				
7495 HD							3	3	4	4	4	4	4
7495 / 7495 HF									3	3	3	4	4

Figure 6: Shovel and truck pass match standards (Caterpillar, 2020)

According to Winkle (1976), no exact rule exists for determining the balance between shovel and truck size. However, proper sizing is somewhat proportional to the tonnage requirements and the haul cycle. A simplified example of Winkle (1976) shows that a shovel-truck match of 4-6 passes per truck is optimum. The larger truck-to-shovel size is becoming more attractive with longer-haul roads. The study of Winkle (1976) is still relevant after almost half a century because the equipment used has not been radically changed. During this half century, there has been a lot of improvements, but no radical changes have been made. According to Caterpillar (2019), four passes are ideal for the shovel and the truck. This study will also use this four-pass match as the standard.

3.3.2 General loading cycle of a shovel

Shovels are needed to load the (blasted) material onto trucks, which will take the material to the next step in the mining process. When taking a closer look at the load cycle of a shovel, four different steps can be identified. The first step is to empty the bucket into a truck (see figure 7). After this, the bucket swings back empty towards the muckpile (a heap of blasted material). Excavating the muckpile and filling the bucket is the third step of the load cycle. Lastly, the swing back with a full bucket is the last step before starting the cycle over again by dumping the bucket.

The locations of three different buckets are dug at locations 1, 2, and 3. The digging locations are shown in figure 7. The shovel operator will start digging when an empty truck arrives at digging location one. Followed by swinging towards the trucks and emptying the bucket. Digging locations 2 and 3 are used for the sequential buckets. However, a combination of digging locations 2 and 3 are used when the pass match is more than three. There may be differences in the length of one pass, but the loading time for the trucks will be similar. So, there are differences in the load cycle level due to the different loading locations. However, the loading time for each truck should be approximately the same since every truck needs the same number of passes to fill the truck. The main takeaway is that digging location 1 is used when trucks exchange because the longer swing time will not impact productivity.

Figure 7: Example of a loading cycle (Caterpillar, 2014)

3.3.3 Loading techniques

Depending on the technique, different loading techniques will have certain advantages and disadvantages. Before the different loading techniques are explained, the truck spotting for a large mining shovel will be explained (see figure 8). Truck spotting or truck exchange is the time it takes until an empty truck is reversed in position. Figure 8 shows the difference between a front and an electric rope shovel. For correct loading of the truck, the shovel should be able to reach the centre point of the truck. The tail swing, operator position, and centre line of the truck (dashed line) are also shown in figure 8. When a truck has reversed incorrectly, the truck will need to relocate. This relocation reduces the production that can be achieved since the shovel will have to wait longer to resume loading.

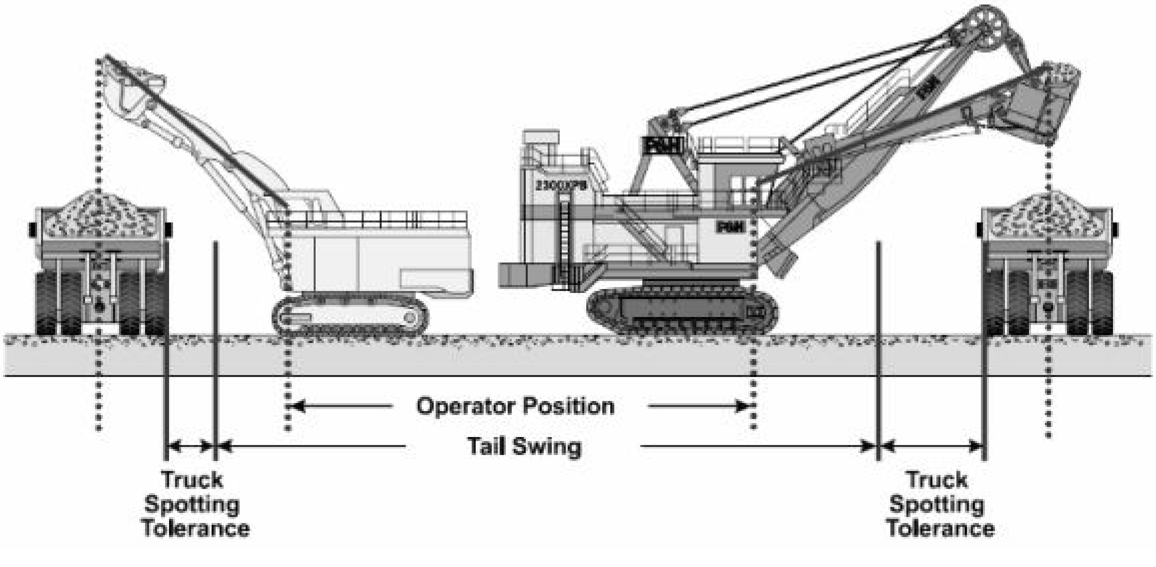


Figure 8: Truck spotting tolerance for the large mining shovels (retrieved from Services (2003))

All the information about the different loading techniques is retrieved from Caterpillar (2014), an explanatory video of the different loading techniques. The four most common loading techniques are single back-up, double back-up, drive-by, and modified drive-by loading (see figures 9 and 10). Every loading unit will have its advantages and disadvantages, which will be explained in this section.

The single backup loading technique (see figure 9a), better known as single-sided loading, has three advantages. Firstly, single-sided loading will be an effective technique in restricted mining areas because the space needed for trucks and shovels is kept to a minimum. Furthermore, there is no need for cable towers. The trucks arriving at the shovel are not allowed to drive over the high voltage power cables that supply the shovel with electricity. These high voltage power cables are not an issue with diesel-powered hydraulic shovels. Cable towers will the truck to reach the shovel without driving over the power cables. The last advantage is that the required truck operator skill for single-sided loading is reduced. There are two disadvantages to single-sided loading. Firstly, the truck spotting and exchange time are long, impacting productivity. Secondly, during clean-ups of the bulldozer, the loading must be stopped. The stoppage of the loading will impact the productivity and the time usage model, which will be explained later in the section.

The double backup loading technique (see figure 9b), better known as double-sided loading, has three advantages. Firstly, the need for truck spotting and exchange time is eliminated. Trucks can position to load when the shovel is loading the other truck, which minimises loading delays. Furthermore, the bulldozer can clean one side of the shovel while loading continues on the other side. Lastly, the power cable is less prone to rock damage as the cable is further away from the working bench. The disadvantages of double-sided loading are the requirement of cable towers and the higher skill level of truck operators.

(a) Single back-up or single-sided loading

(b) Double back-up or double-sided loading

Figure 9: Two of the four most common loading techniques (retrieved from Caterpillar (2014))

The drive-by loading technique is common in coal operations. There are two advantages to drive-by loading (see figure 10a). Firstly, the crawler tracks are aligned with the working bench, allowing the shovel to move straight ahead. Secondly, the loading is only done at the cab side of the shovel, which allows for a good vision of the truck. Furthermore, the drive-by loading technique is a very effective loading method for belly-dump style trucks. However, a significant disadvantage of drive-by loading is the long swing angels that the shovel must make.

The modified drive-by loading technique was developed to reduce the swing angles of the shovel (see figure 10b). The advantages of the modified drive-by and drive-by loading technique are the same. Also, both loading techniques are commonly used in coal operations. However, truck operator skills will need to be higher for the modified drive-by loading technique. Furthermore, the modified drive-by loading technique is more suitable for end-dump trucks.

(a) Drive-by loading **(b)** Modified drive-by loading

Figure 10: Two of the four most common loading techniques (retrieved from Caterpillar (2014))

Four standard loading techniques are used in the mining industry. However, the drive-by and modified drive-by loading techniques are often used in coal operations. Therefore, single-sided, double-sided or a combination of both loading techniques are commonly used in all mining operations. The knowledge of the different loading techniques will be used for a better understanding of different case studies.

3.4 General Key Performance Areas (KPAs) and Indicators (KPIs)

The global market for resources and commodities is very competitive. Therefore, measuring performance is the key to being and staying competitive. Key Performance Areas (KPAs) are valuable tools for evaluating and managing performance. Key Performance Areas (KPAs) are ”these areas of performance that are explicitly or implicitly reflected in the organisation’s vision and strategies.” (Barker, 1997). A KPA is a specific area of focus: safety, product quality, or costs. However, a KPI is a specific indicator that is measured. So, KPA is a classification, while KPI with the data is measured. When a mining company wants to focus on KPA safety by reducing injuries, the management can use the KPI of LTFR (Loss Time Frequency Rate) to see if changes have an effect. Mining operations generally focus on measuring profitability and performance to control and monitor the mining operation. Control and monitoring people is a fundamental reason for measuring performance. However, performance measurement systems generally focus on learning about current performance and advising management on improving it. Therefore, the focus of performance measurement systems should be to investigate current performance and inform management on improving performance. Another reason to collect performance measurements is to inform external stakeholders and comply with external reporting rules and information requests (Dougall and Mmola, 2015).

Each KPA may have several associated KPIs, of which several examples are shown in table 2. For shovel performance, the KPA for fleet management will be the source where most of the data is. The results of these KPI measurements often are the basis on which shovel production or productivity is based (availability and utilisation). Therefore, it is critical to determine what is measured and how it is measured to obtain the correct image of the potentially available data. Furthermore, the KPA for delivery (production) shows the amount of material that has been moved, which is the primary goal of loading and hauling.

Table 2: Key performance areas and their associated key performance indicators (Dougall and Mmola, 2015)

Key performance areas and their associated key performance indicators			
KPA	**Measure**	**KPI**	**Description**
Safety and health	Zero harm	LTFR FRR	Loss time injury frequency rate Fatality frequency rate
	Occupational disease / illness	NIHL	Noise-induced hearing loss
Product quality	Degree of purity and physical characteristics	Grades Cavity	Quantity of metal in ore expressed as a percentage Index of abrasivity; total moisture; and yield
Cost	Maintenance Labour Operational Sundries	Variance against budget	
Delivery	Production	Mineral production Waste mined Dilution Recovery Yield	
	Productivity	Unit output per employee	Ratio of outputs to inputs for any given activity
Fleet management	Maintenance	Availability Downtime	
	Production	Utilisation Cycle time Relocation time	

The KPAs and KPIs in table 2 are measured with different time intervals and units. Therefore, the examples in table 2 will be highlighted related to the time and units that mining operations could use.

- Safety and health
  - LTFR is calculated by ([Number of lost time injuries in the reporting period] x 1,000,000) / (Total hours worked in the reporting period). The reporting period of LTFR is yearly.
  - FRR is the fatality frequency rate, which is the number of fatalities per year, which is also measured annual.
- Product quality
  - The grades are measured in a percentage per ton. The time interval can be per shift, daily, weekly, monthly, or yearly.
- Cost
  - Maintenance can be measured by cost per unit or worked hour, depending on the mining operation. The time interval can be per shift, daily, weekly, monthly, or yearly.
  - Operational can be measured for the whole mine with OPEX (Operational Expense) or each machine. The time interval can be per shift, daily, weekly, monthly, or yearly.

- Delivery
    - Mineral production can be measured in Mt per year. The time interval can be per shift, daily, weekly, monthly, or yearly.
- Fleet management
    - The availability of the machine can be measured in the percentage of time the machine is ready to operate. The time interval can be per shift, daily, weekly, monthly, or yearly.
    - Utilisation is measured using the time usage model, which has a time interval spanning a whole year.

Therefore, the most common KPIs will be summarised with a short explanation of the relevance. According to Dougall and Mmola (2015), the following KPIs are commonly used:

- Average bucket weight; is the average of each measured weight during the cycle of a shovel. The average bucket weight could be measured with measuring sensors or by using the payload of the loaded weight in the truck and the number of passes to fill.
- Average loading time; total cycle time, and truck spotting time that a shovel uses to load a truck.
- Average fuel use per machine; is more relevant for trucks but can also be used for shovels to get an indication regarding the diggability of the muckpile and the costs of operating the machine.
- Average payload; the average payload of a truck can be used for different KPIs relevant to the shovel (such as the bucket weight).
- The number of equipment failures per day/week/month/year.
- Production rate - bank cubic metres (BCM) / hour (cubic metres of material moved per hour); with BCM standing for the in-situ volume of material present in the ground before excavation has started (Noaks and Landz, 1993).
- Production rate - loose cubic metres (LCM) / hour (cubic metres of material moved per hour); with LCM standing for the volume of material after it has been disturbed by drilling, blasting, and excavation, which will result in swelling of the material in volume (Noaks and Landz, 1993)
- Utilisation.

The KPIs summarised above will be tracked in every mine. However, every mining operation is unique. Therefore, the number of measured KPIs and the precision of the measured KPIs can vary for each mining operation. For this reason, all KPIs provided by mining companies should be checked for precision, or a range should be used.

3.5 Time usage model

Mining operations use every hour of every day of the year (when this is legal) to keep the processing plant fed with enough material. In section 3.4, data are needed to be able to measure performance. Therefore, machine activities are recorded for every minute of the year. This information is used to report KPIs regarding the performance of different machines in the operations. It will be used to determine the yearly production rates of shovels.

For this reason, all activities performed throughout the year are classified using a time usage model. The Global Mining Guidelines Group (GMG) developed a standardised time classification framework for mobile equipment in surface mining, published in 2020. This standard will allow mining companies to compare data with other mining operations. Furthermore, this standard will be used as the time usage model for this study. This standardised time classification framework was developed in collaboration with mining companies, OEMs, OTMs, research organisations, academia, regulatory agencies, consultancies, and industry associations, all represented by the GMG network (GMG, 2020). Figure 11 is a graphical representation of the classification of different productive activities, non-productive activities, statuses, and events in a mining operation. In the report of GMG (2020), the following standardised classification of different time categories is provided:

- Calendar Time (CT): Total Time Available (in one year)
- Scheduled Time (ST): Equipment is required to meet business plan objectives and is assigned to an operation, project, or job
- Unscheduled Time (UT): The equipment is not scheduled or assigned to the system because it is not required due to external events
- Downtime (DT): The equipment is required, but it is not in a condition to perform its intended function
- Available Time (AT): The equipment is required and is in a condition to perform its intended function
- Standby (SB): The equipment is available but not operating. (Operating Standby: Equipment is available but not operating, and there is no immediate intention to operate due to a management decision or reasons within management control. External Standby: The equipment is available, required, and committed to a project or site but cannot be operated for reasons beyond operating management control's immediate influence.)
- Operating Time (OT): The equipment is available and under the control of a human or system
- Operating Delay (OD): The equipment is operating but temporarily stopped or prevented from performing work due to delays that are inherent to the operation or the immediate physical and environmental conditions
- Working Time (WT): The equipment operates as assigned, performing its intended function and performing activities that contribute or do not directly contribute to production.
- Non-Productive Time (NP): Unavoidable activities that do not directly contribute to production but are required to enable continued, safe, and efficient operation.
- Productive Time (PT): The equipment performs its intended function and activities that directly contribute to production.

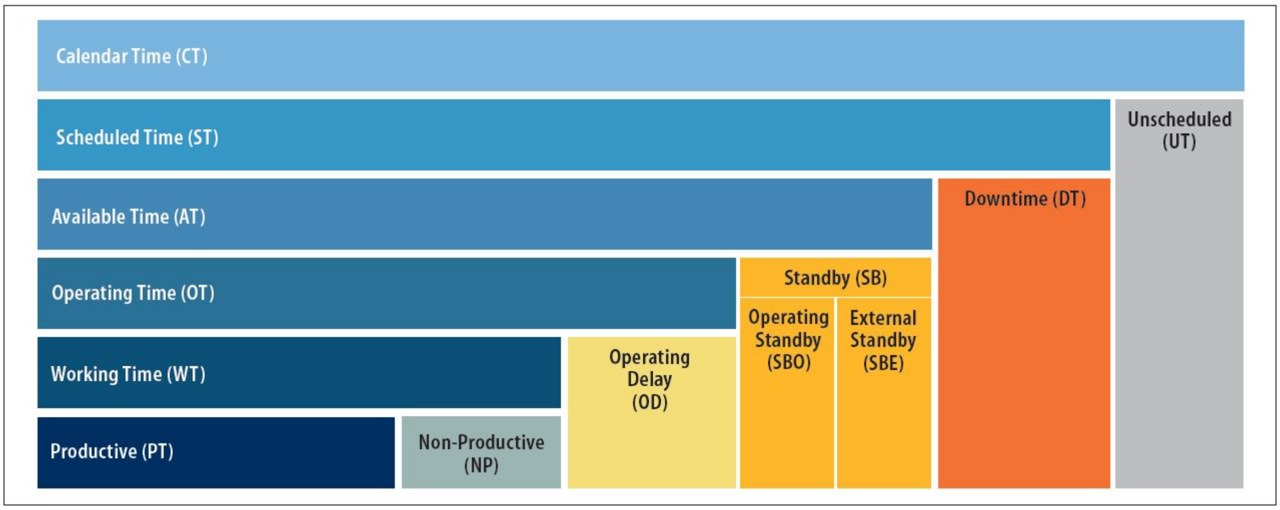


Figure 11: Time Usage Model (GMG, 2020)

To be able to compare different time usage models. All activities, equipment statuses, delays, and events used to describe and record operational activities must be classified into different basic time categories. This classification can be found in table 3. All possible activities a shovel can do during the year are classified into different time categories. The activities in the productive time are the four steps of the loading cycle, which is the only time the machine is moving material. The non-productive time is all activities that need to be done to be productive. These activities include face preparation and cleaning or repositioning the shovel to reach the material. Activities classified in operating delay, standby, and unscheduled time will reduce the amount of time available for productive or non-productive time. The classification of all activities can be seen in table 3. The goal of the time usage model is to manage time, report, and compare the performance of different equipment. Detailed data collection is a critical driver in a good classification of all events. These classified events can be used to determine different key performance indicators (KPIs). These KPIs can be measures of asset availability, asset utilisation, and effectiveness (GMG, 2020).

Table 3: Basic Time Elements

Productive Time	Non-Productive Time	Operating Delay	Standby		Unscheduled Time
			Operating standby	External standby	
Shovel – Load – Swing – Dump – Return	Shovel – Face prep and clean-up – Cable reposition (by shovel) – Reposition – Rehandle – Wait for trucks	– Fuelling – Lube – Blasting – Weather – if operator remains on unit – Incident – scene frozen (operator in unit) – Stuck – Power loss – in pit (unspecified cause) – Power loss – due to blast – Re-route cable in pit – operator stays in unit – Change operator – Boarding machine/ Receiving instruction – Survey/ore control delay – Clean cab/ windows – Spill cleanup – operator on board – Wait for assignment / instruction – Wait for shovel bucket cleaning – Communications system delay – Loss of GPS – Loss of site wireless network connectivity – Stop work – safety – Stop work – environmental Shovel – Cable changeover – Bucket cleaning – Waiting for face cleanup equipment – Shovel move	– No operator – Shift change – Lunch / coffee breaks – Equipment checks – Safety meeting – Crew meeting – Training – Stop work – public relations – Re-route cable in pit – operator removed from unit – Investigation – operators removed – Spill cleanup – operators removed – Personal break – Prayer – Safety stand down	– Not required – Work suspended due to workforce shortage – Delayed crew arrival – Site-wide weather outage – Primary power loss to site (<12 hours) – Site-wide loss of high voltage power – Loss of site access (<12 hours) – Work suspension by owner – Loading unit out of digging – Waiting for drill pad (not available for cleanup) – Work area unavailable (geotechnical, water) – Loss of GPS – Loss of site wireless network connectivity	– Scheduled shutdown – Statutory holiday not worked – Inventory management shutdown – Labour dispute – No work – Mobilization/ demobilization – Acts of God – Force majeure – Major site power interruption (>12 hours) – Significant environmental event (>shift) – Loss of site access (>12 hours)

3.6 Determination of shovel productivity

Calculating production rates can be done in several different ways. The focus of this study will be on rope shovels and hydraulic shovels. These different methods will be explained, and, in the end, the best method used in this study will be selected. The five different methods will be compared to calculate the shovel production rates. These methods come from companies/organisations that use their philosophy to determine shovel production rates. The five methods are the following: AUSIMM, SME, Komatsu, Hitachi, and Caterpillar. For these five methods, a reliable source could be found. Furthermore, the methods of three competitors and two branch organisations could be compared. All these methods use the following general formula:

$$Shovel\,production = \frac{BS * BF * \rho * NP * 3600}{TCT} * E \tag{1}$$

All factors in the formula must be estimated, except for the bucket size. BS is the bucket size, BF is the bucket fill factor, ρ is the loose density of the material, NP is the number of passes needed to fill the trucks, TCT is the total cycle time, and E is the efficiency. The bucket's size must be selected based on the loaded material's density, swell factor, and the maximum payload of the shovel.

This general formula is used in different ways when looking into the details. The density and total cycle time variations are used. The Hitachi (2012) method is the only one that uses cubic metres per hour as the unit for production, so it excludes the use of density. However, they use the loose volume of rock. Caterpillar, Komatsu, and SME use the loose density when calculating shovel production (Caterpillar, 2019, Komatsu, 2013 & Darling, 2011). AUSIMM uses a different approach that includes the swell factor. The swell factor depends on the characteristics of the material and the blast (Noaks and Landz, 1993). The bulk density and the swell factor are used to determine the loose density, explained in section 3.4.

The approach for the total cycle time has variations between the different methods. SME states that the total cycle time will be obtained from the information provided by the manufacturer or through time studies of similar equipment (Darling, 2011). AUSIMM uses the following formula $Total\,cycle\,time = Cycle\,time * (Number\,of\,passes - 1) + truck\,exchange\,time$ (Noaks and Landz, 1993). Komatsu uses the loading time per truck (instead of the cycle time for one pass) and the spotting time per truck to obtain the total cycle time (Komatsu, 2013). Hitachi has included an additional factor, the correlation between the swing angle and the digging depth. This factor will increase the basic cycle time to account for larger swing angles and digging depths (Hitachi, 2012). Caterpillar's approach is the most sophisticated because the dumping time of the first bucket is included. Caterpillar uses the following formula: $Total\,cycle\,time = Cycle\,time * (Number\,of\,passes - 1) + truck\,exchange\,time + dumping\,time\,of\,the\,first\,bucket$.

Furthermore, the SME includes two additional factors: the propel factor and the presentation factor. The propel factor considers the time a loading unit takes to move from a working face to a different working face in the mine (Noaks and Landz, 1993). The presentation factor is a consideration regarding the waiting time for a truck (Noaks and Landz, 1993). However, these factors might already be considered within the time usage model. As the shovel moves, the propel factor is accounted for in the time usage category of operating delay. The presentation factor is accounted for in the time usage category of non-productive time, such as waiting for a truck. When the GMG (2020) is used, both the propel and presentation factors will be unnecessary to include.

All five methods are slightly different and will give slightly different production rates. However, selecting a complete formula is vital for the best representation of the real world. Therefore, Caterpillar's method will be used in this study because the Caterpillar method is the only formula that includes the dumping of the first bucket in the formula. Therefore, the Caterpillar method best represents the real world of the five different methods shown in this study.

Yearly shovel production rate

Mining operations work year-round. The production rate and the time usage model will determine the annual shovel production rates. Annual shovel production rates depend on scheduled hours, mechanical availability, and use of availability (GMG, 2020). The formula for annual production is as follows.

$$Annual\,shovel\,production = Hourly\,shovel\,production * Scheduled\,hours * MA * UA \tag{2}$$

The total scheduled hours is depended on the mine planning for the year. Mechanical availability (MA) considers the maintenance that needs to be done on the machine. Lastly, the use of availability (UA) is a measure of how well an operation makes use of available equipment.

3.7 Estimated factors

The estimated factors will be assumptions based on real-world data. The mining industry always works with an amount of uncertainty. These estimated factors must be determined with the highest possible certainty to ensure that the estimated and real-world production rates are the same. Therefore, a reasonable estimate of the factors will result in realistic shovel production numbers in a real-world scenario. If theoretical production comes close to real-world production, then the size of the mining fleet will be better. A good mining fleet has the flexibility to absorb additional production when there are breakdowns. With the breakdowns, the mining fleet should still be capable of achieving the yearly production that the customer expects from the fleet. Furthermore, the mine plan will be easier to follow, and fewer overruns will be needed. So, a well-sized mining fleet will achieve the desired yearly production with the least amount of overruns or changes throughout the year. This well-sized mining fleet will lead to the most cost-effective operation of the mine.

3.7.1 Bucket Fill factor

The bucket fill factor measures the degree to which the bucket is filled after the operator has dug in the muckpile (Noaks and Landz, 1993).The fill factor of the bucket depends on the operator's skills and the fragmentation (Dotto and Pourrahimian, 2018, Babaei Khorzoughi and Hall, 2016, etc).

First, additional knowledge of fragmentation is needed. According to Ouchterlony (2003), fragmentation can be described in terms of fragment size distribution, shape, and angularity or roundness of the fragments. Fragmentation can also be classified as the cumulative size distribution, see figure 12. Where x_N is a measure of the average fragmentation, or the size of the mesh through which a certain percentage of the muckpile passes (N = 20, 30, 75, 80, 90, and 100). So, with x_{80} 80% (or P = 0.8) of the muckpile passes through the mesh size. P_O is the percentage of fragments larger than a certain size x_O, which is relevant for truck loading. The most critical parameter is x_80 or P_80, which are definitions that 80% (or P = 0.8) of the muckpile passes through the mesh size, which will need to be defined.

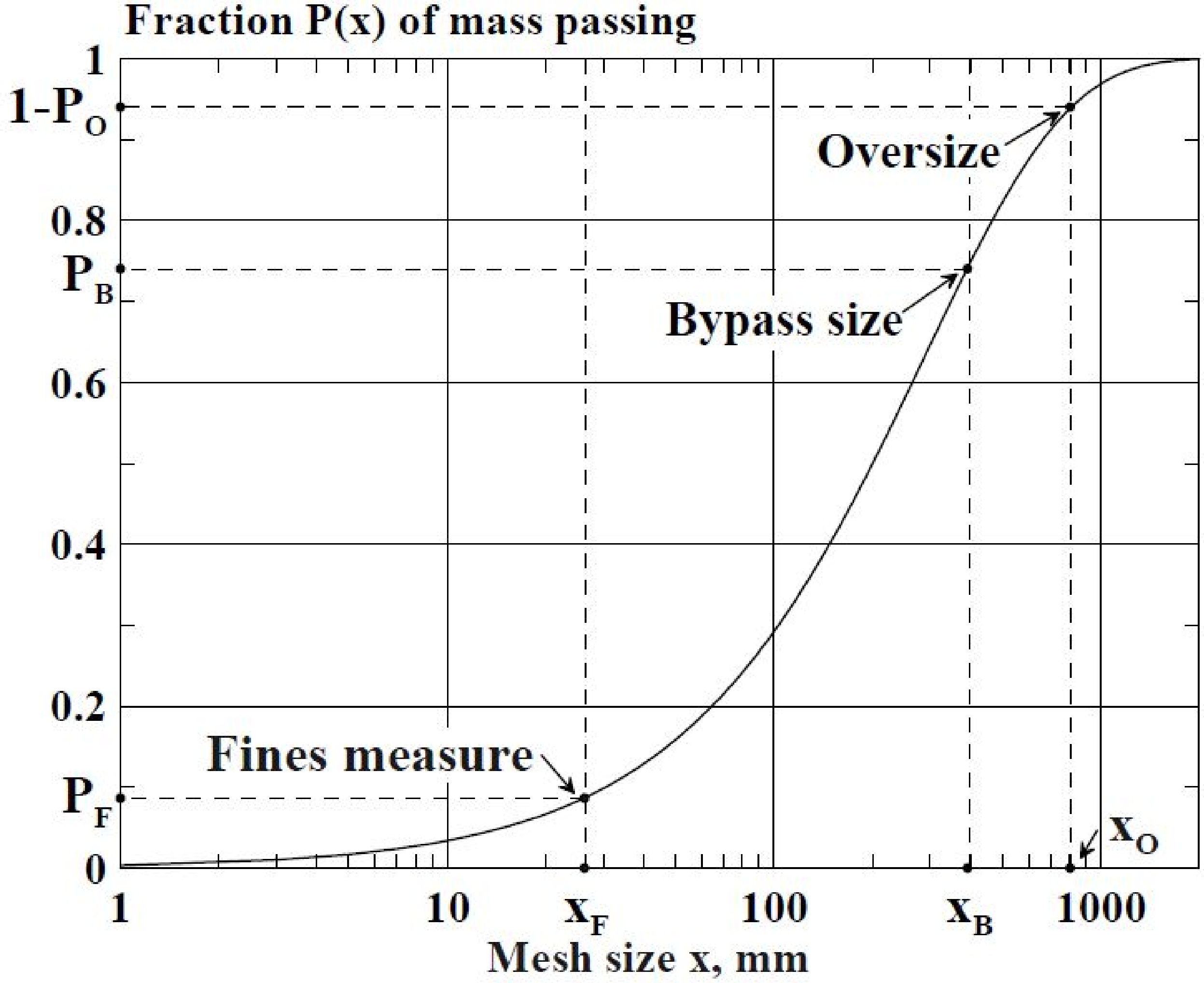


Figure 12: Example of a fragmentation curve (Ouchterlony, 2003)

According to Osanloo and Hekmat (2005), the ideal P_{80} would range from 20 to 40 cm in size, resulting in a bucket filling ranging from 80% to 88%. However, Beyglou et al. (2017) found that the ideal fragmentation size ranged from a P_{80} between 60 to 80 cm. This fragmentation resulted in a fill factor of the bucket of 81% to 93%. Since this study focuses more on the type of shovel used in Beyglou et al. (2017), that study will be used as the preferred fragmentation concerning the fill factor of the bucket. The fragmentation distribution is selected based on the method used in the mining processing plant. The required fragmentation distribution will be small when the material is crushed and milled in the processing plant. A smaller fragmentation distribution will lead to a reduction in energy consumption for crushing and grinding. This reduction in energy consumption will also lead to reduced costs for the mining company, reducing the operation's cost-per-tonne. The crushing and milling are often the case for commodities such as gold and copper. However, high-grade iron deposits can be shipped directly to customers. These high-grade iron ore deposits can sell two types of products: lumps and fines. The lump product can be sold for a premium price because it is better for the steel-making process. Direct shipping will lead to a larger fragmentation distribution to increase the yield of the lump product. In the end, the owner of the mine is responsible for the selection of the fragmentation distribution. If this fragmentation is achieved during operations, it depends on the drill and blast operation optimisation extent.

3.7.2 Density and Swell factor

Density estimates the number of tonnes in a deposit (Makhuvha et al., 2014). According to Lipton and Horton (2014), the QA/QC processes used for sampling and geochemical analysis are often not used to collect density data. However, density and grade estimation are equally important. With the following methods, the bulk density can be determined: Caliper, water displacement, water replacement, sand replacement, core tray, air core drilling, gas pycnometer, hydrostatic immersion (Archimedes) and metal box sample (Lipton and Horton, 2014 & Makhuvha et al., 2014). However, the selection of these methods should be based on the type of ore being analysed.

The importance of adequately estimating the bulk density is shown in the case study in the Los Bronces mine conducted by Makhuvha et al. (2014). This case study determined the bulk density using the core pycnometer and the Archimedes method. The results of both measurement techniques gave a 5% difference in bulk density. This difference would result in Los Bronces with an increase or decrease in the operations reserves by around 100 Mt, equal to one full production year. The same holds for daily production, increasing or decreasing by 20.000 t. 20.000 t is equivalent to around 90 truck cycles per day. This case study in Los Bronces shows the importance of proper bulk density estimation.

Since this study focuses on predicting shovel production in real-world situations, the methods used by mining companies will be necessary. The conclusion of Lipton and Horton (2014) and Makhuvha et al. (2014) was that mining companies should determine the bulk density with at least two (or more) different methods to reduce deviations. Both studies also concluded that methods should be selected based on the ore type because some methods have limitations.

The swell factor is under-researched in the mining industry. This factor is not critical for resources and reserves and, therefore, has no strict rules and regulations for control. For this reason, the swell factor is almost always estimated at 30%. When shovel production is estimated, the customer will need to report the information about the swell factor.

3.7.3 Total cycle time

The total cycle time has three main components: Cycle time, truck spot, and first bucket dumping. The cycle time is defined as the time it takes for a shovel to return to the muckpile after dumping the content of the last bucket and filling a new bucket. These buckets are dumped into the truck until the truck is fully loaded. Dumping the last bucket to fill the truck is the moment the truck spotting begins. The truck will start to reverse to the correct loading spot. The shovel will cycle to get a full bucket, which will be held in a position to help the truck move to the correct position. The first bucket will be dumped when the truck is in the correct place, which takes between 3-5 seconds. The dumping of the first bucket has the slightest variation of all factors because the assumption can be made that the reaction for releasing is constant. On the other hand, both cycle time and truck spotting can have significant variations.

Two main areas influence the cycle time. The first is the technical capability of the shovel, which is related to limitations in engine output and maximum flow through hydraulic hoses. The other area is the mine-specific parameters, which include operator skill, bench height, material fragmentation, penetration resistance, and swing angle (Caterpillar, 2019).

Truck spotting is related to the operator's skill in the truck. The shovel operator is responsible for creating enough space for the truck, keeping the load clean, and ensuring that the reversing truck stops in time. Truck spotting is the only factor on which the shovel operator has no direct influence.

3.7.4 Efficiency

The efficiency indicates how much time in one hour is spent on productive work (excavation of material). The nonproductive fraction of the time is spent on work that does not involve the movement of ore or waste. The efficiency factor is determined using the time usage model. The efficiency factor is expressed as a percentage. Examples of nonproductive activities are clean-up of the work area by the loading unit or bulldozer, fuelling, inspection, and equipment movements (Lipton and Horton, 2014)(see section 3.5 in table 3).

3.7.5 Propel & Presentation factor

The propel factor considers the time lost due to the movement of the shovel in the mine (Lipton and Horton, 2014). This propel factor does only consider the repositioning along the muckpile. The more prolonged movements of the shovel are accounted for in the time usage model.

The presentation factor is the attempt to include the reduction in productivity when there are no trucks available.

3.7.6 Mechanical availability

Mechanical availability refers to the time the shovel is available for operation, which is a percentage of the total time. This KPI can be utilised to recognise the effect of maintenance on the shovel (GMG, 2020).

3.7.7 Use of availability

The use of availability estimates how well shovels are utilised when the shovels are available to be used in production (GMG, 2020). The use of availability is determined by dividing the operating time by the available time. The available time is the amount of time available in a year minus mechanical availability and unscheduled time. The operational time is determined when the standby time is subtracted from the available time. Examples that can be classified as standby time are shown in table 3.

3.7.8 Prediction of the expected frequency distribution of the theoretical production formula

The prediction of shovel production can be achieved by understanding the process and creating an image of the potential data. The potential data will be defined by the frequency distributions shown in figure 13. Figure 13 shows three types of frequency distributions (negatively skewed, normal (no skew), and positively skewed). The effect of skewness is focused on the position of the mean and median (Doane and Seward, 2011). Extreme values influencing the mean and median affect the negatively and positively skewed frequency distributions (Doane and Seward, 2011). Understanding what kind of data points will be given as input to predict shovel production is necessary.

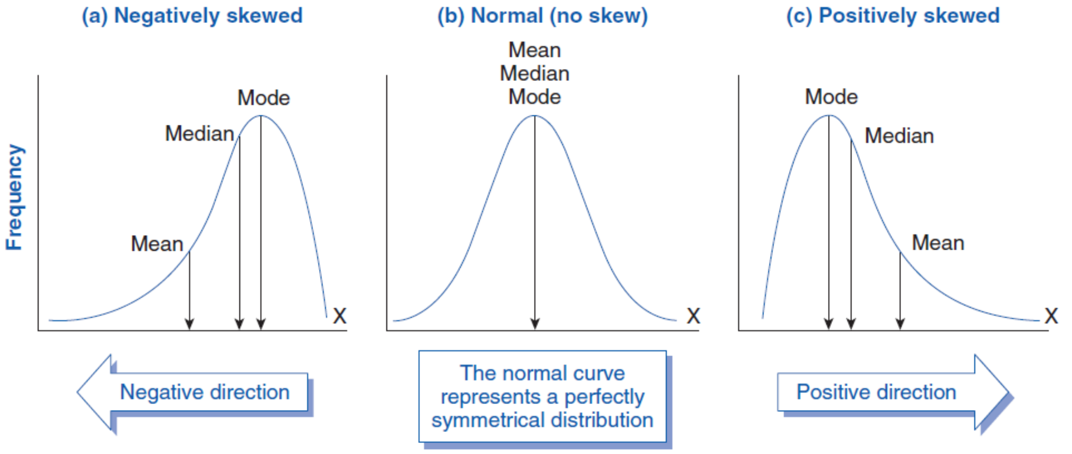


Figure 13: Theoretical frequency distributions (modified from Doane and Seward, 2011)

The following summary will define the expected data for all parameters within the shovel production formula.

- Density - Normal (no skew)frequency distribution; the data should be readily available since it is essential in resource estimation. Furthermore, the division between the ore and the waste rock densities can be made.

- Swell factor - Normal (no skew) frequency distribution; the data depend on the blast and rock properties and is one of the least researched parameters within the shovel production formula. Generally, a swell factor of 30% is used, which is the general assumption.
- Bucket fill - Negatively skewed frequency distribution; the bucket fill can range from 0 to 120% but varies mainly between 75 and 110%. The range of the bucket fill will depend on the configuration of the investigated shovel. So, depending on the configuration of the bucket size, fragmentation, and target payload of the shovel, the correct range for the bucket fill can be selected. The bucket fill factor will have a negatively skewed frequency distribution because a bad operator or fragmentation can lead to data points that will have a negative impact on the frequency distribution.
- Cycle time - Positively skewed frequency distribution; this parameter is limited to the physically achievable performance of the shovel. The shovel cannot move faster than it was designed. Therefore, it is more likely that the cycle time is longer than optimal.
- Truck spotting - Positively skewed frequency distribution; this parameter is also limited to the physically achievable performance of the shovel. Trucks cannot accelerate at the desired speed instantly. Additionally, the range within the frequency distribution of truck spotting time will be the highest, as there is a high probability of delays.
- Dumping of the first bucket - Normal (no skew) frequency distribution; this parameter will have little to no variance since the effect of the difference in gravitation around the world is negligible.
- The number of cycles - unknown; this parameter is mainly affected by other parameters and the pass match between shovel and truck. Underperformance in the bucket fill can lead to the need for an additional bucket to load the trucks full.
- Efficiency - Negatively skewed frequency distribution; high working efficiency is challenging and will never exceed 90%. Furthermore, the efficiency can be very easily
- Scheduled hours - Negatively skewed frequency distribution; this parameter should not have a significant fluctuation and should be consistent throughout the years. However, the parameter can be negatively influenced by uncontrollable events (weather or labour disputes).
- Mechanical availability - Negatively skewed frequency distribution; this parameter is affected by everything that breaks and therefore is highly influenced by unplannable events. Adverse effects will be more likely when the machine has been operating for an extended period.
- Use of availability - Negatively skewed frequency distribution; this parameter is affected by everything that delays the operation. These factors are shown in the time usage model.

3.8 Automation

This study is also related to the impact of automated trucks on shovel productivity. For this research question additional background information is needed on automated trucks. Furthermore, the impact of automated trucks on the mining operation and shovel productivity is investigated by reviewing the literature.

Open-pit miners implemented automation technology more slowly than underground miners. The slower implementation is due to the complexity of open-pit environments and the associated technological hurdles in implementing effective automation(Bellamy and Pravica, 2011). Furthermore, the slow implementation of automation technology resulted in investment in automation rather than employing human operators was not financially justified (Bellamy and Pravica, 2011). This situation has changed over the past few years due to rising cost pressures from rising fuel costs and rising wages. The recent cost pressures from rising fuel prices seem to have exacerbated this situation because as much as 30% of the total mine operating costs are from diesel usage (Soofastaei et al., 2016 and Bellamy and Pravica, 2011).

Moving underground technology to open pits is challenging, as there are larger machine sizes and no walls to restrict the machine movement (Bellamy and Pravica, 2011). Furthermore, many more objects share the same workspace, operate at higher speeds, and open pits are subject to changing weather conditions (Bellamy and Pravica, 2011). A road can be dry and compact and then slippery and muddy. Nevertheless, the continuing improvements in computing power combined with labour shortages have pushed automation onto the surface. Technology limits aside, the first prominent place for open pit automation is in the mine haul trucks. As haul trucks operate on heavily regulated and highly restricted roadways, sometimes following the same route from ore face to ore dump for weeks at a time (Bellamy and Pravica, 2011).

The implementation of automation will have an impact on different parts of the operation. According to Bellamy and Pravica (2011) and Price et al. (2019), the benefits of automation are the following: Wages, fuel, truck availability, tyre life, labour costs, and safety. According to Bellamy and Pravica (2011) and Price et al. (2019), the different benefits of automation will be summarised below.

- The wages of the haul-truck drivers is replaced by a computer guided control system. Bellamy and Pravica (2011) study showed that the cost of automation would be paid back within two years through saved wages and driver costs.
- Fuel costs will be reduced by the onboard computers, which slow the haul truck down if the truck is idle at the destination.
- Truck availability is increased by automated trucks because there is no need for shift changes or other operator-related delays. According to Bellamy and Pravica (2011), approximately 23 days per year are lost by driver-operated trucks.
- Tyre life is extended with the use of automated trucks. The programmed route is the main benefit of extending the tyre life of automated trucks. Price et al. (2019) stated that the typical tyre life is 5000 hours at a manned operation. An autonomous mining operation can have a potential tyre life of 7500 hours.
- Labour costs will increase for the needed technical specialist to support automation than truck operators, but the workforce will be smaller. Therefore, automation will decrease the overall labour costs of the operation.
- The employees' safety is increased by automation because the employees are removed from the operational danger. Automation also reduces the fatigue-related errors of employees during the night shift.

The benefits stated by Bellamy and Pravica (2011) and Price et al. (2019) show significant similarities with Gollschewski (2015). Gollschewski (2015) stated that safety, reliability, efficiency, and productivity would increase when automation is implemented. Furthermore, Gollschewski (2015) also included a case study that quantifies the benefits of the different factors. Gollschewski (2015) showed that there had been zero sprain and strain injuries due to autonomous haulage operations in 2014.

Furthermore, the implementation of an autonomous haulage system resulted in a 14 per cent higher effective utilisation of automated trucks over manned trucks (Gollschewski, 2015). The higher effective utilisation of trucks impacts the loading fleet. The higher effective utilisation can be used in two ways. If the production of the loading fleet is kept constant, fewer automated trucks will be needed. According to Brundrett and Eng (2014), seven autonomous trucks can haul the same quantity of roe as nine manned trucks. When the production of the loading fleet is increased by better utilisation (reduced truck spotting time or higher use of the entire loading fleet), the number of automated trucks will be constant. The reason for the increased production is the increased number of trucking hours available. These additional trucking hours can be used to move more material with a constant number of trucks. However, the shovels need to be able to load more trucks without the need for an additional shovel. So, a mining company will have two options when implementing automation, either increase production by keeping the fleet size of the trucks consistent or keep production consistent by decreasing the fleet size of the trucks.

The implementation of automated trucks will have an impact on the loading fleet. Depending on the direction chosen by the mining company, production will increase with the current fleet size or the production is kept constant with a smaller fleet. Both measures will impact the loading fleet differently.

3.9 Synthesis

Mining companies can reach their goals by taking different paths with the same result. These paths can be created by using different loading techniques for the shovel fleet or adjusting the time usage model for their specific site. Furthermore, KPAs and KPIs are used to measure performance. The data collected by the different KPIs are used to estimate the potential production rate of a shovel. However, these KPI-based production rates can be significantly influenced by the average values used in the calculations. When these averages are used, the corresponding frequency distribution should be known. The shape of the frequency distribution will significantly impact if the used averages are reliable. Using the shovel formula with a theoretical number will not lead to a good representation of the production rate that can be achieved in the real world. The numbers filled in the production formula should be based on a frequency distribution related to the number to achieve a realistic production rate for the real world.

4 Case studies

4.1 Case study 1: Sensitivity analysis of theoretical production rate

During the literature study, different formulas were investigated to calculate the hourly production of shovels. These different formulas were used to see the effect of incorrect estimation of the different variables that can be filled in. A sensitivity analysis will show the impact of different variables. Caterpillar's method will be used because the Caterpillar method is the only formula that includes the dumping of the first bucket in the formula. Therefore, the Caterpillar method best represents of the real world of the five different methods shown in this study. The effect of uncertainty (or incorrect estimation) on shovel productivity is relevant, as the mining industry always works with a level of uncertainty that varies for each operation. Therefore, a sensitivity analysis will show which factors are affected by uncertainty and the effect on the theoretical production rates. Knowing the effect of uncertainty on different factors in shovel productivity calculation will help increase the probability of achieving the estimated production rates. This chapter will investigate the effect of realistic uncertainty levels in mining and the factors most sensitive to this uncertainty.

4.1.1 Results

In the appendix, three tables (A1, A2, and A3) contain the data used to produce figure 14.

Figure 14 shows the impact of the uncertainty on the theoretical production rates. The base numbers are selected from Caterpillar (2019) and represent best-in-class production methods. The cases (-20%, -10%, +10%, and +20%) are a good representation of uncertainty levels in the mining industry.

For every factor in the shovel formula, the different cases were multiplied by the base case number (see table A1). So, the base for the swell factor is 1.3, which leads the -20% case to be 1.04. The production rate in table A2 is calculated using the shovel production formula. The base case is calculated using the number in the base case column in table A1. The case -20% for the swell factor is calculated. The base case is used for the other factors, but the swell factor is changed from the base case (1.3) to the case -20% (1.04). The number is the production rate for the case -20% for the swell factor. Lastly, the percentile change from the base case production is calculated by the difference between the base case and the case -20% divided by the base case. The percentile change is shown in table A3. Table A3 is visualised in figure 14. The lines in figure 14 represent one of the different cases calculated in tables A1, A2, and A3.

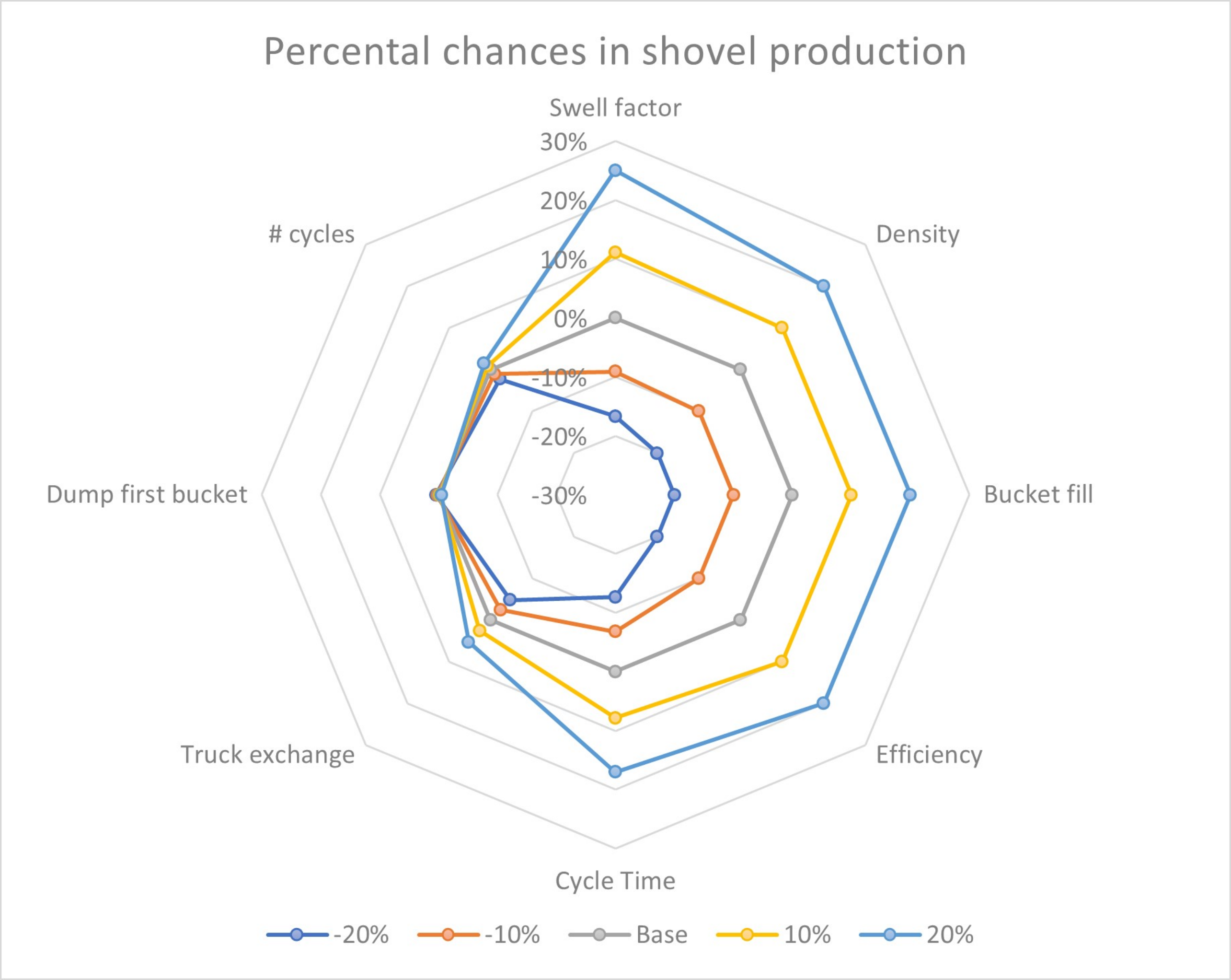


Figure 14: Sensitivity analysis of different factors in the shovel formula

In figure 14, some parameters, such as the number of cycles, the first bucket dump, and the truck exchange, influence the production rate less than the change in the case. However, the swell factor, density, bucket fill, efficiency, and cycle time reduce/increase the production rate by the same amount as in the base case. Therefore, incorrect estimation of these parameters will lead to the exact change in the final calculated production rate.

4.1.2 Discussion

Due to the limited data available, there is no frequency distribution for the different parameters. Therefore, some parameters could have a more significant deviation range than 20%. This deviation is the case for the truck exchange time, which could become several minutes instead of the estimated 33 seconds used as the base case. The other parameters should be investigated further with the frequency distribution of data from multiple mines. The assumption is made that all factors are independent, while in the real world, they impact each other. Low bucket fill will lead to underloading of a truck, which will have to be compensated with an additional bucket. Therefore, an additional pass will be made, which is not currently represented.

4.2 Case study 2: Analysis of Copper Mines in South America

For this thesis, two Encare benchmark reports (second semester 2016 (July until December) and first semester 2017 (January until June)) were provided to analyse copper mines in South America. Encare is a company dedicated to the economy, management, and best practices in the natural resource sector. The Encare portfolio comprises more than 100 benchmarking studies covering a wide range of production and management processes in the mining industry. In the benchmark report, the part on the benchmarking of shovels was the only relevant part for this study. The benchmark report shows analyses for electric rope shovels with buckets of 73-yd (56 m^3) and 56-yd (43 m^3). In total, 14 different mines participated in the Encare benchmark report. Tables A4 and A5 are shown in the appendix. In these tables, the data collected by Encare, including data regarding the mine (anonymous), equipment model, number of equipment models, average age, availability, nominal operating utilisation, available operational use, operational performance, MTBF (mean time between failures) and MTTR (mean repair to time). The Encare benchmark reports do not specify the methodology or methods used to collect data. The data in the Encare benchmark report will be compared with the theoretical production rate of a shovel with the same-size bucket, and some assumptions will need to be made. The assumptions to determine the theoretical production rate are shown in table A6. The Caterpillar handbook was used as a guide for the assumed values. All values result from a best-in-class shovel operation, which can be achieved with Caterpillar equipment.

4.2.1 Results

Mines often operate multiple shovels to achieve the required production target, which is also the case with the Encare benchmark report. However, this will result in a benchmark report comprising averages from multiple machines (see figures 15 and 16). Since extremes heavily influence averages within the dataset, the decision was made to compare the data that includes one of a particular shovel model. The impact of averages is shown in figure 15 with mines X16 and X40. The impact of multiple shovels in a mine is shown through the error of the barplot (see figure 15). The comparison mine x16 and x40 to mine X8. The same pattern is visible in figure 16 with mine X1 and X15 compared to mine X14 and X18. The exclusion of averages results in seven data points for the 73-yd bucket-size class and twelve data points for the 56-yd bucket-size class. These data points will be compared to the theoretical best-in-class and worst-in-class productions. This comparison can be seen in 17 and 18.

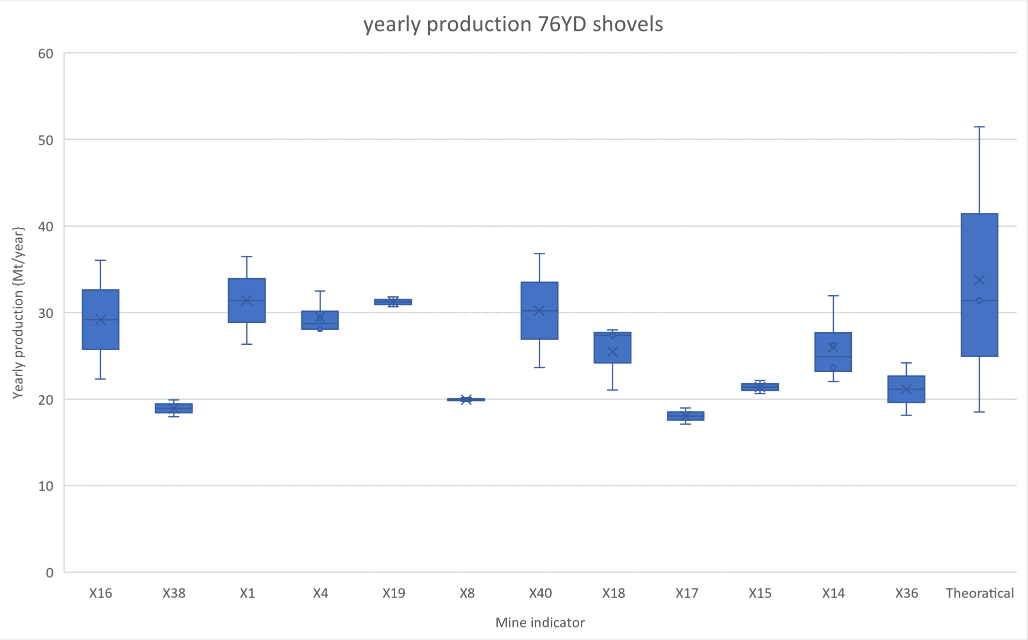


Figure 15: All 73 yd shovels from the Encare benchmark report

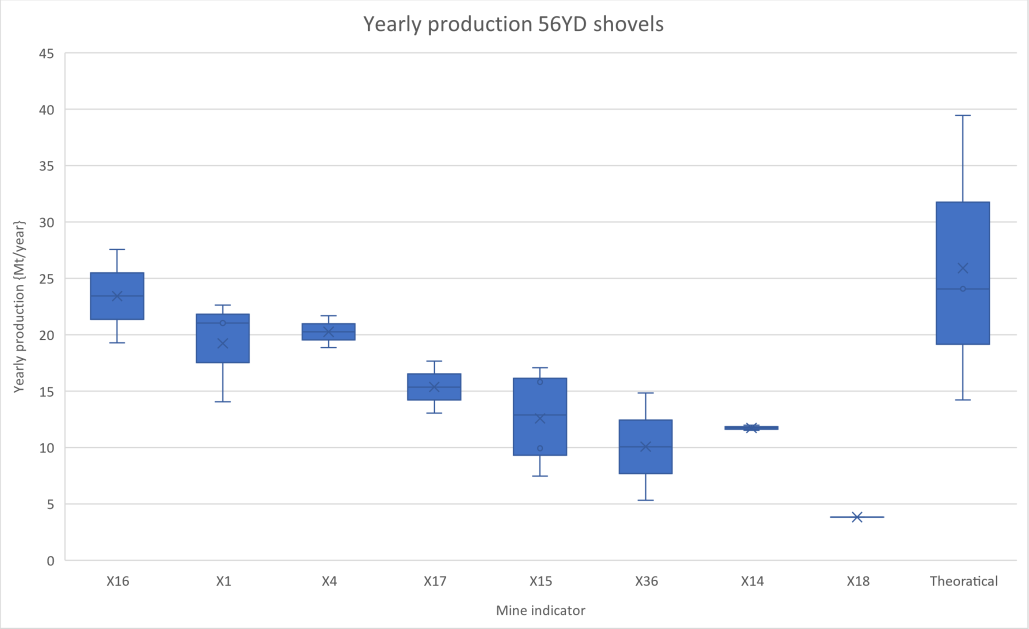
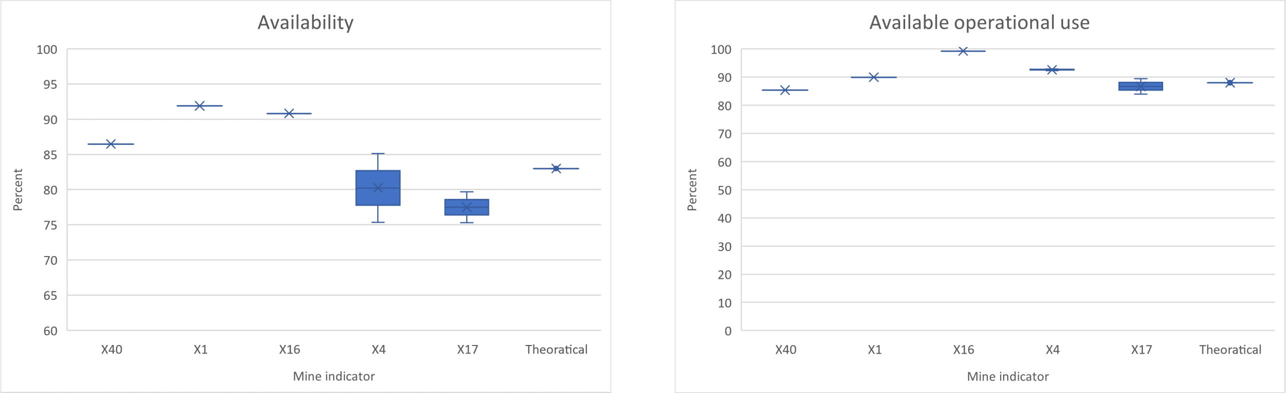


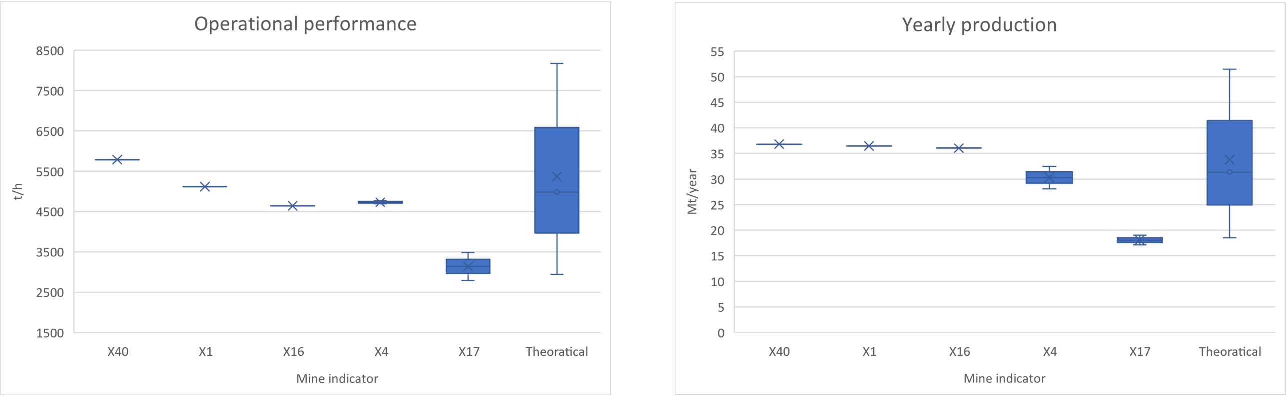
Figure 16: All 56 yd shovels from the Encare benchmark report

Figures 17 and 18 show the data for two different bucket sizes. Before starting with the observations, both figures will first be explained shortly. Figures 17a and 18a show the availability of all the machines operating in the different mining operations, which is the mechanical availability of the machine. Figures 17b and 18b show the available operational use, which is better know in this study as the use of availability. The available operational use is explained in section 3.6. The operational performance is shown in figures 17c and 18c, which show the production rate is mt/h, as explained in section 3.6. Figures 17d and 18d are the yearly productions achieved using values presented in the past three sub-figures.



(a) Availability

(b) Available operational use

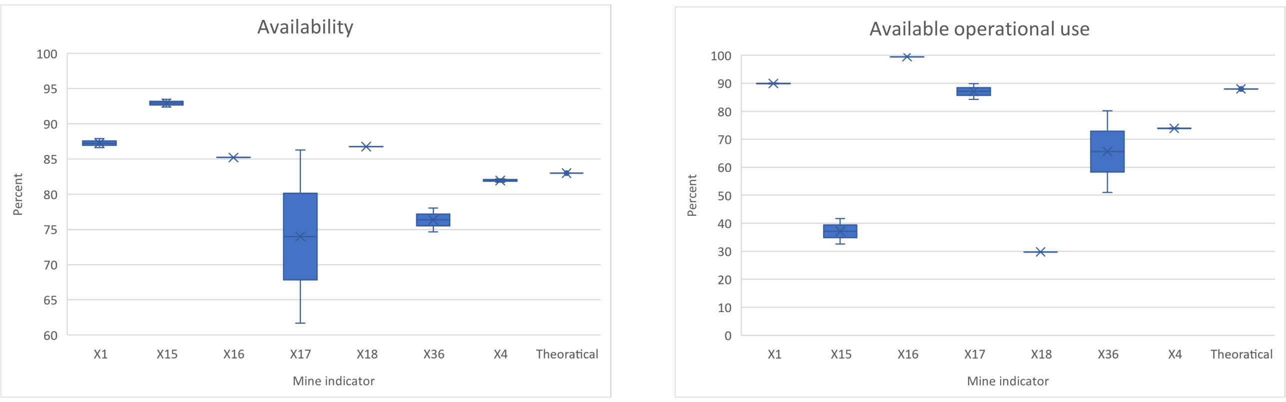


(c) Operational performance

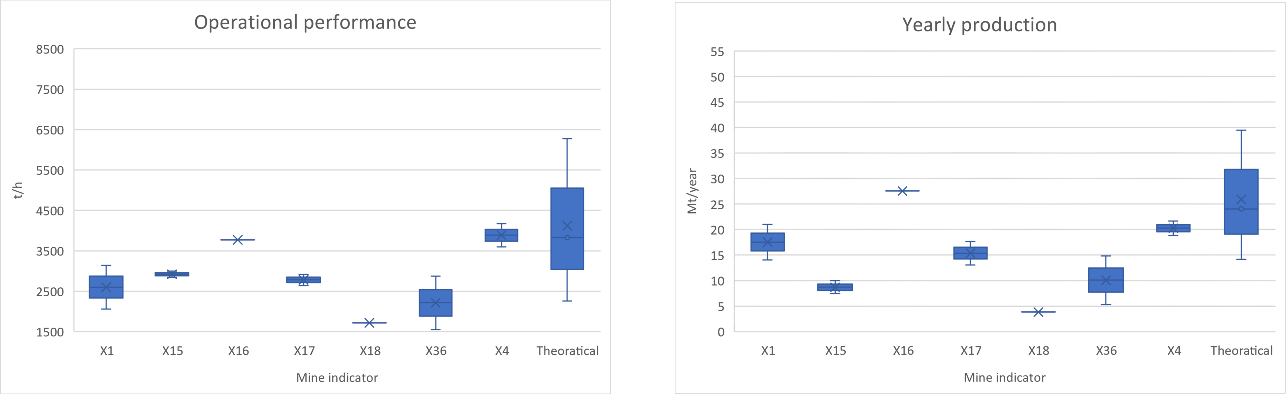
(d) Yearly production

Figure 17: Encare benchmark report data of the single 73 YD shovels (the only model that was operating in the mine)

From figures 17 and 18, three important observations can be made. The first observation for the 73 and 56 yd shovels is that high operational performance will result in better yearly production than focusing on high availability or use of availability. The second observation is that there is a significant difference in operational performance between the best-in-class theoretical production and the real-world production achieved in the mines. Lastly, the operational performance of some 56-yd shovels is below the worst-in-class theoretical production, which is not the case with 73-yd shovels. However, the performance of the mine indicator X17 is around the worst-in-class theoretical production. For the mining indicator X17, the underperformance results from a decreased operational performance (see figure 17c). The availability and the available operational use of the X17 mine are similar to those of the other mines, so these can be excluded as a cause of underperformance. Therefore, this underperformance can be caused by factors in the shovel productivity formula, which could be the following: density, swell factor, bucket fill, number of passes, cycle time, truck exchange time, and efficiency.



(a) Availability **(b)** Available operational use



(c) Operational performance **(d)** Yearly production

Figure 18: Encare benchmark report data of the single 56 YD shovels (the only model that was operating in the mine)

The 56-yd shovel operational performance can often be classified as average or worst-in-class theoretical production. The cause for this under-performance cannot be determined by reverse engineering the factors influencing the shovel productivity. However, the smaller size bucket might give some suggestions for the cause of the underperformance. These smaller bucket-size shovels could operate in sub-optimal cuts that lead to a less efficient operation. Furthermore, in the 56-yd shovel data set, there are two cases in which two different models operate in the same mine. Mine X1 operates a 495BI and 4100A+. The 4100A+ has about 20.000 more operating hours than the 495BI (91.000 operating hours). However, the operational performance of 4100A+ is 2060 t/h, and 495BI is 3140 t/h, which is a difference of 1080 t/h (see figure 18c). Both machines report the same numbers for availability and use of availability (availability is 88 % and use of availability is 90 %). The difference in operational performance leads to a yearly production for the 495BI of 21 Mt/year. In comparison, the 4100A+ has a yearly production of 14 Mt/year. These yearly production numbers are on the low side of the theoretical production range (see figure 18d). The other mine where two models can be compared is X36. The mine X36 operates an older 4100XPA with 110.600 operating hours and a new PC8000 with 24.540 operating hours. Both machines have approximately the same availability. However, the use of availability and the operational performance of the PC8000 (51% and 1554 t/h) are significantly worse than the numbers of 4100XPA (80% and 2871 t/h). The yearly production for 4100XPA is 15 Mt/year, and PC8000 is 5 Mt/year.

4.2.2 Discussion

Since the Encare benchmark report does not explain the methodology and methods that have resulted in the data, the results can only be used for superficial data analysis. The most significant influence will be the time usage model used to collect the data on availability and the use of availability. The probability that the eleven companies all used the same time usage model is doubtful.

Furthermore, the exclusion of the average values of the same type of machines in the same mine significantly reduced the size of the data set. This exclusion of the average values also contributes to the superficial analysis that can be done regarding the Encare benchmark report.

Lastly, the underperformance of the 56-yd shovels can be explained through non-optimal usage. However, due to the limited amount of data, the cause for this level of underperformance is hard to trace. This non-optimal usage of the 56-yd shovels can result from operating in cuts that are not correctly designed.

4.3 Case study 3: Annual production versus theoretical fleet production

Mining projects are located worldwide, where multiple shovels move material that produces a variety of commodities. The previous two case studies focused on the individual machine level and the resulting performance. However, mining companies and operations come in all shapes, sizes, and commodities. In this case study, three different commodities (gold, copper, and iron) will be compared concerning the size of the shovel fleet and the annual production achieved by the operation over 16 years. The 16 years included the cyclical movements expected in the mining sector. The selected operations have a variety of geographical locations, size of the owner, size of the operation, and availability of data. The annual production of the mining operations was retrieved from the S&P Capital IQ database (S&P Global, n.d.). The fleet composition of the operations was retrieved from variable sources within Caterpillar. However, a significant drawback of the data is the unknown accuracy, as the data set is not verified with the different mining operations. All the data are snapshots of the situation at a specific time. These snapshots could be an incorrect interpretation of the situation in the mine. This incorrect interpretation is because mining companies can have varying fleet sizes throughout the years or months. Since these snapshots are a specific moment, the yearly or monthly variations in fleet size are not considered. Furthermore, several assumptions are made to calculate the fleets' production rates based on best-in-class assumptions that are not specific to each mining operation.

4.3.1 Results

The assumptions for the production rates for a shovel that operators as the best-in-class are as follows:

- Bucket Payload is based on the maximum payload of the machine, which was retrieved from Caterpillar (2019)
- Bucket fill of 90% (a realistic assumption would be ranging from 70-85%)
- Pass match of 4 passes (standard is four, but mining companies can use a different pass match)
- Average cycle time for each type of machine extracted from Caterpillar (2019) (mining operations can have longer cycle times when the digging conditions are nonoptimal or the operators are less experienced)
- Truck exchange time of 33 seconds (The truck exchange time can be highly variable in the day-to-day operations)
- An efficiency of 83% (The efficiency in the real world will be between 50-75%)
- scheduled time in a year of 8616 hours (8760 hours in a year, but two days for holidays and four days for weather delays are unscheduled)
- Use of availability of 83% (the use of availability can range from 70-90% in real-world operations)
- Mechanical availability of 88% (mechanical availability depends on the age of the equipment, which can range from 75-90%)

Figures 19 to 35 show the graphs of different mining operations. The lines represent the yearly production of waste (blue), ore (orange), and total material (grey). Furthermore, figures 19 to 35 also show the total theoretical production of the shovel fleet (total shovel production shown in yellow). Lastly, the ratio between theoretical and real-world production (total material) is added as a bar chart (blue) in figures 19 to 35. This ratio will enable a faster comparison between different mines. When this ratio is equal to 1, then the theoretical and the total material are equal. When the ratio is lower than 1, the actual production is higher than the theoretical production capacity of the loading fleet, which should be impossible. So, the ratio will range from 1 to 10, depending on the mining operation.

The data will only be used to look for general trends that are visible in the data. Although the accuracy of the data is uncertain, the following general observations can be made from the data:

- The annual production of ore should be consistent throughout the years, which will indicate the maximum utilisation of the processing plant
- The ratio of theoretical production to real-world production should range from 1 to 2.5. A ratio of 1 indicates that the theoretical and real-world production are equal. So, the assumptions made in this study match the real world. A mining operation achieving a ratio of 1 can be classified as a best-in-class operation. When assumptions represent the real world better, a ratio below 2.5 will still represent an average-in-class mining operation.
- When the theoretical production ratio to actual production is higher than 2.5, the equipment is not used to the total capacity. This high ratio can indicate that some improvements can be made or that the mine is still ramping up.
- The different commodities do not result in different trends. Therefore, the different commodities will not lead to different use of shovels

In figures 19 to 35, all the different operations are shown. These figures will highlight the best, average, and worst practices. This classification will result in a better understanding of the general findings that were previously discussed. The mining operations in figures 19, 21, 22, 25, 28, 29, 30, 33, and 34 can be classified as best practices because they have a constant annual ore production, and a ratio of theoretical production to actual production is between 1 and 2.5. These mining operations could improve their operation when focusing on specific details, which would only be possible in cooperation with mine owners. The average mining operations are shown in figures 23, 26, 27, and 35, which will benefit substantially from the mining performance solutions offered by Caterpillar. The worst performing mining operations are shown in figures 20, 24, 31, and 32. These mining operations could benefit from an in-depth productivity analysis, followed by a corrective action plan.

4.3.2 Discussion

Some mining operations presented in figures 19 until 35 cannot be classified as truck and shovel operations, as shown in figures 28 and 29. Therefore, the data of these operations cannot be considered very accurate. The mining operation in figure 28 also uses wheel loaders that need a different calculation. Additionally, the wheel loader bucket's size is unknown, making it challenging to make reasonable assumptions. The mining operation in figure 29 has implemented in-pit crushers that eliminate the need for truck exchange time. Eliminating truck exchange time results in equal use of the theoretical and real-world production rates. However, the theoretical production is not adjusted for this case, so the theoretical production will be higher than shown in figure 29.

Lastly, the mining operations in figures 31 and 32 are part of a larger mining complex with multiple open pit mines. These large mining complexes make it challenging to find the correct data for one or two specific open pit mines within the mining complex.

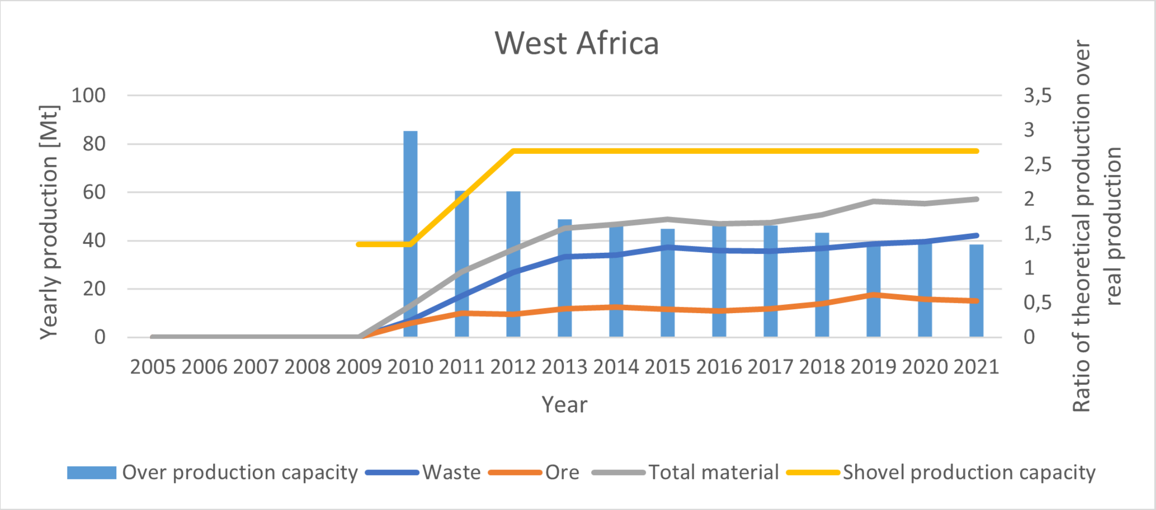


Figure 19: Gold operation in West Africa owned by a mining company in the top 100 in terms of market value. Mining fleet consisting of backhoe shovels

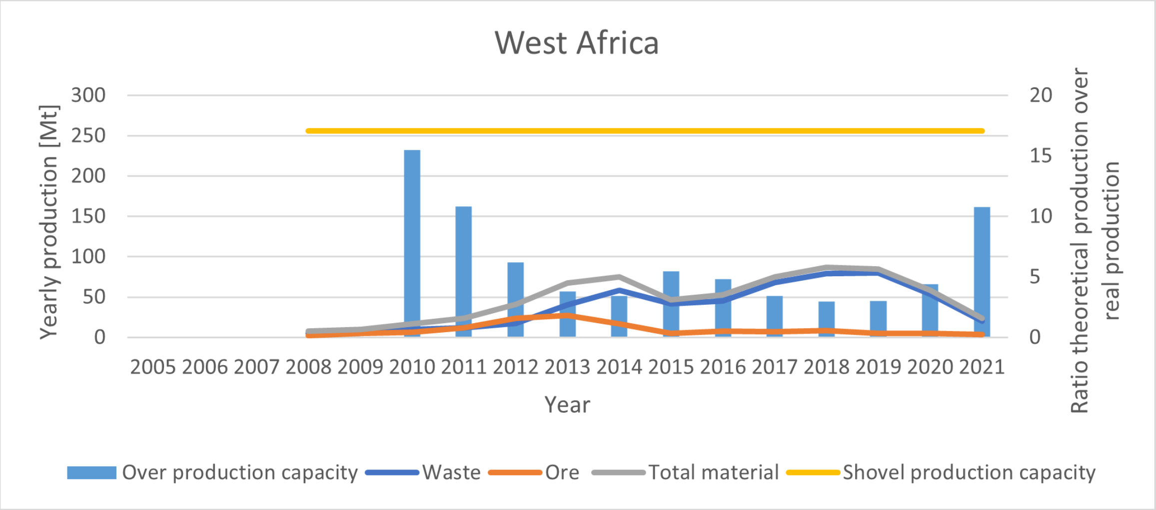


Figure 20: Gold operation in West Africa owned by a mining company in the top 50 in terms of market value. Mining fleet consisting of backhoe shovels

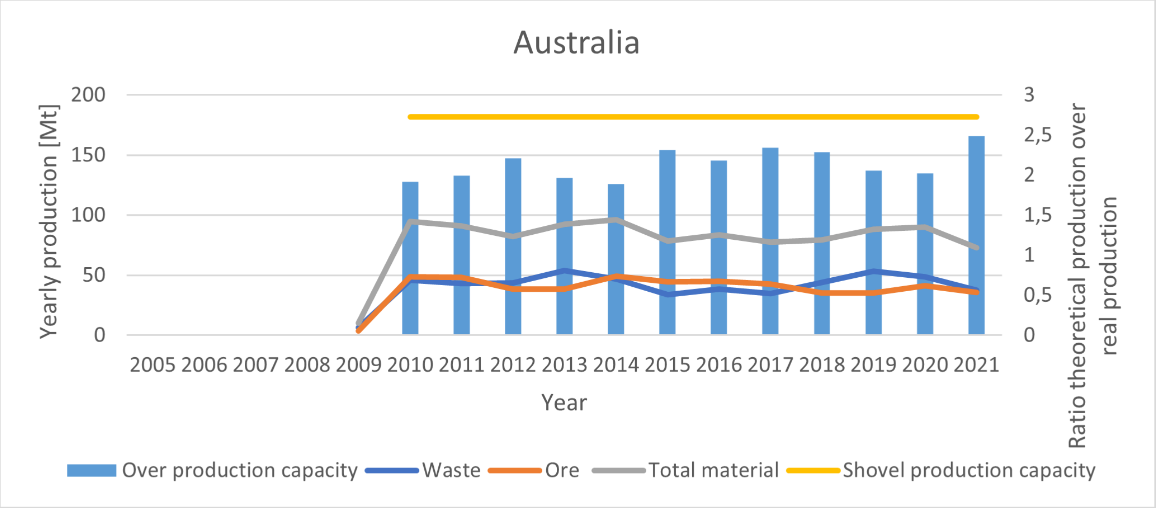


Figure 21: Gold operation in Australia owned by a mining company in the top 25 in terms of market value. Mining fleet consisting of backhoe, front and electric rope shovels

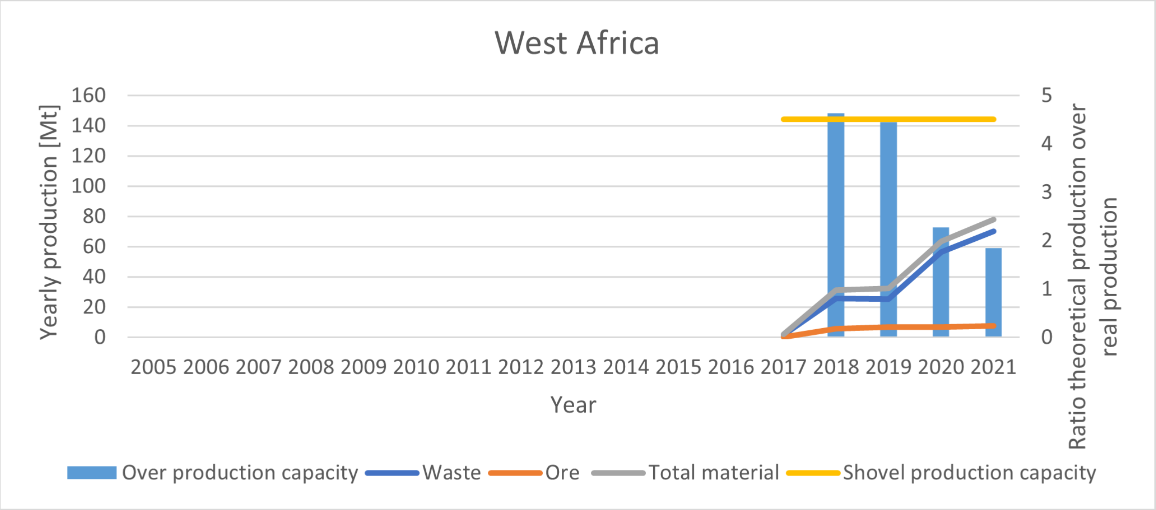


Figure 22: Gold operation in West Africa owned by a mining company in the top 50 in terms of market value. Mining fleet consisting of backhoe shovels

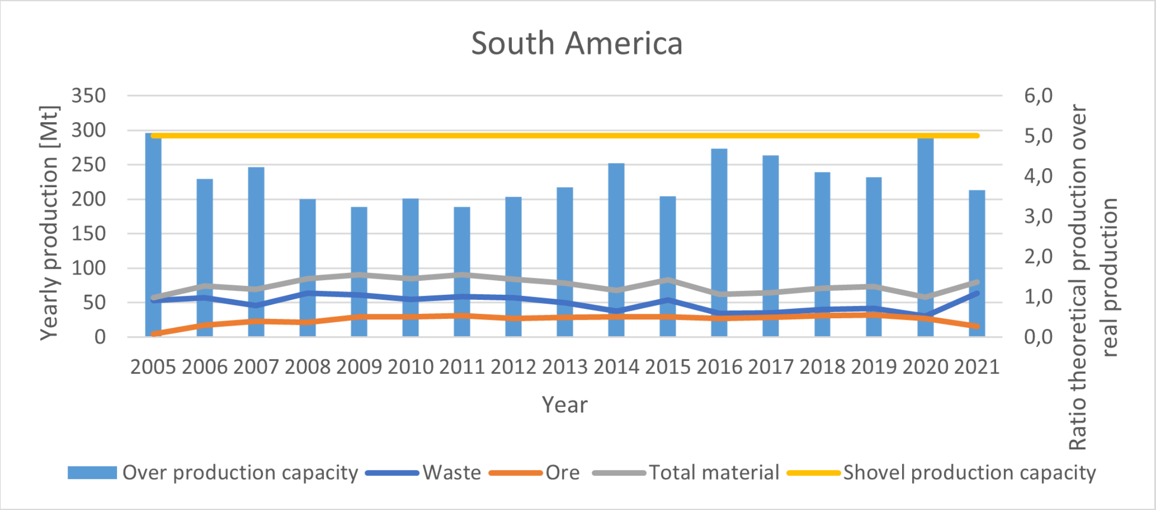


Figure 23: Gold operation in South America owned by a mining company in the top 25 in terms of market value. Mining fleet consisting of backhoe and front shovels

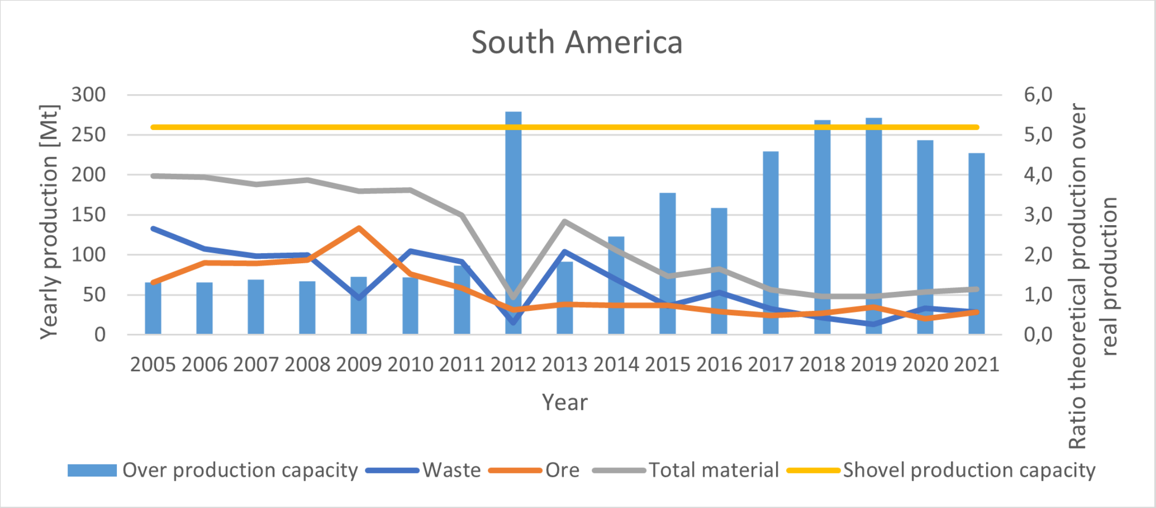


Figure 24: Gold operation in South America owned by a mining company in the top 25 in terms of market value. Mining fleet consisting of backhoe and front shovels

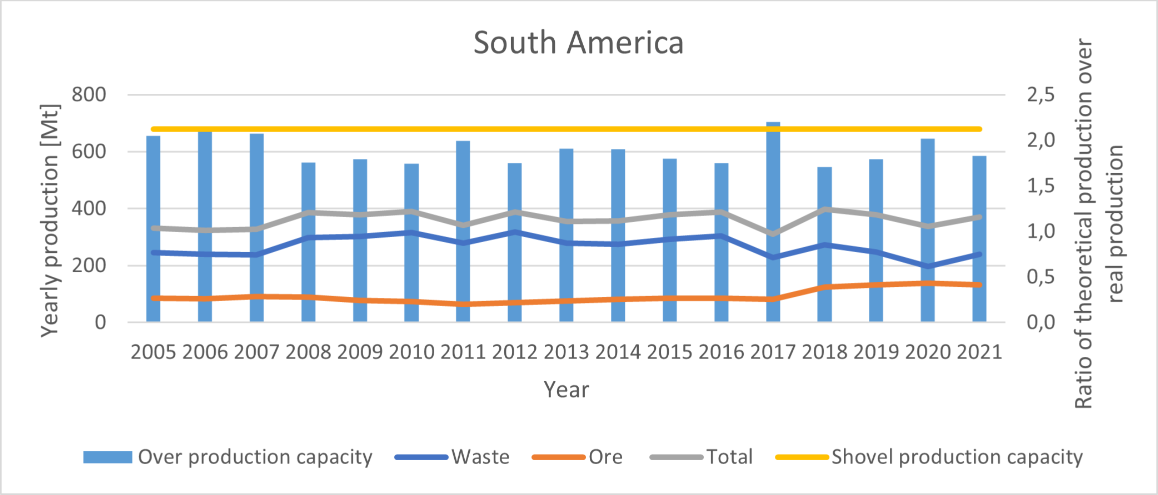


Figure 25: Copper operation in South America owned by a mining company in the top 5 in terms of market value. Mining fleet consisting of electric rope shovels

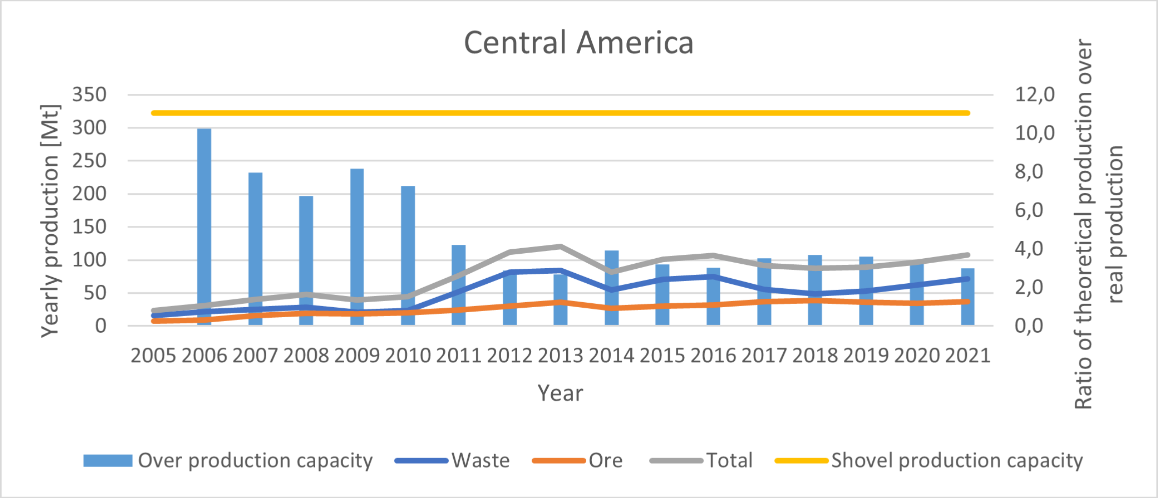


Figure 26: Copper operation in Central America owned by a mining company in the top 50 in terms of market value. Mining fleet consisting of backhoe and front shovels

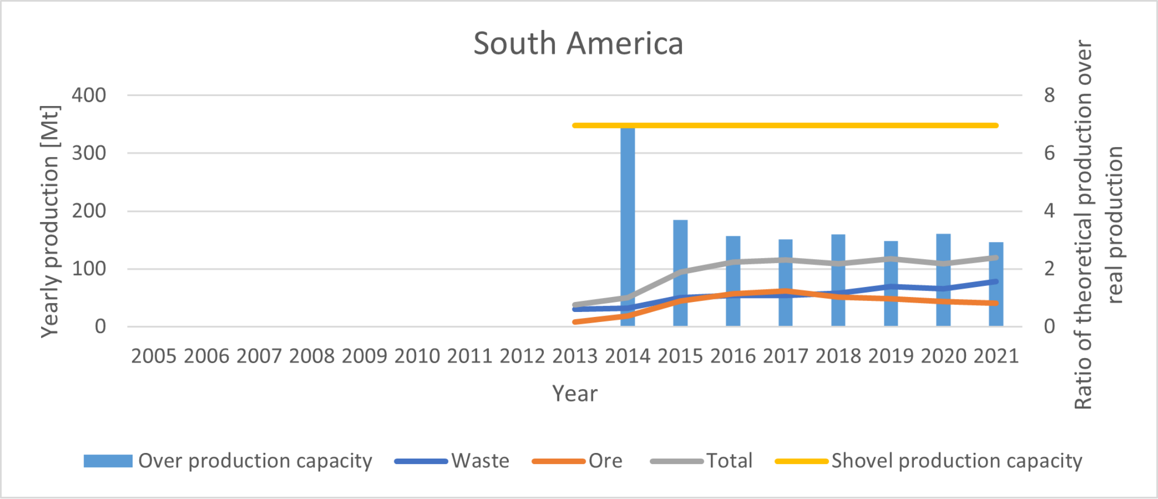


Figure 27: Copper operation in South America owned by a mining company in the top 5 in terms of market value. Mining fleet consisting of electric rope shovels

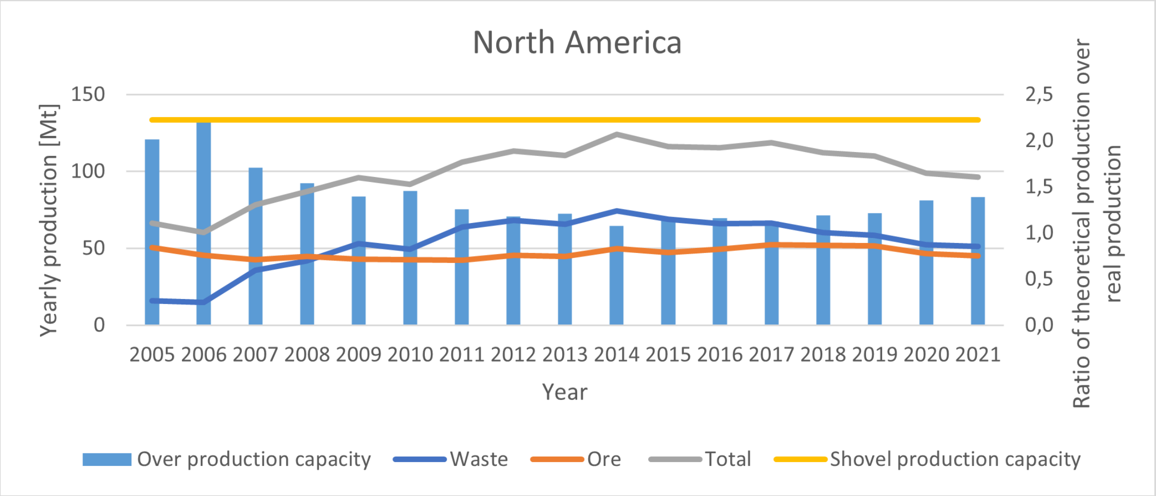


Figure 28: Copper operation in North America owned by a mining company in the top 25 in terms of market value. Mining fleet consisting of electric rope shovels and wheel loaders

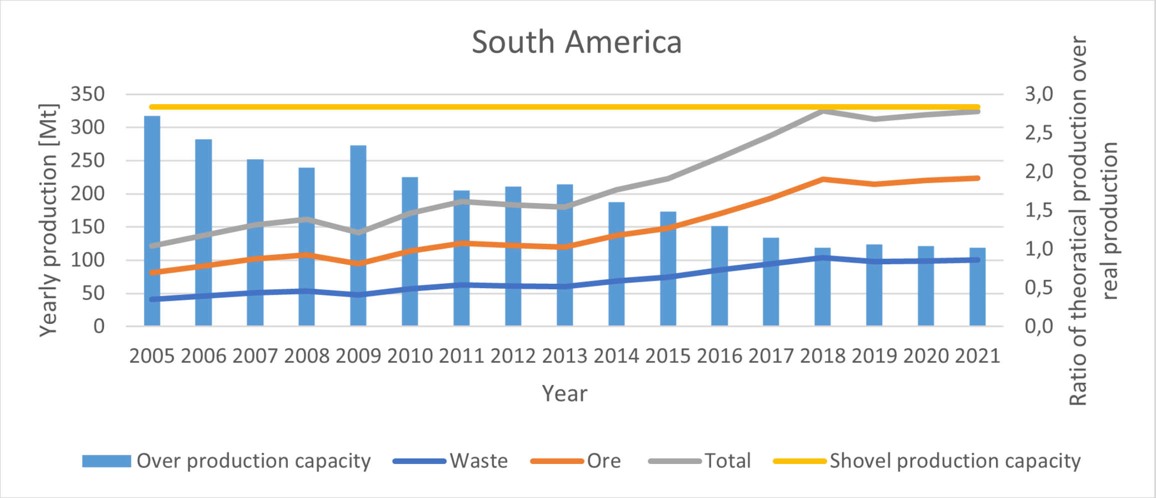


Figure 29: Iron ore operation in South America owned by a mining company in the top 5 in terms of market value. Mining fleet consisting of backhoe and electric rope shovels

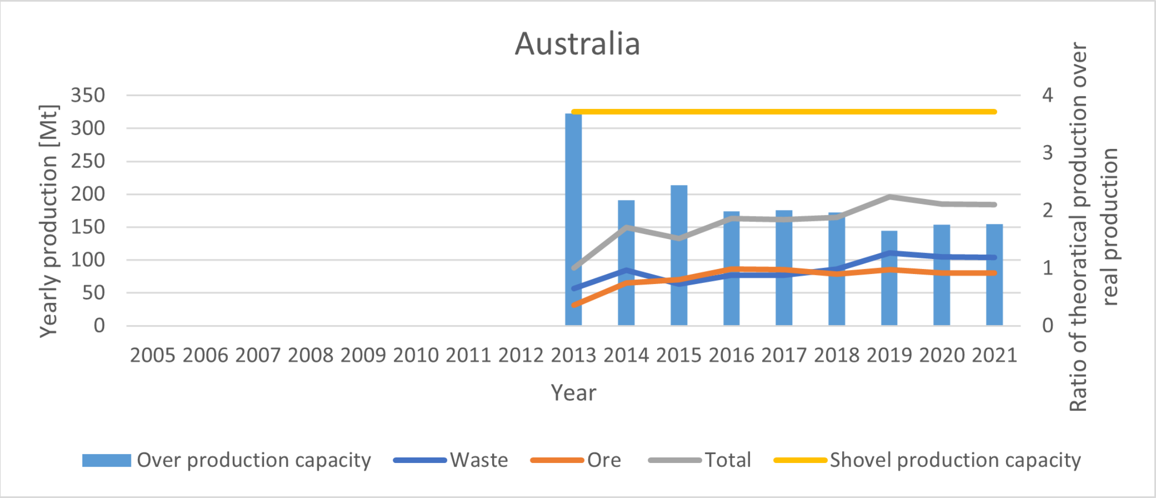


Figure 30: Iron ore operation in Australia owned by a mining company in the top 25 in terms of market value. Mining fleet consisting of backhoe and front shovels

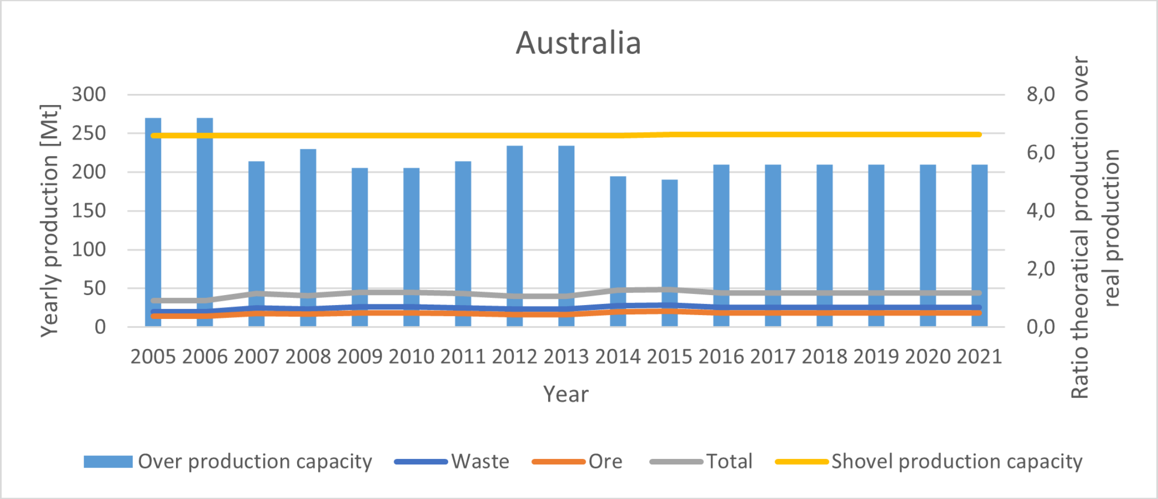


Figure 31: Iron ore operation in Australia owned by a mining company in the top 5 in terms of market value. Mining fleet consisting of front shovels

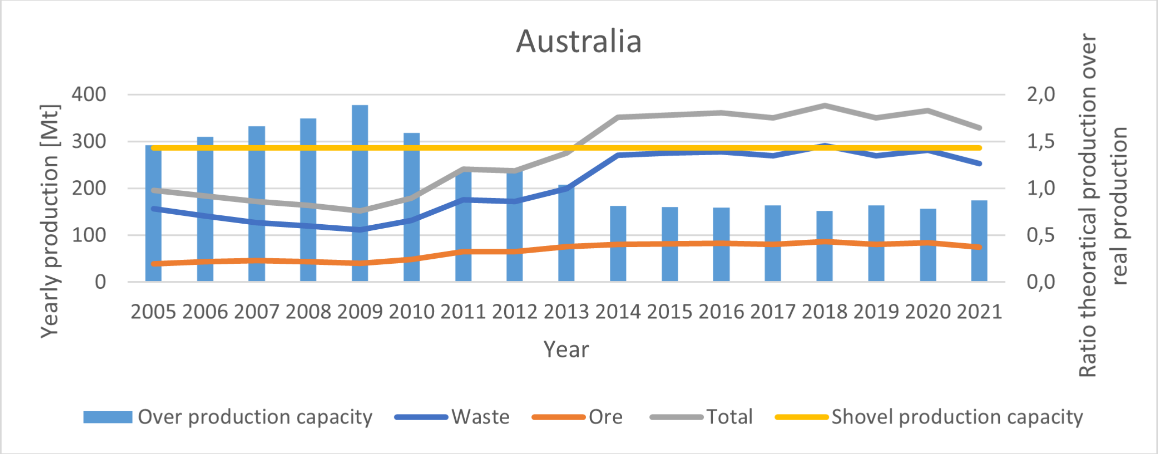


Figure 32: Iron ore operation in Australia owned by a mining company in the top 5 in terms of market value. Mining fleet consisting of backhoe and front shovels

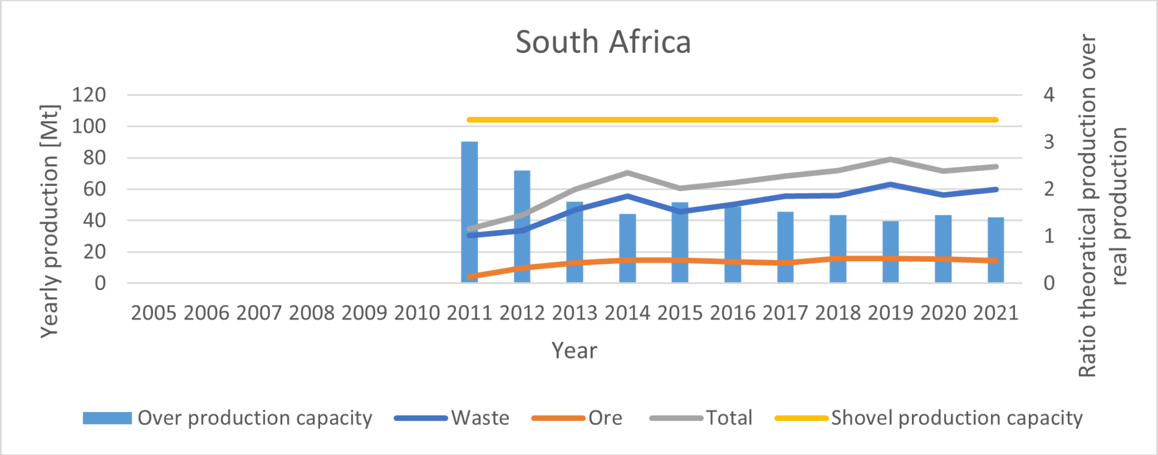


Figure 33: Iron ore operation in South Africa owned by a mining company in the top 50 in terms of market value. Mining fleet consisting of backhoe and front shovels

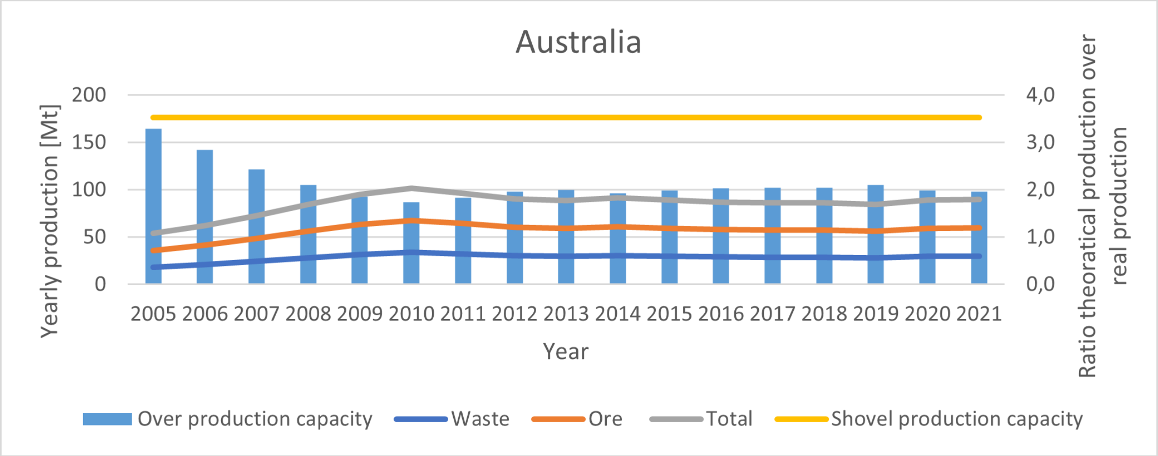


Figure 34: Iron ore operation in Australia owned by a mining company in the top 5 in terms of market value. Mining fleet consisting of backhoe and front shovels

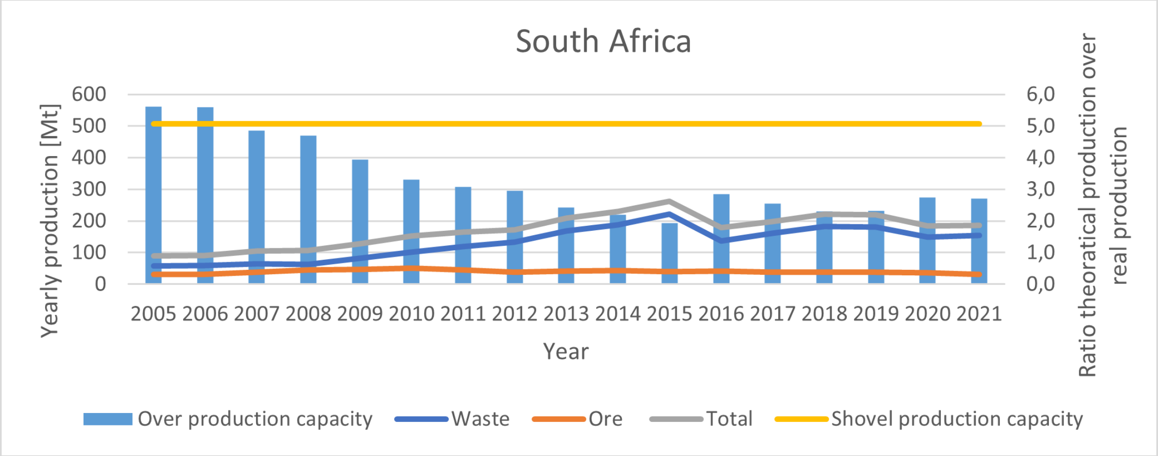


Figure 35: Iron ore operation in South-Africa owned by a mining company in the top 50 in terms of market value. Mining fleet consisting of backhoe, front, and electric rope shovels

4.4 Case study 4: Interviews with industry professionals and experts

Interviews were conducted with 11 mining professionals. These mining professionals had the following job titles: Mining engineer, teacher, consultant, senior management technical marketing, director automation, hydraulic mining shovel application specialist, technical solution engineer, senior mining engineer, technical service manager, and mining sales engineer. Furthermore, the interviewees have a great variety of work experience ranging from young professionals (+3 years of work experience) to senior management (+20 years of work experience). Lastly, the geographical location of the interviewees ranges from North and South America to Europe and Australia. These interviews will better understand the difference between theoretical and real-world production rates. The interviewees have a wide variety of experience, positions, locations, and commodities. Therefore, the results give a good overview of the mining industry. The objective of the interviews was to understand what determines the real-life achievable productivity of a shovel. The interviews have a standard part that all the interviewees answered. All interviews started with questions about factors influencing shovel productivity, mine planning regarding shovels, uncertainty within the mining industry, and the time usage model. The next set of questions aimed to identify factors that significantly impacted shovel productivity more than others. Furthermore, additional questions were asked to make good use of their knowledge depending on the interviewee's expertise.

The responses to what factors influence shovel productivity were very diverse. Therefore, all the different factors mentioned below will be summarised. The results are a general list of factors that influence shovel productivity.

- Unplanned maintenance
- Fragmentation
- Diggability
- Shift changes/coffee breaks/lunch breaks
- Electric cable points
- Stand-by time
- Operator skill
- Truck availability
- Weather conditions
- Floor conditions
- Ancillary equipment support
- Blasting delays
- Match between truck and shovel
- Blast movement
- Blending
- Training
- Motivation
- Maintenance plan
- Size of the blasts
- Truck exchange time
- The geometry of the cut (length-width ratio)
- The proximity of the shovels
- Fleet resilience[1]
- Mine planning
- Commodity
- Deposit style
- Smallest mining unit
- Frequency of shovel moves
- Conditions at the working face
- Type of material
- Need for stockpiling

The effect of mine planning on shovel productivity was then discussed with the interviewees. The mine planning department has to deal with input from different departments, so an ideal plan for the drill and blast team might not be the best for the load and haul team. Therefore, the mine planning department will have to find a balance for this. One of the main points that emerged from the interviews was that shovel movement should be limited to the absolute minimum. Reduction in shovel movement (or shovel tramming) can be achieved by having a large number of open faces, which prevents the unnecessarily tramming of shovels. However, the mine plan could be altered for the benefit of the processing plant. When this is the case, movements can be reduced by having sufficient stockpiles that reduce the need for shovel tramming. Since the mine planning department has to balance the mine plan around the restrictions of different departments. The mine plan can lead to a non-optimal use of the shovel.

As mentioned in section 3.7, mining always works with a degree of uncertainty. Regarding uncertainty, all interviewees were asked what level of uncertainty is acceptable and how it affects shovel production rates. The question mentioned above was the first question where not all interviewees gave the same answer. Three of the four interviewees who answered this question indicated that the uncertainty within the mining industry is between 5-10%. The other interviewee stated that uncertainty does not influence production rates but only the quality of the output. Another interviewee highlighted that the operations delays would have an uncertainty below 5%, which does not include orebody, fragmentation, density, and type of material in the waste/ore. Therefore, there is variation in answers to what the cause is for uncertainty and what the effect will be on production rates.

The time usage model has a significant impact on the yearly production rates. The reason is that it determines the mechanical and use of availability. This led to the question of which category of the time usage model had the most negative impact. The interviewees answered that unplanned maintenance has the most significant negative impact on shovels (or any other type of equipment). An interviewee also stated that weather delays had a tremendous negative impact. However, this is very

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[1] The number of shovels (or trucks) that can break down before the production will be reduced. So, a mining operation can achieve its production with three shovels, but the shovel fleet consists of six shovels. This means that if the fourth shovel breaks down, the production is reduced. However, two machines are sold due to the cost of the six shovels. This makes the loading fleet less resilient because if a second shovel breaks down, the production will be reduced.

specific to the site and is not always the case, resulting in the conclusion that unplanned maintenance is generally negatively impacted most. The following interview questions aimed to represent better which factors have a more significant influence than others. Several questions about the factors that could significantly influence were asked to arrive at a reasonable conclusion. These questions concern operator training, cycle time, fragmentation, and the top five factors influencing shovel productivity.

The first question was about additional training when an operator performs below average. Three interviewees agreed that the whole picture of the operator would need to be improved. The operator skills are improved with a mining training coach giving the operator the right directions. These mining training coaches monitor shovel operators and give them additional training if needed. The following two questions that the interviewees were asked were given two choices. The first question was about the preference between a slower cycle time and an above-average bucket fill or a faster cycle time and a lower-average bucket fill. Three interviewees answered this question. They would prefer a slower cycle time and an above-average bucket fill. The last interviewee did not know the answer but suggested it as an excellent experiment in a small-scale mining operation. The sensitivity analysis of the shovel production rate from section 4.1 shows a similar conclusion. The sensitivity analysis showed that a decrease in the cycle time of 10% would decrease the production rate by 7%. The increased bucket fill of 10% will increase the production rate by 10%. Therefore, the overall production rate with a slower cycle time and above-average bucket fill will increase.

The other question was whether fragmentation or operator skill had a more significant influence on shovel productivity. Six interviewees responded that fragmentation has a more significant influence. An interviewee stated that operator skill has greater influence unless fragmentation is extremely poor. The last interviewee stated that both have an equally significant impact. The following example is the best example of a good idea whose factors have a more significant impact. A good blast will enable a bad operator to get a well-filled bucket. In contrast, with bad fragmentation, even a good operator will have difficulty getting a will-filled bucket.

The last question of the interview is about the top five factors that influence shovel productivity the most, according to their experience. There are two approaches. The first list is based on the times a specific factor is mentioned. The second list is based on the weighted amount on the place in the list (so the first mentioned factors will get a higher score than the last mentioned factor). All the top fives of all interviewees are summarised below.

The ranking of factors based on the times the factor is mentioned:

1. Mine planning
2. Operator skill of shovel and truck operator
3. Fragmentation
4. Unplanned maintenance
5. Truck availability
6. The geometry of the cut (length-width ratio)
7. Ancillary equipment
8. Weather
9. Stand-by time
10. Proximity of shovels
11. Fleet resilience
12. Pass match between shovel and truck
13. Operator breaks
14. Mine design
15. Floor conditions
16. Blending requirements

The ranking of factors based on the weighted amount on the place in the list is mentioned:

1. Fragmentation
2. Unplanned maintenance
3. Operator skill of shovel and truck operator
4. The geometry of the cut (length-width ratio)
5. Truck availability
6. Proximity of shovels
7. Mine planning
8. Fleet resilience
9. Pass match between shovel and truck
10. Stand-by time
11. Weather
12. Floor conditions
13. Blending requirements
14. Operator breaks
15. Ancillary equipment
16. Mine design

The difference between the two lists is visible with several factors. First, the mine planning drops six places, indicating that many interviewees mentioned the mine planning as an influencing factor. However, they did not think it would be the main reason for the underperformance of the shovel. Mine planning focus on the sequencing of the mining face. So, the mine plan will dictate when and where a shovel will be moving material. Fragmentation, unplanned maintenance, and operator skills are mentioned a lot and are also given as high-impact factors, consistent with the answers to other questions about these topics.

Some interviewees only discussed interview questions, while with other interviewees, the interview was more flexible. Therefore, some interviewees made additional comments on some additional topics. Some of these additional comments are site-specific but will highlight specific problems some mining companies will have. These additional comments are summarised below.

- The equipment size is too large with the current mine plan and design. Smaller equipment would have been more productive and better for operation (specific for a mining operation).
- The geographical location of a mine does not matter when a large mining company operates it because they use the same standards throughout all operations. However, when a small or local mining company operates a mine, this can significantly impact the operation because of the lack of knowledge and expertise within small or local mining companies.
- The turning circle of the large trucks was too large, so they could not be used in the first part of the lowest bench (specific for a mining operation).
- Seasons can have an impact on different aspects of the operation. The impact of seasonality can greatly vary for each mining operation.
- Due to the data available at the mine site, an excellent internal mining engineering department will always be better than an OEM (Original Equipment Manufacturer) can produce.

Lastly, three interviews were conducted with subject matter experts, resulting in a modified interview highlighting questions about their expertise. The experts' specialised subjects are blasting, automation, and hydraulic mining shovels. These three interviews will be summarised below.

4.4.1 Blasting

The goal of the interview with the blasting subject matter expert was to gain more knowledge about the blasting of material with a focus on densities, fragmentation, and the swell factor. The interview started with a question about the design of the blast pattern. The blast pattern is variable depending on the mining operation. Some mining operations outsource everything to an external blasting and explosives company. In contrast, other mines make the designs in-house and only outsource the explosives loading. The next question was about the blasting design parameters for different commodities. The two main drivers of the blast design parameters are the downstream processing method and the rock characteristics. These two main drives hold for all commodities. The question of whether density changes are considered in the blast design was answered by saying that different patterns are used for blasts in ore and waste. However, all designs are based on information provided by the mining company. Therefore, the designs are limited to the information provided.

Questions about the swell factor were asked to validate the findings in the literature. The literature review has shown that swell factors are often neglected and not well known. Therefore, a swell factor of 30% is an industry-wide assumption. The assumption of 30% for the swell factor used throughout the industry is correct. However, the swell factor can be estimated using a computer program that calculates the new volume after the blast. There is no method to predict the swell factor before the blast. The swell factor depends on the characteristics of the rock, the structures in the material (orientation of the fractures), the explosives factor, the sequence of the explosion (short delays between holes will result in an upward movement of the material, and long delays between holes will result in sideways movement of the material), and fragmentation.

Lastly, fragmentation questions were asked to determine whether the desired fragmentation is always achieved and whether the fragmentation is adjusted with shovel size. As mentioned above, fragmentation depends on the processing plant, which is more important than adjusting the frag- mentation for the shovel size. The success rate in achieving the desired fragmentation is around 80%. However, this also depends on the person who designed the blast design. When the desired fragmentation is achieved, two factors can be held accountable. First, the design input was incorrect; second, there were deviations in the drill pattern. However, when the input is good and the plan is followed, the desired fragmentation is achieved most of the time.

4.4.2 Hydraulic mining shovels

The following interview was with the two subject matter experts in hydraulic shovels who work for Caterpillar. The interview was mainly about how the shovel production rates are calculated within Caterpillar and the factors influencing shovel productivity (similar to Section 3.7). The main points of the interview are summarised below.

- The amount and details of the information provided depend on each customer. Therefore, some companies provided different densities for ore and waste. In contrast, others only gave the global average density of the mine. Additionally, the accuracy of the information provided also varies for each customer. Therefore, Caterpillar will always work with limited information with potential errors, which should be used to determine achievable shovel production rates.
- The filling of the bucket depends on the diggability of the material. The diggability is dictated by the fragmentation of the blasted material. The loading cycle (as described in section 3.3.2) has the highest variation in time when filling the bucket, representing 40% of the time.
- Generally assumed, the operator efficiency of 83% per cent can be proved by short-term testing (shift of 8 hours) under perfect conditions. However, these numbers are not achievable over long periods

- Different factors are added to determine long-term production rates to compensate for the deduced production rates. This number is based on the years of experience of hydraulic shovel subject matter experts, which resulted in a long-term performance factor of 60/70%. This long-term performance factor is added to the calculation of shovel productivity over more extended periods. For example, in the previous bullet point, an operator efficiency of 83% is achievable over short periods under perfect conditions. A realistic operator efficiency over the long-term will range from 50-75%, which impacts the production rate significantly. The quantification of the short-term and long-term operator efficiency is precisely the goal of this study. However, the long-term performance factor should be quantified in more detail for every factor, which can be used to solve the underperformance of operational shovels.
- Hydraulic shovel subject matter experts stated that employees of mining companies knew very well what size they needed in the mine, which another interviewee also stated.
- The different loading methods have an impact on shovel production rates. Generally, hydraulic shovel subject matter experts stated that they do not recommend the use of double-sided loading. Double-sided loading gives high production rates in the short term. However, the benefit is negligible in the long term due to the frequency and length of the shovel relocation.
- Electric rope shovels need a certain bench height to be able to fill the bucket. The bench height has a more significant impact on electric rope shovels than on hydraulic shovels. Hydraulic shovels are more versatile and can work with any bench height.
- The production rates of two 6040 shovels should equal one 6060 shovel. Therefore, mining companies can achieve their desired production rates with a combination of different amounts and types of shovels.

4.4.3 Automation

The last interview will be summarised with the automation subject matter expert. During the interview, multiple subjects were discussed, such as load and haul models, the cut geometry and the effect on loading techniques, automation, fleet flexibility, fleet selection, and blasted material.

The interview starts with an insightful statement about the ability to model load and haul operations. The main difference between these two simulation models is that the inputs for the haul simulation model are relatively consistent compared to the loading simulation model. The factors in the haul simulation model are haul distance, grade (slopes), machine horsepower, and payload. When a simulation model is made for the loading fleet, all physical parameters are consistently and constantly variable (see section 3.6 for the factors). The factors in the loading simulation model are density, bucket fill, swell factor, shovel operator skill, truck operator skill, truck availability, truck exchange time, and cycle time. The consistently and constantly variable factors make it more difficult for a loading model to work correctly. Also, shovel underperformance occurs in many different ways. The underperformance of shovels is non-linear and variable over time. Therefore, finding the root cause of shovel underperformance is not straightforward.

The geometry of the pit and the cut (blast) depends on the geology of the orebody. Therefore, the geometry of the cut can lead to non-optimal usage of a shovel because deviations will have to be made from the ideal standard. A cut with a geometry of 150 by 150 metres will give optimal use of 75% double-sided and 25% single-sided loading. If the cut dimensions change to 150 metres in width by 50 metres in length, then 30% will be double-sided loading, and 70% will be single-sided loading. Lastly, the dimensions of the cut are 50 metres in width and >75 metres in length. There will be no added value of double-sided loading, so everything is loaded single-sided. As mentioned in section 3.3.3, single-sided and double-sided loading have advantages and drawbacks, affecting the shovel productivity. However, both of these loading methods also affect truck productivity. So, double-sided loading is more productive for the shovel. The shovel can go from the loading cycle to the loading cycle without waiting for a spotting truck. However, the trucks will be waiting longer in queue. The result is that an operation will have to decide to optimise with a priority for shovels or trucks.

The next topic discussed was the proximity of shovels to each other. The main point was that the interaction of the trucks that the shovel will load would destroy value (monetary or production). The trucks leaving the first shovel may have to wait for the arriving trucks for the second shovel, which will affect the cycle time of the trucks. Therefore, the proximity of two shovels working on the same bench could already lead to a decreased production because the trucks of both shovels will interact with each other.

Implementing automation for the trucking fleet will impact dynamics within the mining operation. Automation of the trucking fleet will result in additional trucking capacity. The added value of autonomy depends on the number of available trucks for each shovel. Autonomy will not generate additional value when the available trucks are queuing at the incorrect shovel. Furthermore, the shovel fleet will need to be able to absorb the additional trucking capacity created with autonomy. Additionally, automation reduces the flexibility of the mining fleet because everything is already stretched to the maximum capacity to extract the value of automation. For example, finding a different shovel to redirect the trucking capacity when a shovel breaks down will be impossible.

The flexibility of the fleet reduces with automation because additional trucking capacity needs to be used. In addition, the flexibility of the fleet also changes when choosing between electric or diesel-powered machines. Electric machines will need more human resources because the power cable also needs to move. Diesel-powered machines can start walking without additional human resources. However, the need for this flexibility often comes from the frequency of moving the machines, which can result from blasting differently from the original design. Therefore, the need for flexibility might result from deviations in other parts of the operation.

Additionally, fleet selection can create flexibility. The selection of the primary and auxiliary fleets will need to be matched with each other. The ancillary fleet needs to be able to work in harmony with the primary fleet. This harmony can be achieved by selecting an auxiliary shovel that can load a truck of the primary fleet, which might not be an optimal match. However, the shovel can still load the truck.

Another factor that influences the productivity of the shovel is the type of broken stock that has to be loaded. All the blasted material is ready to be loaded on paper, but some of these broken stocks can be found on small pads or wall trimmings. These small pads and wall trimmings are not optimal for shovel productivity. The available broken stocks can vary between the mine planner's paper and what is found in the field. The assumption made by the mine planner might not be valid, leading to non-optimal usage of the shovel.

Lastly, implementing automated shovels could improve the synergy with automated trucks. An automated shovel and truck will work without human interference, which could benefit both automated procedures. Research by Dunbabin and Corke (2006), Bi et al. (2020), Li et al. (2021), Marshall et al. (2016), and Zhang et al. (2022) shows that the development of automated shovels is still in the development stage. Furthermore, the literature review showed that implementing automated trucks has taken several decades to materialise in the mining industry. Also, a haul model is less complex due to the relatively constant factors. However, a load model is more complex due to the consistently and constantly variable factors. Therefore, automation of a load model will give new and complex challenges.

4.5 Case study 5: Visit to a mine site in North Africa

The last case study consists of the findings of a visit to a gold mine in North Africa. This gold mine consists of an open-pit mine and a new underground development. The mine visit had two focuses; the first was to make cycle time measurements to get data on the real-world production rate. Secondly, to gain knowledge about the operational side of shovel production. The visit consisted of two full days at the mine site, mainly spent doing as many cycle-time studies as possible. The rest of the time was spent talking to several on-site employees to understand the operation better. The knowledge gained on the operation is particular to the mine site, making it difficult to use this information for a general application. However, these mine-specific issues highlight this study's complexity and variability. some operational decisions are interpreted differently by employees. The effect of these operational changes depends on the employee's place within the organisation. First, the operational information specific to this mine site will be discussed, and the general operational information will be discussed at the end of this paragraph. The engineering department on site was very well informed about the parameters used in calculating the shovel production rate. Furthermore, the engineering team performed the reconciliation at frequent time intervals, as explained in section 3.1. However, the engineering department does not rely on real-time technology to monitor the shovel productivity. Therefore, the exact production rate of the shovel is known after months when all the surveying has been completed.

The operational parameters used by the engineering team are as follows:

- Loading fleet consisted of a combination of 6040 (backhoe configuration) and 6040FS (front shovel configuration)
- The bulk density is 2.6-2.7 t/m^3
- The loose density is 1.8-1.9 t/m^3
- The swell factor is 40%
- The maximum size of the material is 0.8 m (limitations of the primary crusher)
- The goal bucket fill is 85%
- The goal bucket weight is 35 tons

One of the issues that the mine site faced was concerning blast performance. The blast performance or the success of the blasts was reduced because the underground voids increased as part of their underground operation. These underground voids absorb some of the energy of the surface blast. These voids resulted in some blasts not achieving the designed fragmentation size and will need to be reduced in size with a rock breaker. The change in fragmentation caused by underground voids results in poor shovel performance.

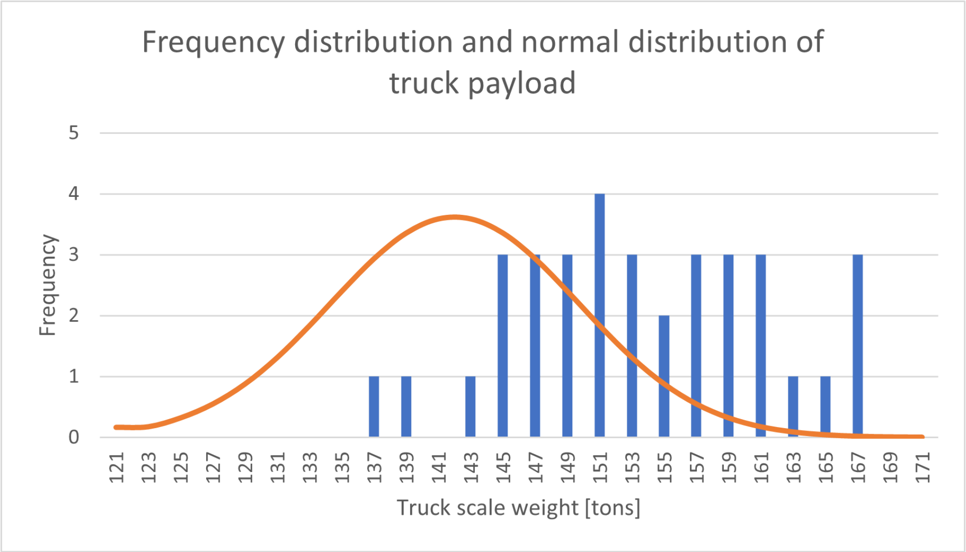
When a large portion of the open faces are at the bottom of the pit, the mining operation is forced to shovel out of production (park). The decision to park one shovel was made due to the length of the truck travel time, leading to long waiting times for all shovels on trucks.

Replacement of the worn-out truck bodies was needed for the mining operation. Therefore, the old bodies were replaced with new lightweight bodies. These lightweight bodies increased the loading capacity of the trucks. The new lightweight bodies lowered the empty weight of the trucks, which led to an increase in payload before the maximum gross machine weight was reached. However, this also changed the payload of the trucks. Consequently, it also changed the pass match between the shovel and the truck. These lightweight bodies changed from 4 to 4.5 passes to load a truck. The importance is explained in section 3.3.1. For example, the average cycle time is 26 seconds, each pass will load 40 mt (the half pass loads 20 mt), and the truck exchange time is 35 seconds. With 4 passes, the shovel can fill 26 trucks per hour with 160 mt; with 4.5 passes, the shovel can fill 22 trucks per hour with 180 mt. The hourly production rate for 4 passes will be 4160 mt/h, 200 mt/h more than with 4.5 passes. Therefore, the additional half pass will result in lower yearly production. The senior mining engineer on-site stated that lightweight truck bodies were purchased to increase the payload of the trucks. The same statement was made in the annual report of the mine owner. The annual report shows an increase of 5% in payload due to the purchase of lightweight truck bodies. However, during discussions with the technical service manager, the lightweight truck bodies should reduce the wear on the truck tyres. The difference in understanding between the technical service manager and the senior mining engineer may result in the improper use of the lightweight truck bodies by pursuing different objectives. So, the different objectives within departments will result in differences in the implementation of instructions by the management. The technical service manager wants to ensure the long-term performance of the equipment by using lightweight bodies as a reduction measurement for maintenance. In contrast, the mining engineer in the production department uses lightweight truck bodies to increase the production of the mine. Different interpretations between employees and departments could be classified as general operational information, as management interprets the objectives at every mine site.

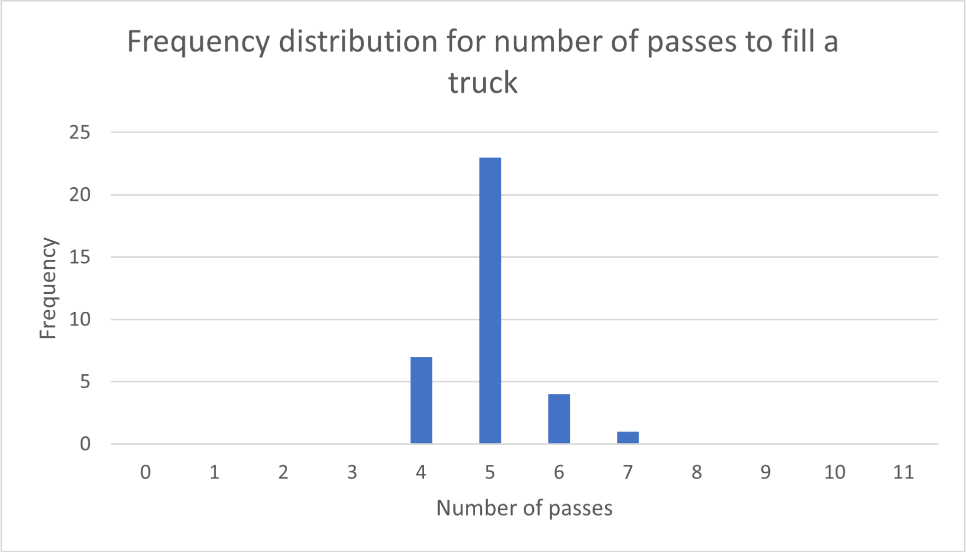
The general operational information retrieved from the mine site visit is the interpretation of objectives by management, the experience of the operator, and the reduction in unplanned maintenance. These three points apply to every mining operation. Therefore, the most valuable part of on-site interviews. The second general operational information that could be concluded from the mine visit was the relationship between operator experience and training. At the mine site, the shovel operators had between 4 and 10 years of experience. These shovel operators have received professional training in the last two years. Professional training resulted in an increase in production without additional equipment. Only the effectiveness of the training was lower due to the habits the shovel operators developed during their years before professional training. Therefore, the experience that operators have is not all of the same quality. So, operator experience will depend on the years of operation, and the professional training received.

Lastly, unplanned maintenance had the most significant negative impact on shovel performance when viewed with the time usage model, which was concluded in section 4.4. During interviews with employees on-site, the negative effect of unplanned maintenance was significantly reduced due to the service contract with Caterpillar that was in place. An additional benefit of a service contract is the vendor-managed inventory on site. The vendor-managed inventory changes the way breakdowns are handled. When a breakdown is observed, a service team will go to the broken machine to inventory the necessary spares. The breakdown will be communicated to the inventory storage facility, where all spare parts will be ready for collection by the service team, which will solve the field failure. The vendor-managed inventory will mitigate the waiting time for delivery of critical parts that break down unexpectedly. Therefore, the time required to solve unplanned maintenance is significantly reduced with a service contract and vendor-managed inventory.

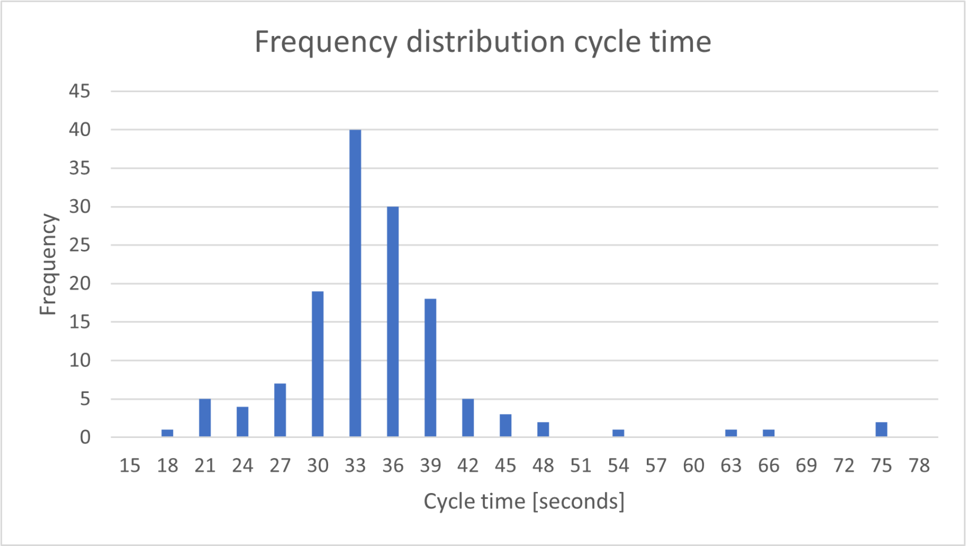
The purpose of the mine visit was to perform cycle time studies, which could be used to show the differences between theoretical and real-world production rates. Cycle time studies were done on shovels with a backhoe and face shovel configuration, three shovel operators, and three different working faces. All studies were carried out at different times during the day shift. During the mine visit, 2 hours and 10 minutes of cycle time studies were carried out. However, the duration of the cycle-time studies was not long enough to conclude any effects over a day, week, month, or year period. Furthermore, no conclusions can be drawn on the difference between shovel operators, as the duration of the studies was too short. Figure 36 shows the frequency distribution of all the truckloads, the number of passes and the cycle time. Every study's data are combined with a sufficiently large data set for this frequency distribution. In the graph of the truckload frequency distribution (see figure 36a), a normal distribution was added with a mean equal to that of the collected data. Figure 36a shows a clear difference between the data and the normal distribution, where the data are more spread out than the normal distribution. However, the total number of data points is only 35, which explains the more significant spread of the truckloads. Second, the number of passes graph (see figure 36b) shows that the operators did not achieve the desired pass match during the study period. This has two reasons; the first is the change in the truck bodies, which increases the number of passes with a half pass. Second, the skill of the shovel operator has improved in the last two years. However, the improvement is not linear for the different operators. In the last figure 36c, the frequency distribution of the cycle time is shown. Under ideal loading conditions, the cycle time for this type of shovel would be 24 s, achieved only a couple of times during data collection. According to Caterpillar (2019), a cycle time of 33 seconds would indicate difficult to severe digging conditions. However, the digging conditions during the data collection were fair, resulting in a cycle time of 28 seconds. Therefore, there is an underperformance concerning cycle times. Furthermore, the cycle-time frequency distribution in figure 36c is similar to a positively skewed frequency distribution, explained in section 3.7.8. The similarity between the predicted and measured frequency distribution shows that shovel production could be predicted. However, similarity has been proven with one variable of the theoretical production formula, which cannot be interpolated onto the other variables.



(a) Truckload distribution



(b) Number of passes distribution



(c) Cycle time distribution

Figure 36: Cycle time study frequency distributions

5 Synthesis

The different case studies discussed in the previous chapter have shown that a shovel has to deal with more than the primary focus of moving material. The literature review and case studies have led to the development of the flow chart in figure 37. All these factors will affect shovel productivity in different ways. Therefore, the factors will be divided into the following three classifications:

1. Factors that cannot be controlled, such as location, weather, and orebody, which are all dark grey boxes in figure 37
2. Factors that directly influence shovel productivity, such as production rates (mt/hour), use of availability, and mechanical availability, are all directly needed to produce these factors. These factors are shown in figure 37 in the boxes with orange colour. The other coloured boxes (purple, yellow, green, and light grey) represent the factors used to determine the orange boxes.
3. Factors that indirectly impact shovel productivity can lead to underperformance when these factors are not implemented correctly or changed due to managerial decisions. All these factors are stated in the white boxes in figure 37. In addition, the blue boxes represent the departments that make decisions that indirectly impact shovel performance.

5.1 Uncontrollable factors

The first classification of factors is the factors that are uncontrollable by the mining operation. These factors include the orebody, geographical location, and weather. The mining operation can only adjust to these uncontrollable factors that have the most negligible impact on shovel productivity (and the rest of the operation). The orebody is formed by natural processes, which could lead to a non-optimal design concerning the ideal shape of the pit. Furthermore, the type of rock in the orebody can vary. This variation depends on the orebody, on which the mine design will need to be adjusted. Lastly, the properties and characteristics of the rock are inconsistent throughout the orebody, impacting all types of factors, such as fragmentation, blast performance, density, processing, and mine planning. The consequences of uncertain changes in the orebody can only be mitigated until a certain level because eliminating uncertainty comes with too high costs.

The geographical location of the mining operation is selected by nature, which can be deep in the arctic circle, on the highest mountains, in the driest deserts, or next to a city. The location of the operation will dictate the constraining factors of the mine, which can be related to climate, infrastructure, or personnel. The constraining factors for the geographical location of the mine can only be mitigated up to a certain level.

The weather in the mining location is also related to the geographical location. However, the weather is much more variable than the geographical location once a mining operation has started. Furthermore, the impact of climate change will require adjusting mining operations. Climate change will lead to more extreme weather and more frequent weather delays. The more frequent weather delays will need to be included in the time usage model, impacting the shovels.

The orebody, geographical location, and weather are all factors the mining operation cannot control. The impact of these factors on shovel productivity can only be mitigated to a certain level.

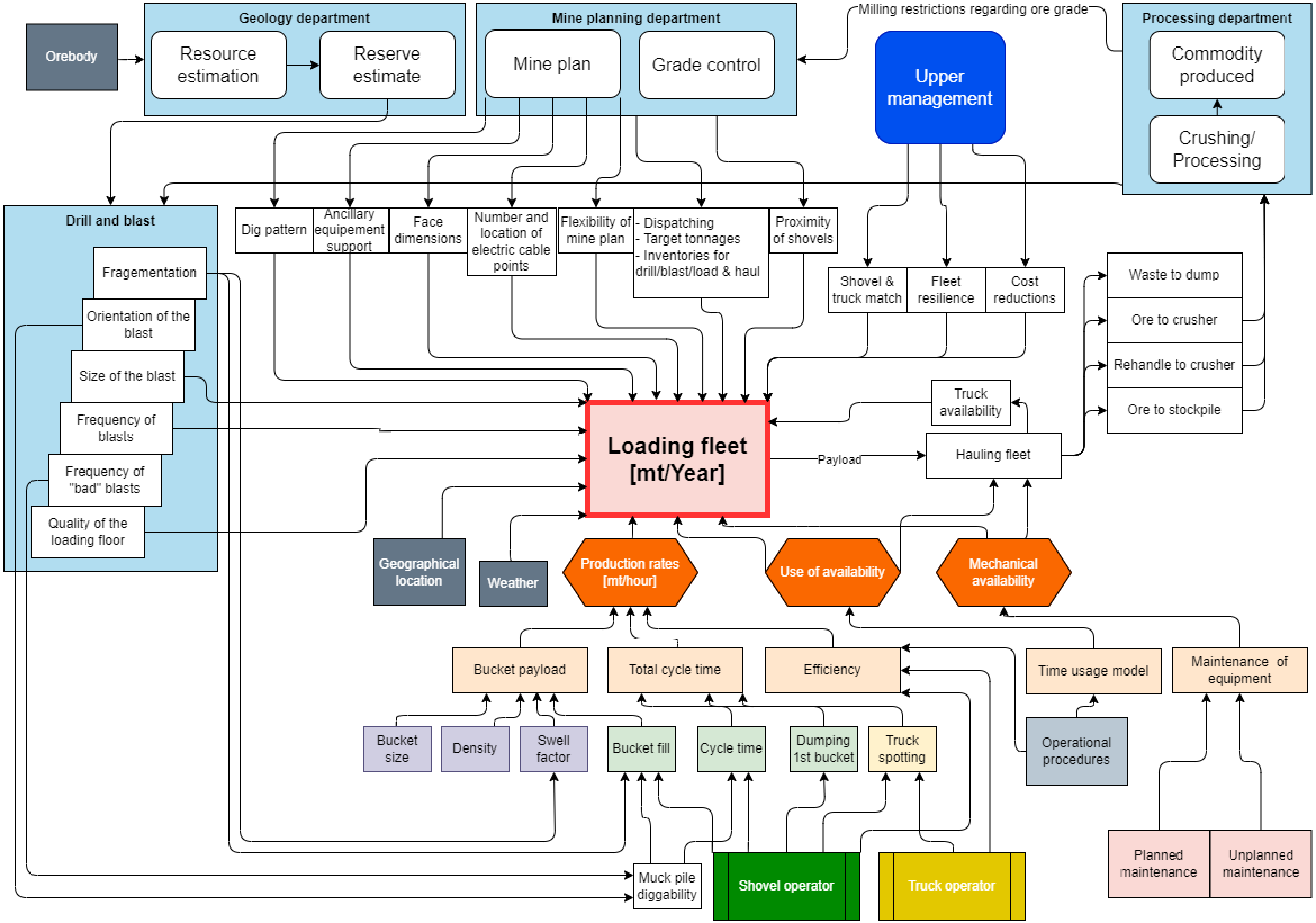


Figure 37: Flow chart of the factors of influence on shovel productivity

5.2 Factors that have a direct impact on shovel productivity

The calculation of annual production can be divided into three main parts: the hourly production rate, the use of availability, and the mechanical availability, which are based on different factors (see figure 38). The factors that directly influence the productivity of the shovel are also the factors that are used to calculate the annual production rate of the shovel. The introduction of these factors was done in section 3.6.

The hourly production rate has three main components, the bucket payload, the total cycle time, and the efficiency. The bucket payload depends on the specifications of the used shovel because every machine has certain limits that will eliminate excessive usage. The light purple boxes (bucket size, density, and swell factor) in figure 38 will determine how the maximum payload is achieved, depending on the type of material loaded with the shovel. For example, a 6040 shovel has a bucket payload of 40 mt with a standard bucket size of 22 m^3. The loaded material has a density of 2.7 mt/m^3 and a swell factor of 50%, which will load the bucket to the maximum allowed bucket payload. However, when the loaded material has a density of 3.0 mt/m^3 and a swell factor of 30%, the standard bucket size of 22 m^3 will lead to a bucket payload of 50 mt. Therefore, the size of the shovel bucket should be adjusted to the loaded material to avoid excessive usage. Density can vary throughout the orebody. As discussed in case study 1: the sensitivity analysis of the shovel production formula, a change in density will have a 1-to-1 impact on the shovel production rate. Therefore, when the changes in density are not considered in operation, the predicted production will become unachievable. The selected fragmentation and the rock properties within the orebody determine the swell factor. In section 3.7, the lack of research done on the swell factor was highlighted. Due to the lack of research on the swell factor, there will be potential for optimisation at many of mining operations. Even though the lack of research on the swell factor, the factor has approximately a 1-to-1 impact on the shovel production formula (see section 4.1). Furthermore, the bucket payload is also influenced by the degree to which the shovel operator fills the bucket. The bucket fill is shown in the light green box in figure 38. The bucket fill will indicate how well the maximum payload of the bucket is used. Section 4.1 shows that the bucket fill translates 1-to-1 into the shovel production rate. In conclusion, the bucket payload depends on the shovel's mechanical parameters, the material's properties, and the operator's skill.

The total cycle time is the next component influencing the hourly production rate. The total cycle is the time required to fill a truck, which depends on the cycle time for each pass, the dumping time of the first bucket, and the spotting time of the truck. The cycle time for each pass and the dumping time of the first bucket depends on the skill of the shovel operator. Case study 1 showed that the cycle time does not give a 1-to-1 change in the production rate. However, underperformance can be easily measured and improved with a benchmarking study followed by professional training for the shovel operator. Lastly, truck spotting time is the only factor in the entire flow chart that the truck operator influences. So, the total cycle time is greatly influenced by the operators that are in the machines.

The last factor that influences the hourly production rate is efficiency. The efficiency is influenced by the shovel operator, the truck operator, and the mining operations procedures. These factors are quantified using a detailed time usage model. However, these factors will be difficult to quantify due to the high variability within these factors.

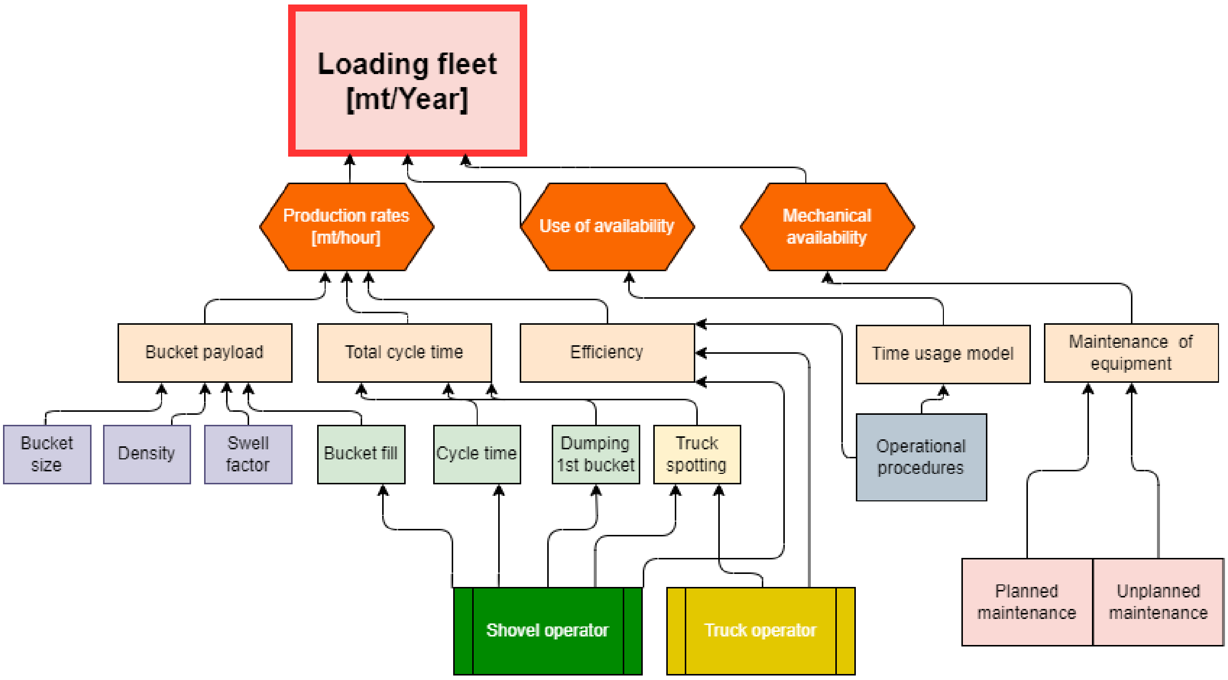


Figure 38: Flow chart of the factors that directly influence shovel productivity

The second factor that has a direct impact on annual production rates is the use of availability, which is a measure of how time is used throughout the year. The use of availability is extracted from the time usage model, explained in section 3.5. The operational procedures implemented in the mine will affect the time usage model. For example, when an additional coffee break is implemented during the day, it will affect the time usage model used throughout the year and the use of availability.

The last factor that directly impacts annual production rates is the mechanical availability of the shovel. The mechanical availability has two significant components, planned and unplanned maintenance. Both planned and unplanned maintenance will occur throughout the year with the shovel. However, the frequency of these events depends on the maintenance quality and the number of hours the shovel has operated. Furthermore, the equipment operating in the field is equipped with many sensors to predict the breakdowns of different parts. Therefore, the parts that break down in a short period will be ordered in advance for planned maintenance. However, there is a limit to what the sensors can detect, which results in unplanned maintenance. Due to the unpredictability of the unplanned maintenance, the repairs can take longer because of the lack of available mechanics, lack of knowledge, or lack of parts. The unpredictability of the unplanned maintenance will result in longer repair times for the shovel. So, depending on the frequency of maintenance, the mine can buy new equipment or rebuild the machine, which will reduce the maintenance needed.

5.3 Factors that have an indirect impact on shovel productivity

The indirect factors are all the factors that are not directly related to the shovel production formula. Some indirect factors related to the drill and blast department could also be defined as direct factors. However, since other departments also influence these parameters, the decision was made to classify these factors as indirect. This section will be built up with the indirect factors that could be described as direct to indirect factors influenced by company-wide policies.

The drill and blast operation affects factors that directly impact shovel productivity. The drill and blast operation department has many effects on shovel productivity since shovels can only move the material that has been blasted. The factors on which the drill and blast operation department has influence are shown in figure 39.

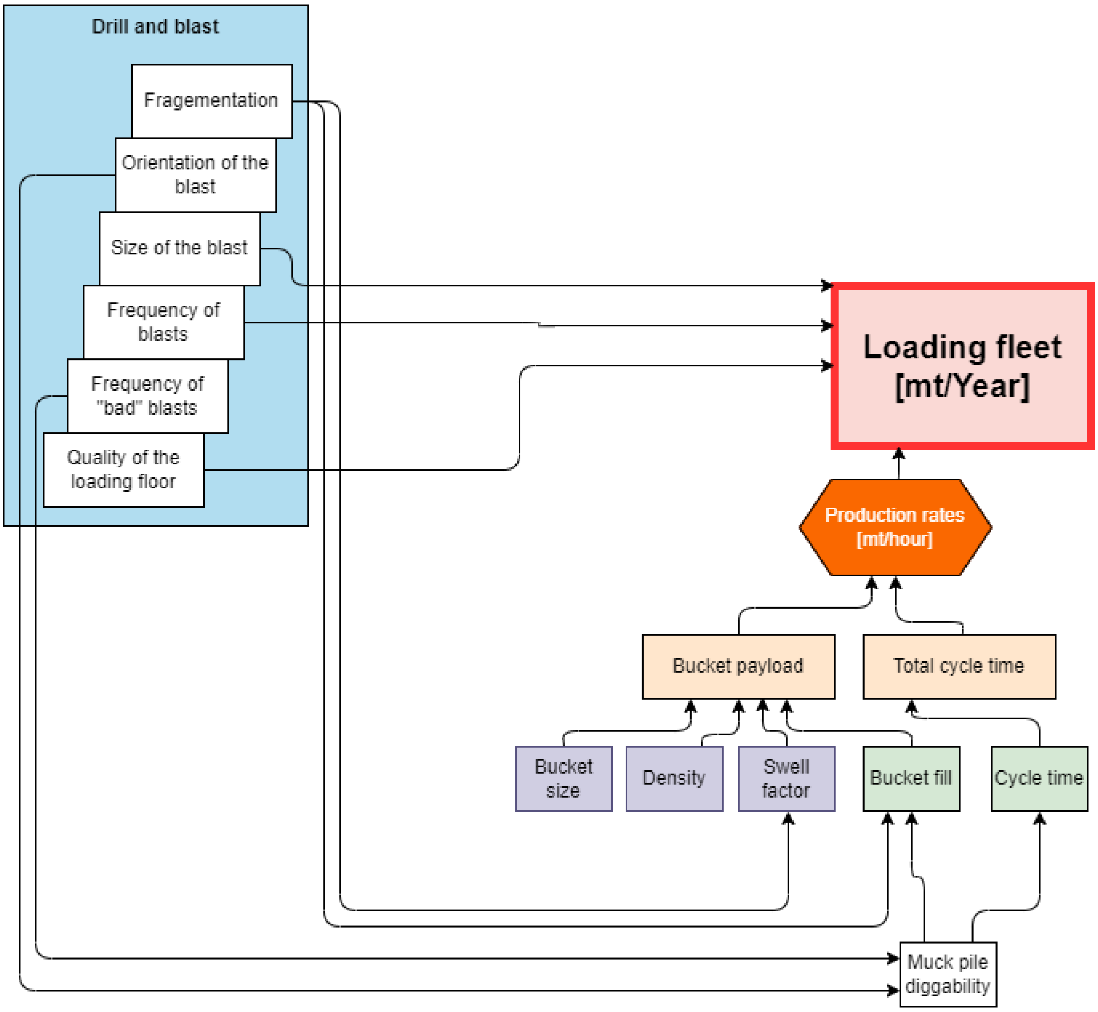


Figure 39: Flow chart of the factors changed by drill and blast that indirectly influence shovel productivity

Fragmentation is an essential factor that influences a direct factor of shovel productivity. Fragmentation influences the swell factor and the bucket fill. First, the swell factor of the blasted material depends on the fragmentation distribution selected by the mining operation. Furthermore, the swell factor can only be determined after the blast. The bucket fill also depends on the selected fragmentation distribution, explained in section 3.7. So, fragmentation could significantly impact factors that directly influence shovel productivity. The other factor that directly influences the direct factors is the diggability of the muckpile. The diggability of the muckpile influences the bucket fill and the cycle time of the shovel. The diggability of the muckpile depends on the orientation of the blast and the frequency of bad blasts. So, similar to fragmentation, the diggability of the muckpile could significantly impact factors that directly influence shovel productivity. Both of these factors could result in tougher digging conditions for the shovel, reducing the bucket fill and increasing the cycle time.

The last three factors are the blast's size, frequency, and quality of the loading floor. These three factors have an indirect effect on shovel productivity. The size of the blast is related to the number of tons that can be moved with the shovel, which will impact the amount of time spent on one face. The frequency of the blasts will impact the time usage of the shovel. Shovels must be moved out of the way to protect machines from blasts. Lastly, the quality of the floor will affect not only the shovel but also the trucks. A poor quality floor will result in an uneven load distribution, which could increase the need for maintenance. These three factors could influence shovel productivity in different ways, which could lead to underperformance.

The different departments within a mining operation often indirectly impact shovel productivity. This impact through various aspects, some of which are shown in figure 40. All these departments are essential for a well-running mining operation. However, the focus of these different departments is not always on shovel productivity. Therefore, the different factors will be explained and what effect they will have on shovel productivity.

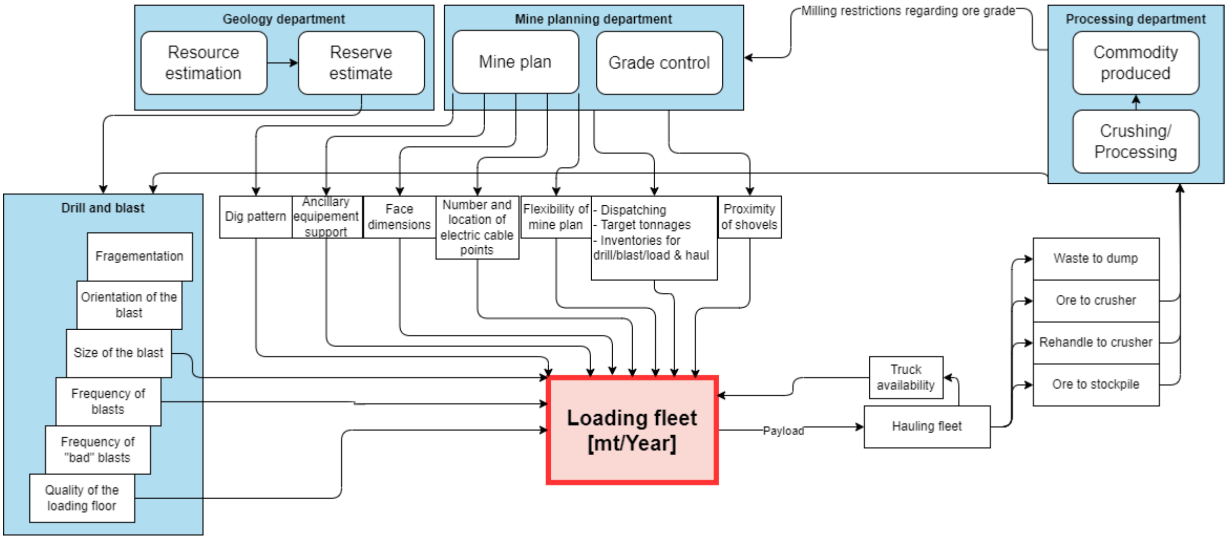


Figure 40: Flow chart of the factors changed by the departments that indirectly influence shovel productivity

The processing plant is designed with a set of specifications for optimal use. These optimal specifications will need to be managed by the mine planning department, which will ensure that the correct ore grades are sent to the mill. The processing (and crushing) department has indirect impacts on shovel production. The crushing department has limitations regarding the maximum material size, which is connected to the fragmentation of the material. The processing department has particle behaviour limitations, which depend on the rock type and properties. Depending on the milling restrictions, the mine plan could be changed, resulting in additional shovel movement. Furthermore, the processing department will considerably influence the design of the fragmentation achieved by the drill and blast department. The processing plant will again have certain specifications that must be respected. Therefore, the ideal fragmentation for the shovels and the processing plant could not align, leading to a non-optimal use of the shovels.

The geology department provides all the information regarding the ore body of the mine. The mine planning department uses the information about the ore body to make the mine plan, and the drill and blast crew use the information to design the most efficient blasts. The information about the ore body collected by the geology department is used throughout the mining operation, which is used as input for different factors related to shovel productivity. Furthermore, a mining operation can focus on high-quality material because of the high profitability. The issue that results from focusing on high-quality material will be that the lower-quality material is wasted (no blending possibilities). Furthermore, the stripping of waste material can be neglected because of the focus on high-quality material, which can lead to additional costs for hiring contractors or lower production later. Lastly, ore and waste can be treated differently by a mining company. The difference between ore and waste are regarding fragmentation and hauling. Fragmentation for ore is more critical because of the benefaction that follows, which is not the case for waste material. The hauling distances for waste will be significantly longer because the waste needs to be dumped on the edge of the ultimate pit limit.

Furthermore, the loading and hauling fleets are part of the production department, which is focused on moving the blasted material to the processing plant. The production department should use shovels and trucks most efficiently to move the most material at the lowest cost. The availability of trucks indirectly impacts the productivity of shovels because when too many trucks are out of service, the shovel will be waiting for empty trucks.

Lastly, the mine planning department has different factors that impact shovel productivity, which could lead to underperformance. These factors will be listed below, and an explanation will be given on how these factors influence shovel productivity.

- Dig pattern: influence shovel productivity through the selectivity of the dig pattern. The dig pattern depends on the blast and the material that is present in the working face.

- Ancillary equipment support: with ancillary equipment support, the shovel can focus more on moving material than cleaning the working area or moving material onto the muckpile. The ancillary equipment can be bulldozers, water trucks, or smaller wheel loaders. The selection of these machines depends on the mining operation.
- Face dimension: The size of the working face where the shovel is located will impact the shovel's productivity. Production rates can be negatively influenced when the shovel works in a small area. Furthermore, trucks will have less space to manoeuvre, resulting in longer truck spotting times.
- Number and location of electric cable points: This factor will only impact electric-powered shovels (electric rope shovels and hydraulic shovels). The electric cables will need to be moved to the working face for these machines. The speed of the relocation of the electrical cables will affect the standby time of the shovel. Therefore, the number and location of the electrical cable points will affect the standby time of a shovel.
- The flexibility of the mine plan: The mining industry's uncertainty could lead to mine plan changes. These changes in the mine plan could lead to additional shovel movement, which reduces the production rate. The extra shovel movement could be reduced by having a mine plan with enough flexibility.
- Dispatching, target tonnages, and face inventories: All three factors are decided by the mine planning department. When not enough trucks are dispatched to the correct shovel, then under-performance of the shovel will occur. The dispatcher can also allocate the incorrect number of trucks for each shovel, which depends on the material (ore or waste). The haul distance for waste is generally longer for mining operations because the waste dumps on the edges of the ultimate pit limit. The difference in haul distance for ore and waste is a factor that the dispatcher should consider when allocating trucks. The targets are never achieved when the target tonnages are set at unrealistic values. The high targets could lead to motivation problems with the operators. Lastly, the face inventories should be managed so that a shovel always has a new face to work on after finishing the previous one. However, this new face should not preferably be on the other side of the mine.
- The proximity of the shovels: Two shovels that work closely together on the same working face will significantly reduce the productivity of one of the two shovels. The reason for this is the queue of trucks, which will have to be prioritised for one shovel. Therefore, the mine plan must ensure that the shovels do not work too closely together.

The upper management of the mining operation or the company can make many decisions that influence shovel productivity differently. Figure 41 shows three factors are shown in which upper management influences shovel productivity, limited to the factors mentioned during the interviews in section 4.4. However, the upper management influences many decisions made at the mine. The match of shovels and trucks and the resilience of the fleet are related to the significant capital expenditures made by the upper management. The match between shovel and truck depends on the combination of equipment purchased. Furthermore, the resilience of the fleet is related to the size of the fleet. The mine can decide to buy just enough equipment to achieve the annual production target, but this could result in not reaching the target when there are setbacks during the year. On the other hand, a larger fleet with overcapacity will result in a larger investment, more maintenance, and costs. The last factor is related to the cost reductions that are implemented by the upper management. These cost reductions can have a positive impact on the profitability of the mining operation. However, they often will result in other issues in the mine. Therefore, the upper management significantly influences the decisions made in the mining operation, which can positively or negatively influence the productivity of the shovel.

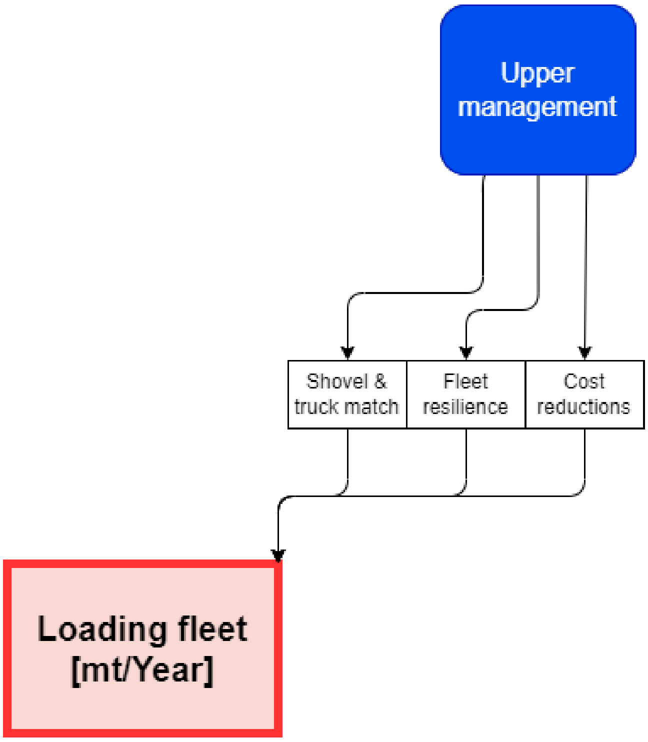


Figure 41: Flow chart of the factors changed by management decisions that indirectly influence shovel productivity

Many factors influence shovel productivity, some of which are explained in this chapter. However, quantifying the effect of these factors with a number will be difficult. Direct factors could be quantified with enough data from long periods of operation. Indirect factors are often not persistent over extended periods and more challenging to quantify. For these direct factors, KPIs could be defined as giving consistent information over extended periods. The risk of uncontrollable factors in the mining operation can be mitigated to a certain extent. However, there will always be some residual risk. Therefore, mining companies must always be adaptable and flexible.

6 Discussion

6.1 Data validation and accuracy

The accuracy of the data was questioned during the different case studies that were done during the study. Most of the data was retrieved from external sources because of the limited available time. Therefore, this study would have benefited substantially from collecting all the data. The impact of external data is shown in case studies 2 & 3.

Case study 2 uses a benchmarking report of Encare, a company that specialises in benchmark reporting. However, the report of Encare only shows the results of the finding. The methods used to develop the results were not included in the report. The unknown methods resulted in a superficial analysis of the benchmark report. Suppose the methods or the raw data of the benchmark report were available. In that case, data could be used to compare different models of different OEMs. The comparison of different models of different OEMs could show potential design differences. The design difference could motivate OEMs to change the design of the shovel.

Case study 3 uses external data of S&P Capital IQ and various sources within Caterpillar. The S&P Capital IQ data is not verified by external sources or the different mining operations included in this study. S&P Capital IQ often uses one verified data source, which is used to interpolate the rest of the data. Furthermore, the data of Caterpillar is a snapshot of a specific moment in time, which is not representative of the 16 years used in case study 3. If the time was available to collect the data, there were more possibilities for detailed analysis. The detailed analysis could have resulted in different or better results.

6.2 Assumptions throughout the study

The study is based on several assumptions: the independence of the factors in the shovel formula and the input values for the shovel formula. These assumptions were essential to compare the theoretical with real-world production rates. These assumptions will also be made by the OEMs when a customer requires a new mining shovel. The correct estimation of the production rate by the OEM will be essential for the satisfaction of the customer.

In case study 1, the shovel formula's independence was assumed by the factors. This independence means that all factors are constant except the changed factor. However, in reality, this independence cannot be confirmed. This shows in two different parts of the formula: the bucket payload and the truck payload. The bucket payload will need to be optimised for the maximum bucket payload. The bucket payload depends on bucket size, density, swell factor, and bucket fill. A decrease in one of these factors must be compensated with a change in the other factors. For example, when the density of the material increase, the additional weight can be compensated by increasing the swell factor (hard to achieve), decreasing bucket fill (requires operator training), or decreasing the bucket size (easiest option). Therefore, the independence of the factors related to bucket payload cannot be confirmed. The truck payload is currently not included in the formula since the focus is on shovels. However, the trucks need to be loaded to the nominal payload for efficient operation. If the truck payload needs to be kept constant, then the bucket payload and the number of passes will be kept to an equilibrium. In case study 1, the number of passes is changed from 4 to 3; then the bucket payload should increase from 37.5 mt to 50 mt, an increase of 25% on bucket payload. The increase in bucket payload can be over the maximum payload of the shovel. So, the bucket and truck payload shows that the independence of the shovel formula cannot be confirmed.

Furthermore, the study makes assumptions regarding values in the shovel formula. The assumptions in this study were based on the best-in-class performance of shovels. However, in case study 3, it was shown that the best-in-class performance of shovels would be hard to achieve. Therefore, in section 7, the classification was made to quantify the performance of different mining operations. The classification in section 7 will need to be continuously developed when it is used in the project because of the potential difference between a desk study and a mining operation.

7 Fleet size diagnostic guide

The main question of this chapter is to find an approach that will solve the reduced performance of a shovel. Therefore, a short explanation of what is needed to have a highly productive shovel and the classification of a highly productive shovel will be given. Next, all different factors will be categorised that were explained in chapter 5. Lastly, the factors will be quantified when this is possible.

There are three main pillars for the high annual production of a shovel. These three main pillars are high hourly production, high use of availability, and high mechanical availability, which are the direct factors of section 5.2. Values considered high should be defined for the three pillars, shown in table 4. Defining a production rate number for all shovels will not be possible due to the different specifications of the shovels. Therefore, a percentile change from the production rate of the sales catalogue will be used to classify the performance of the shovel. For the classification of both the use of availability and mechanical availability, the time usage model of GMG (2020) will be used to define the standard. These three pillars should be looked at separately to be able to implement the correct improvement strategies. The pillars could have other direct and indirect factors that influence them. These direct and indirect factors will be classified concerning the effectiveness of improving the factor.

Table 4: Classification of the fleet size diagnostic guide

Classification	Production rate	Use of availability	Mechanical availability
Excellent	>90% of the sales catalogue production rate of the shovel	>90%	>95%
Good	75-90% of the sales catalogue production rate of the shovel	80-90%	85-95%
Average	60-75% of the sales catalogue production rate of the shovel	70-80%	75-85%
Fair	45-60% of sales catalogue production rate of the shovel	60-70%	65-75%
Poor	<45% of the sales catalogue production rate of the shovel	<60%	<65%

The production rate pillar has three components that influence it. These three components are the bucket payload, the total cycle time, and the efficiency. When underperformance in the production rate pillar is determined, the improvement strategies can be divided into three factors, ranked below. The goal and result of each factor can be different, which will be explained in the different steps.

For the production rate optimisation, the following steps should be followed:

1. Bucket payload
    (a) The density should be verified with the geological department, and as mentioned in section 3.7, the density should be measured with at least two different methods
    (b) The swell factor should be verified with the fragmentation of the
    (c) Bucket size should be changed when significant changes in density and the swell factor have been determined
    (d) For bucket fill, three factors can be considered for optimisation: shovel operators, fragmentation, and muckpile diggability.

    - A bucket fill frequency distribution should be made for all shovel operators. This frequency distribution will show the general performance of all operators and each operator's performance. When there is a general underperformance, the indirect factors of fragmentation and muckpile diggability should be optimised. Professional training should be provided when underperformance at the individual shovel operator level.

2. Total cycle time
    (a) To start a cycle-time study over a long time should be done. The cycle-time study will show where the underperformance is. After different improvement strategies can be implemented
    (b) Truck spotting can be improved by giving additional training to the truck operators. The shovel operator can be trained to focus on assisting the truck operator (clean reverse area and in time signalling) The following indirect factors could also be considered if this does not improve performance.
        - Face dimensions
        - Dig pattern
        - Ancillary equipment support
        - Quality of the loading floor
        - Dispatching
        - The proximity of the shovels
        - Truck availability
        - Expanding the truck fleet
        - Automation of the truck fleet should only be considered with excess shovel capacity.
    (c) Cycle time can be improved by adding additional training for shovel operators or by improving the diggability of the muckpile. The following indirect factors could also be considered if this does not improve performance.
        - Shovel and truck match
        - Orientation of the blast
        - Frequency of "bad" blasts
3. Efficiency
    (a) The efficiency is based on the shovel operator, the truck operator, and the operational procedures. The efficiency will need to be monitored throughout a shift because it will not be representative over shorter periods. Furthermore, the efficiency will be extracted from the time usage model in a yearly time frame. Furthermore, some indirect factors will be mentioned that affect efficiency.
        - Size of the blast
        - Frequency of the blasts
        - Cost reduction
        - Number and location of electrical cable points

The time usage model should be used to find factors to improve the use of availability and mechanical availability. The time usage model of the customer will need to be compared to the Caterpillar standard. The differences between the time usage model of Caterpillar and the customer will need to be optimised. The time usage model in section 3.5 gives an idea of what factors could be improved. Since the time usage model for each mining operation will be unique, there is no benefit in highlighting specific basic time elements. Therefore, the use of availability will result in a custom approach for every mining operation. Mechanical availability can be divided into planned and unplanned maintenance. Maintenance is vital to keep the equipment in excellent condition. However, the impact of unplanned maintenance is much more significant than planned maintenance. According to the Caterpillar standardised time usage model, unplanned maintenance should not be more than 20% of the planned maintenance per year. The following steps can be implemented to increase the mechanical performance of shovels:

- Change operational procedures to reduce maintenance
- Improve the floor conditions
- Reduce the use of the undercarriage
- Vendor-Managed Inventory at the mining operation.
- The service contract between Caterpillar and the mining operation should be made.
- Replace or rebuild the existing mining fleet

As mentioned before, all mining operations are unique. Therefore, the underperformance of a shovel will also be unique in every mining operation. For this reason, it will not be possible to solve all problems with one solution. The three pillars will give directions in which improvements have the most significant impact.

8 Conclusion

What are the factors that contribute to deviations from the predicted performance?

- The interviews showed that a great variety of factors influence shovel productivity. Furthermore, the list of factors influencing shovel productivity could be expanded when additional interviews were conducted.
- The factors can be divided into direct, indirect, and uncontrollable.
- The direct factors are bucket size, density, swell factor, bucket fill, cycle time, dumping of the first bucket, truck spotting, use of availability, and mechanical availability.
- The indirect factors are fragmentation, the orientation of the blast, size of the blast, frequency of "bad" blasts, quality of the loading floor, dig pattern, ancillary equipment support, face dimensions, number and location of electric cable pints, the flexibility of mine plan, dispatching, target tonnage, inventories of drill/blast/load/haul, the proximity of shovels, truck availability, shovel and truck match, fleet resilience and cost reductions.
- The uncontrollable factors are weather, geographical location, and orebody.

What factors are the most significant?

- The quantification of every factor was not achievable within this study. Significantly, the effect of indirect factors is hard to define.
- Solving underperformance in the direct factors will solve the majority of the problems.
- The matching of the theoretical production can be achieved with constant monitoring of all factors. These measurements will need to be done over long periods to see the greater picture.

What is the effect of automated trucks on shovel productivity?

- Both the literature and the interview showed that automated trucks would create additional trucking capacity, which will need to be absorbed by the shovels. When automated trucks create additional trucking capacity that the shovel fleet can absorb, then more material can be moved without buying additional machines (excluding the capital costs of implementation of the automated system)
- These additional trucking hours could lead to increased production if the shovels often waited on trucks.
- The production can also be kept constant when the maximum shovel production is already reached. Therefore, the optimisation of the shovel fleet might be needed to extract the value of the additional trucking capacity.

Can a data-driven model be developed to predict the actual productivity of the shovel in the real world?

- A data-driven model can be developed to predict the actual shovel production rate in the real world. However, the amount of data that will be needed is not accessible by Caterpillar. The data needed will range from the block model, the mine plan, all information on the equipment, and the processing plant. This data will need to be shared by the mining operations, which is unlikely to happen.
- The mining operation's in-house engineering department can predict the production rates using reconciliation, which is unavailable to Caterpillar.
- A data-driven model is not a realistic goal that Caterpillar should be pursuing. Caterpillar should be pursuing the quantification of the different factors. For this, some recommendations will be made.

9 Recommendations

The limited time available for this study led to subjects that could benefit from more research. This section will highlight three areas where additional research will benefit the effectiveness of the fleet size diagnostic guide. The fleet size diagnostic guide will be more effective with better input data. This can be through quantifying the frequency distributions of the factors of the shovel production formula and the effect of fragmentation on the production rates with different bucket sizes. Lastly, quantifying the indirect factors will improve the fleet size diagnostic guide for complicated improvements.

9.1 Frequency distribution of all factors in the shovel production formula

The sensitivity analysis of the shovel production formula in section 4.1 showed that some factors significantly influence others. Furthermore, the impact of skewed frequency distributions on averages is shown in section 3.6. However, this study's limited time prevented these two parts from being combined. Firstly, the expected frequency distributions from section 3.6 should be referenced with real-world data to verify the skewness of the distribution. The effect of the frequency distribution for every factor in the shovel formula can be shown in two ways. The sensitivity analysis should be adjusted to include the mode, median, and mean. The mode, median, and mean will give three the same values when there is a normal frequency distribution. For a skewed frequency distribution, the mode, median, and mean will be different (see section 3.6). This method will limit the variation of the shovel formula. However, it will show the effect of skewness on the shovel production formula. The other method relays on the standard deviation of the frequency distribution of all factors in the shovel formula. The standard deviations of the different factors can be used in the sensitivity analysis. The standard deviations will improve the range of the production rate. Furthermore, the factors with a high standard deviation will also be better represented in the sensitivity analysis. The best example of this is the truck exchange time. The truck exchange time to estimate the production rate is 33 seconds, which could be realistic on paper. However, mining operations can easily double or triple truck exchange time (66 or 99 seconds). Therefore, a sensitivity analysis that uses standard deviation will give more representative production rates. Caterpillar can use the sensitivity analysis based on the standard deviations to estimate realistic production rates for different mining operations.

9.2 Effect of fragmentation on the bucket fill with different bucket sizes

In different parts of this study, the effect of fragmentation on the bucket fill factor was shown. The relation between fragmentation and bucket fill was shown in the research of Beyglou et al. (2017) and Dotto and Pourrahimian (2018). Caterpillar could gain a competitive advantage when the research of Beyglou et al. (2017) and Dotto and Pourrahimian (2018) is done with the Caterpillar hydraulic and electric rope shovels. The competitive advantage will not only be related to the improvement of the shovel production rate but also the initial selection of the best equipment (size and number of machines) with the achieved fragmentation in the mining operation. The fragmentation effect on the bucket fill should be done in the most controlled environment possible. Therefore, the experiments should be done with an experienced operator, which is able to perform all the experiments. Furthermore, the experiments should be conducted over a shift (12 hours). During the experiments, every bucket will need to be monitored with similar bucket fill estimation tools as used in the research of Beyglou et al. (2017) and Dotto and Pourrahimian (2018). The fragmentation distribution should be selected after market research on common fragmentation for different mining operations. This market research will reduce the project's scope to evaluate commonly used fragmentation size distribution and increase the potential value of the research.

9.3 The correlation between fragmentation and swell factor

The literature review showed that the swell factor is one of the least researched factors of the shovel production formula. The lack of knowledge makes the mining companies assume that the swell factor is 30%. Furthermore, the interview with the blasting subject matter expert (see section 4.4.1) mentioned the correlation between swell factor and fragmentation. The swell factor can only be determined after a blast. Therefore, the correlation between fragmentation and swell factor could make fragmentation an indicator for the swell factor. This research could be done simultaneously with the research on the effect of fragmentation on the bucket fill.

These three studies will significantly improve the potential that the theoretical production rates will match real-world production rates. Every mining operation's uniqueness will also have a significant impact. However, these three studies will not solve all the problems because too many factors influence shovel productivity.

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I Appendix

I.1 Three shovel types

Figure A1: Backhoe hydraulic shovel

Figure A2: Front shovel

Figure A3: Electric rope shovel

I.2 Variance of variables

Table A1: The data used to determine the variance of variables that are incorrectly estimated.

		-20%	-10%	Base	10%	20%
Bucket size	m^3			16.5		
Swell factor	%	1.04	1.17	1.3	1.43	1.56
Density	t/m^3	1.44	1.62	1.8	1.98	2.16
Bucket fill	%	0.72	0.81	0.9	0.99	1.08
Efficiency	%	0.6	0.675	0.75	0.825	0.9
Cycle Time	seconds	19.2	21.6	24	26.4	28.8
Truck exchange	seconds	26.4	29.7	33	36.3	39.6
Dump first bucket	seconds	2.4	2.7	3	3.3	3.6
# cycles	#	4	4.5	5	5.5	6

Table A2: The hourly production with the changing variables in table A1

	-20%	-10%	Base	10%	20%
Swell factor	1752	1912	2103	2337	2629
Density	1682	1893	2103	2313	2523
Bucket fill	1682	1893	2103	2313	2523
Efficiency	1682	1893	2103	2313	2523
Cycle Time	1836	1960	2103	2268	2461
Truck exchange	2003	2052	2103	2157	2214
Dump first bucket	2112	2108	2103	2098	2093
# cycles	2056	2082	2103	2120	2135
All	759	1278	2103	3421	5552

Table A3: The percentage changes with respect to the base production of the shovel.

	-20%	-10%	Base	10%	20%
Swell factor	-17%	-9%	0%	11%	25%
Density	-20%	-10%	0%	10%	20%
Bucket fill	-20%	-10%	0%	10%	20%
Efficiency	-20%	-10%	0%	10%	20%
Cycle Time	-13%	-7%	0%	8%	17%
Truck exchange	-5%	-2%	0%	3%	5%
Dump first bucket	0%	0%	0%	0%	0%
# cycles	-2%	-1%	0%	1%	2%
All	-64%	-39%	0%	63%	164%

I.3 Encare benchmark report data

Table A4: Encare benchmark report for 73yd shovels

Indicator	Model	Number of equipment	Average age	Availability	Nominal operating utilization	Available operational use	Operational preformance	Preformance	MTBF	MTTR	Yearly production
X35	4100XPC	2	12948	NAN	NAN	NAN	NAN	77.19	33.5	1.83	NAN
X35	CAT 7495	2	12865	NAN	NAN	NAN	NAN	73	32.93	1.85	NAN
X37	4100XPC	3	NAN	NAN	NAN	NAN	NAN	52.53	NAN	NAN	NAN
X18	4100XPC	3	NAN	92.99	72.87	78.36	4463	78.05	NAN	NAN	28
X1	4100XPC	1	533	91.91	82.66	89.94	5118	77.95	11.3	0.77	36
X18	495HR	7	NAN	90.96	NAN	NAN	NAN	35.75	NAN	NAN	NAN
X16	4100XPC	1	15627	90.82	90.15	99.26	4642	92.01	15.05	1	36
X15	495HR	4	31251	89.99	69.28	76.99	3457	52.82	124.11	1.48	21
X18	4100XPC	3	NAN	89.44	NAN	NAN	NAN	59.2	NAN	NAN	NAN
X15	495HR	4	28480	89.22	70.05	78.51	3675	50.87	99.56	2.72	22
X38	4100XPC	2	12692	89.11	83.76	93.99	2761	55.5	33.55	1.78	20
X19	4100XPB	7	19672	88.8	78.36	88.25	4710	88.5	24.32	1.62	32
X19	4100XPC	7	22887	88.11	77.67	88.14	4581	84.63	24.12	1.79	31
X1	495HR	4	49682	87.94	78.82	89.63	3882	73.24	14.68	0.97	26
X18	495HR	8	NAN	87.51	64.58	73.8	3785	58.67	NAN	NAN	21
X18	4100XPB	5	NAN	87.35	70.95	81.22	4477	76.24	NAN	NAN	27
X40	495HR2	1	12036	86.48	73.83	85.37	5788	101.59	50.18	7.88	37
X18	4100XPB	5	NAN	86.39	NAN	NAN	NAN	NAN	NAN	NAN	NAN
X14	4100XPC	4	NAN	85.45	66.27	77.55	4594	73.06	37.66	1.8	26
X8	4100XPB	4	59602	85.19	75.54	88.68	3033	55.34	49.69	2.56	20
X4	4100XPC	1	18728	85.14	79.05	92.85	4769	66.69	48.04	1.19	32
X36	4100XPC	4	40570	84.98	69.46	81.74	3028	49.59	45.36	2.61	18
X38	4100XPC	2	16256	84.81	71.19	83.94	2929	49.92	24.52	1.7	18
X40	4100XPC	5	25952	84.44	65.96	78.12	4157	65.19	37.46	6.95	24
X14	4100XPC	4	25611	83.98	69.5	82.75	5332	88.93	26.04	2.97	32
X4	4100XPB	3	88191	82.42	68.58	83.21	4970	66.6	36.73	1.42	29
X17	TZWK55	1	NAN	79.68	71.26	89.44	2790	47.73	s/i	s/i	17
X4	4100XPB	3	84693	79.38	65.92	83.05	4942	58.9	29.42	1.19	28
X14	495HR	4	NAN	78.5	65.1	82.93	4214	65.85	36.52	2.83	24
X8	4100XPB	4	56799	78.48	68.51	87.29	3414	56.14	37.72	3.52	20
X36	4100XPC	4	41876	77.5	58.82	75.9	4773	51.8	55.43	3.53	24
X4	4100XPC	1	27271	75.33	69.56	92.34	4689	66.34	49.04	1.29	28
X17	TZWK55	1	NAN	75.32	63.23	83.95	3488	41.99	s/i	s/i	19
X37	4100XPC	3	NAN	73.14	NAN	NAN	NAN	NAN	NAN	NAN	NAN
X16	495HR	2	41463	72.82	72.05	98.95	3596	57.64	22.18	1.82	22
X14	495HR	4	46301	70.57	57.19	81.04	4469	61.35	20.16	4.5	22

Table A5: Encare benchmark report for 56yd shovels

Indicator	Model	Number of equipment	Average age	Availability	Nominal operating utilization	Available operational use	Operational preformance	Preformance	MTBF	MTTR	yearly production
X18	495B	1	NAN	89.32	NAN	NAN	NAN	11.47	NAN	NAN	NAN
X16	495BII	1	83287	85.22	84.87	99.59	3770	70.62	12.94	1.63	28
X4	4100	1	109115	81.73	60.27	73.74	4174	46.42	39.93	5.08	22
X1	495BI	1	91018	86.63	77.78	89.78	3140	58.58	11.39	1.07	21
X4	4100	1	111043	82.18	60.86	74.06	3596	41.98	31.78	2.05	19
X17	495BI	1	NAN	86.29	77.58	89.9	2643	49.21	NAN	NAN	18
X36	4100XPA	1	110602	74.67	59.92	80.24	2871	40.58	58.66	5.74	15
X1	4100A+	1	111972	87.89	79.14	90.05	2060	39.08	17.77	0.9	14
X17	495BI	1	NAN	61.7	51.98	84.24	2917	36.39	NAN	NAN	13
X15	495BI	1	88623	92.39	38.46	41.63	3000	19.99	69.4	0.79	10
X15	495BI	1	89714	93.49	30.49	32.61	2839	18.97	50.63	5.61	7
X36	PC8000	1	24540	78.02	39.81	51.02	1554	14.69	25.28	6.83	5
X18	495B	1	NAN	86.77	25.82	29.76	1718	10.65	NAN	NAN	4
X1	4100	2	116149	89.19	80.16	89.88	3275	63	14.43	1	23
X16	4100XPA	2	130801	84.36	61.83	73.29	3623	49.96	10.29	2.22	19
X15	495BII	2	68163	89.89	64.83	72.12	3056	42.1	61.31	2.53	17
X15	495BII	2	66289	77.63	57.61	74.21	3187	35.57	52.18	3.96	16
X14	495BII	2	114299	78.36	54.88	70.04	2531	33.33	22.28	3.17	12
X14	495BII	2	NAN	75.92	53.99	71.11	2475	32.07	21.24	4.43	12

Table A6: Theoretical production assumptions used for the comparison with the Encare benchmark report

Theoretical production assumptions		
Density	2.55	t/m^3
Swell Factor	1.3	-
Bucket fill	0.9	-
# of buckets	4	-
Cycle time	35	seconds
Truck spotting	33	seconds
First bucket dump	6	seconds
Efficiency	0.83	-
Availability	0.83	-
Use of availability	0.88	-
Scheduled hours	8616	-