Evaluation of Hydraulic Excavator and Rope Shovel Major Maintenance Costs in Operation

by

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ABSTRACT

In this thesis, results of a comparison study of rope shovels and hydraulic excavators undertaken by the author between September 2014 and May 2015 is presented. The study was implemented by a literature search, collecting data from KMG (Komatsu Mining Germany) which is the Komatsu Limited manufacturing facility for super large hydraulic mining shovels (16 to 42m^3 Bucket Capacity) in Europe, and receiving and analyzing information from a coal mining company about performance parameters of rope and hydraulic shovels with bucket capacities ranging from 10 up to 33m^3.

The objective of the study is to compare the effectiveness of two types of excavators in surface mining during their life cycle from 0 up to 60,000 operational hours. Each machine performance was surveyed on a month by month basis and involved assessing such parameters as: operational hours, scheduled inspections and maintenance, unscheduled repairs, number of failures, production. Consequently it allowed calculating general indicators to have to be priced in the study and their change with increase of total operational life. These indicators were: physical availability and hourly output of an excavator (normalized to 1m^3 of bucket capacity). Moreover, expenditures related to possession of mining shovels (spare parts, fuels, lubricants, electricity, consumables) were also taken into consideration to calculate and compare life cycle costs of machines.

The results obtained from the investigation show that use of hydraulic excavators in open cast mining allows to get considerably higher production

rates in comparison to rope shovels of the similar age. Electric cable shovels, however, compensate their high initial purchase cost by comparatively low service expenditures and, wherefore, $1m^3$ of excavation with use of rope shovels become cheaper by about 5 years (30,000 hours) of operation.

For confidentiality, no mining site names can be found in this thesis. However, description of geological, engineering and climatic conditions of the sites is presented in the thesis.

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LIST OF ABBREVIATIONS

KMG	Komatsu Mining Germany
FS	Front Shovel
BH	Backhoe
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
HEX	Hydraulic Excavator
RS	Rope Shovel
HMR	Hour Meter Readings
S.M.A.R.T.	Surface Mining Association for Research and Technology
OMZ	United Engineering Factories (Obedinyonnye Mashinostroitelnye Zavody)
LL	Liquid Limit
PL	Plastic Limit
PI	Plastisity Index
DC	Direct Current
PA	Physical Availability
r	Correlation Coefficient
Stdev	Standard Deviation
CAD	Canadian Dollar

CHAPTER 1

INTRODUCTION

1.1 Statement of the Problem

One of the most typical machines used in surface mining for excavating and loading material is a single-bucket mining shovel. In turn, there are two essential types of this heavy equipment, which are rope shovels and hydraulic excavators. Both can be found at virtually all modern large-scale surface mining sites.

To provide optimal production rates on site and consequently to ensure a company`s profitability, it is important to employ the most suitable pieces of mining equipment including mining shovels. High cost of machines (to purchase, maintain and service them) makes a large impact on the capital and operational investment of a company, so the selection of excavating equipment is a vital aspect of every mine design.

Both rope shovels and hydraulic excavators have advantages with respect to one another and depending on the conditions (geotechnical, engineering, climatic, etc.). In this study analysis of performance of both types of excavator was made as well as determining expenditures associated with their possession and utilization.

1.2 Objectives of the Thesis

This study has three main objectives. The first one was to collect as much data as possible about performance of rope shovels and hydraulic excavators - uptime hours and downtime causes, productivity rates and excavation costs.

The second objective was to assess the application conditions in each operational case and try to find a correlation between such conditions and machine performance.

The third purpose has two stages, as follows: 1) to summarize all the obtained information in order to analyze performance parameters change with life and estimate overall cost of ownership of an excavator; 2) to provide a comparison of mining shovels classified as "Rope Shovels" (RS) and "Hydraulic Excavators" (HEX) based on the results of the study and the parameters examined.

1.3 Methodology of the Thesis

The study has been carried out in four steps. As a first step, an extensive literature survey was performed. It included review of existing single-bucket mining shovels, their design and kinematics, application pros and cons, factors affecting productivity and applied maintenance strategies.

The second step included data collection at Komatsu Mining Germany (which is Komatsu Ltd. Manufacturing facility for super large hydraulic mining excavators) in regards to their machines operating around the globe.

The third stage of information gathering related to a field study of ten hydraulic excavators and twenty rope shovels operating at three directly adjoining coal mining sites called in this thesis Mine “A”.

The final stage comprised analysis of each dataset brought together for examination and comparison of such surface mining equipment models under consideration.

1.4 Thesis Outline

Following the introduction in Chapter 1, Chapter 2 comprised a review of modern hydraulic excavators and electric cable shovels, their design and kinematics, favorable and unfavorable application conditions, factors affecting productivity and employed maintenance.

Chapter 3 contains information about KOMATSU heavy duty excavators and the field conditions in which they work, as well as specific field sources of data obtained at Komatsu Mining Germany (KMG). Description of Mine “A” where production, expenditure costs, uptime and downtime indicators for thirty excavating machines of different types and bucket capacities were gathered can also be found in this chapter.

A comparison of the excavators was made on the examination results of the following indices: 1) physical availability; 2) productivity; 3) operation cost. The results can be found in Chapter 4.

Finally, conclusions related to this study and recommendations for future studies are summarized in Chapter 5.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Surface mining today is not possible without the use of large excavation equipment which is an integral part of the mining process. The most common class of excavation machines working in surface mines are single-bucket excavators. Their duty cycle consists of digging operations, moving the filled bucket to an unloading point, unloading the excavated material from the bucket into a vehicle and returning to the digging face. Duration of the duty cycle depends on the capacity and type of excavators and the working conditions, varying from 20 to 80 seconds [1]. Production level for $1m^3$ of equivalent bucket capacity varies significantly and depends on the operating conditions. Heavy-duty excavation equipment is related to the instability of the mining conditions, loading activity and wear of equipment.

Rope shovels and hydraulic excavators are used to dig any (including the strongest and heterogeneous) earth broken rock materials with large solid inclusions. To work in a soft soil shovels and excavators can be supplied with dippers or buckets of a larger capacity. Hard rocks and frozen ground are usually loosened by means of blasting prior to excavation, and mining shovels are fitted with smaller buckets reinforced for better wear protection.

Development of open cast mining has moved towards a concentration of operations in smaller number of operating machines, increasing the unit power, capacity and consequently amount of the handled material per unit time for shovels. The feasibility of using a particular type of excavation equipment is based on the assessment of the advantages and disadvantages of a variety of existing factors. The factors influencing choice may include: production capacity of the mine; physical and mechanical properties of overburden and minerals, the condition of their occurrence; the accepted mine plan; operating floor slope angles, bench heights; etc. [2].

In turn, indicators for performance assessment of each particular type of excavator could be assessed as follows [3]:

availability — the proportion of time the equipment is available to work;

maintenance needs — the proportion of time required for general maintenance, overhauls and unexpected maintenance (unavailability);

cost per unit of production.

Because of the high number of variables influencing open pit mine equipment selection, in open pit mines not one, but several kinds of excavation and loading equipment are used, each of which best meets the given conditions of a specific operation and provides a high efficiency to the mining operation.

Typically, electrical rope shovels are considered to be more reliable and long-lived machines, they are assumed to be easier and cheaper to maintain [4, 5]. For major long-life sites with well-developed electrical supply networks, where mining and geological conditions do not require selective excavation at one horizon, these machines are often used.

Conversely, where complicated geological conditions exist, hydraulic excavators are usually more preferable as technologically more flexible. The weight of a hydraulic excavator is less, and it can be equipped as a "front shovel" or a "backhoe". It generally has greater power delivery for excavation, considerably higher mobility, and provides qualitative selective excavation [5].

Clearly, differences in design and kinematics make hydraulic excavators and rope shovels successful by application case. This chapter is the result of a literature review focused on comparing the two principle types of surface mining excavation machines.

2.2 Mining Shovel Design

2.2.1 General Overview

Any rope shovel or hydraulic excavator consists of three major assemblies which are an upper structure, a lower structure, and an attachment. The upper structure consists of a machinery house, an operator’s cab and a counterweight. The lower structure contains the propel drive and crawler system as well as provides a stable base for the machine.

The main features that are the base for classification of existing open-mine rope shovels and hydraulic excavators are their bucket capacity or theoretical productivity and attachment power delivery for excavation. Unlike construction or other types of excavators, machines used in surface mining are crawler mounted.

Power delivery for heavy-duty open mine excavators is mainly electrical, however, machines of lower power class use diesel - electric, diesel - hydraulic and electro-hydraulic power mechanisms.

Depending on the application, operational equipment to single bucket shovels has different designs and kinematics. Rope shovels have operational equipment in form of front shovels only, whereas hydraulic excavators can be either front shovels or backhoes. Usually hydraulic excavators in open pit operations use one type of attachment during their working life, in contrast to universal smaller construction excavators using up to ten interchangeable attachments for different tasks.

Four general configurations of front shovels are known at this moment. They are a front shovel with sliding stick, a toggle linkage front shovel, a hydraulic front shovel, and a "Super Front" configuration shovel. "Super Front" shovels are rather rare among machines used in surface mining, while toggle linkage designs are used in powerful striping front shovels and are not wide spread in mining because of low kinematic effectiveness. Therefore, as two commonly utilized front shovel configurations a sliding stick rope shovel and a hydraulic front shovel are discussed below.

2.2.2 Rope Shovels

A sliding stick rope shovel (Figure 2.1) consists of a dipper (1), a stick (2) supported by a saddle block (3), and components of a crowding gear. A boom is abutted by a swinging platform with a pivot hinge (4) and supported by a support cable (5). A hoist cable passes from a hoist (O_1) through a heading block (6) and at the point (B) joins a dipper (7).

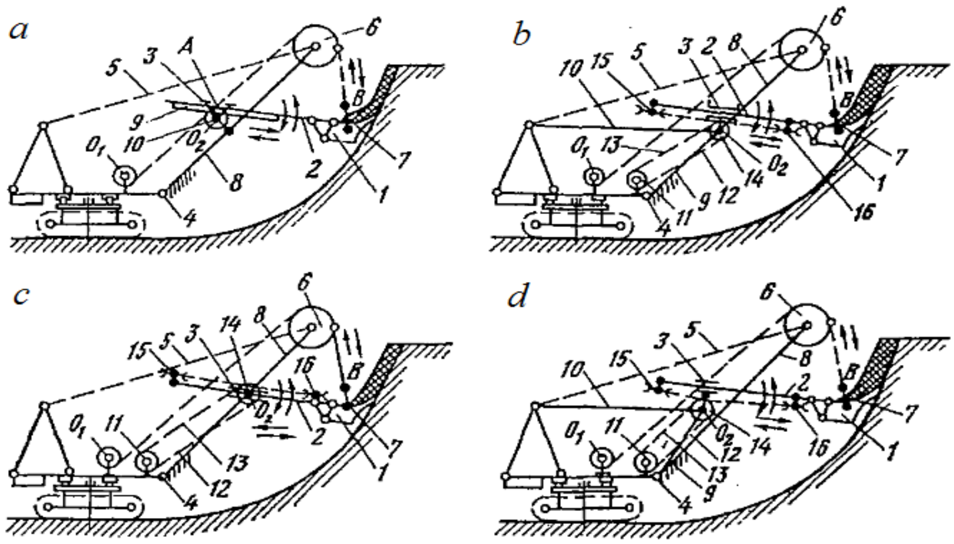

Figure 2.1 Machine arrangement of a sliding stick rope shovel. Adapted from *Mechanical equipment for surface mining* (p. 149) by Poderny R., 2007, Moscow. Copyright 2007 by Poderny R..

Depending on a crowding gear system and a boom design sliding stick rope shovels can be divided into four main groups:

- With a rack-and-gear crowding mechanism (Figure 2.1, a) sited on the boom (8) and transferring the force with a rack gear (10) (rotation axis (O_2)) on a rack bar (9) sited on the stick (2).

- With a rope crowding mechanism (Figure 2.1, b) and a boom divided by a joint (O_2) into two segments – the upper (8) and the lower (9) supported by a brace (10). A crowding winch (11) is sited on the platform. Back and forth movement of the stick is provided by cables (12, 13) enveloping central blocks (14) (rotation axis O_2) and pulleys (15, 16) sited on the stick.

- With a rope crowding mechanism (Figure 2.1, c) and an all-in-one-piece boom (8). A saddle block (3) and central blocks (14) have the rotation axis O_2 and are sited inside the boom. Back and forth movement of the stick is provided by a crowding winch (11) in the same manner as on the scheme shown in Figure 2.1, b.

- With a rope crowding mechanism (Figure 1, d) and a double-girder boom (8). A saddle block (3) is installed in a frame (9) unjointed of the boom. The frame is supported by a brace (10). A crowding winch (11) is sited in front of the platform. Back and forth movement of the stick is in the same manner as on the scheme shown in Figure 1, b.

Positioning of the stick in the saddle block allows it to rotate on the axis O_2 by the hoist cable acting force, as well as to slide inside the saddle block by the crowding mechanism action. Moreover, it provides rotation around the stick center-line. Thereby, three last groups of rope shovels have sticks with three degrees of freedom. A dipper motion is determined by summarizing movement vectors caused by the crowd and hoist mechanisms.

Dipper dumping is implemented by the dipper door opening at the rear. After dumping the dipper is retracted to the lowest point of a bench by means of its own weight and the weight of the stick. The dipper door at the same time closes and the bucket is ready for a new dig cycle.

Rope shovels are intended for mining operations above the machine ground level. Nevertheless, they are able to dig slightly below that level which is enough only for the machine to embed itself when trenching (ditching) and creating a downward ramp.

2.2.3 Hydraulic Excavators

Hydraulic front shovels with a swiveling (curling) bucket are illustrated below (Figure 2.2, a) and has the following elements of the operational equipment: a boom (1) (rotation axis O_1), a stick (2) (rotation axis O_2), a bucket (3) (rotation axis O_3). Rotation relative to O_1, O_2, O_3 axes is provided by a hydraulic cylinder of hoist and descent boom movement (4), a stick crowd cylinder (5), and a bucket swiveling cylinder (6). The bucket swiveling cylinder can be attached either to the stick or the boom.

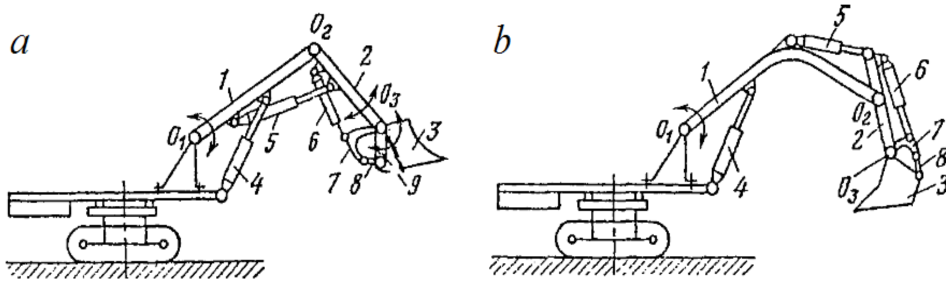

Figure 2.2 Machine arrangement of a hydraulic excavator with changeable attachments. Adapted from *Mechanical equipment for surface mining* (p. 153) by Poderny R., 2007, Moscow. Copyright 2007 by Poderny R..

From the kinematical point of view, a swinging platform is a fixed element of the executing mechanism of an excavator. The excavating trajectory is a combination of motion of the main operational equipment elements.

Bucket dumping is implemented by the bucket jaws opening. For this purpose there are two hydrocylinders attached to the bucket rearwall (clam) and rotating the front part of the bucket on O_3 joint axis. The rearwall is a fixed element of the bucket.

Configuration of a hydraulic backhoe (Figure 2.2, b) boom (1) and a stick (2) differ from a hydraulic front shovel. Rotational motions of a boom, a stick, and a bucket are implemented on the axes O_1, O_2, O_3 by forces provided with hydraulic cylinders 4, 5, and 6. Pull bars 7 and 8 are for the bucket bonding.

Both front shovel and backhoe attachments can be removed and installed on the same machine.

Hydraulic front shovel configurations developed different manufacturers are similar. However, the arrangement of hydrocylinders for different excavator model purposes creates optimal kinematics as a function of application.

For instance, the Orenstein & Koppel (O&K) company (now part of Caterpillar) designed a TriPower system (Figure 2.3) which comprised a three-part rotatable arm sited on the boom and connected to the boom and bucket cylinders. This design provides the bucket to be activated horizontally for each dig height and keeps the angle of the loaded bucket constant to varying positions of the boom and stick.

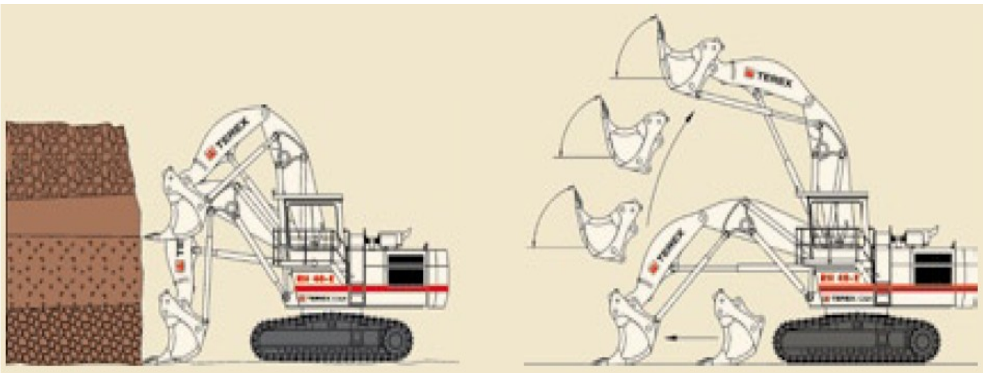

Figure 2.3 O&K`s TriPower geometry [7]

2.2.4 Buckets

The bucket is a working body of an excavator which is a cup-shaped container normally equipped with bucket teeth and is for ground penetration, scoop and loading.

Bucket configurations for mining shovels depend on their connection to the handle or stick. Depending on application, buckets are classified as heavy, medium and light and are used for working in heavy duty, normal, light conditions or coal loading, respectively.

Ninety percent of rope shovels for open pit mining placed on the global market these days have dipper capacities between 30 m^3 and $45m^3$ [8]. However, smaller and larger models from about $10m^3$ (P&H 1900AL – $10,7m^3$, EKG-10 – $10m^3$) to up to almost $80m^3$ (P&H 4800XPC – $77,6m^3$) also exist. Moreover, at many mining sites of former Soviet Union countries smaller old models of rope shovels with dippers capacities of $8m^3$ (EKG-8) and even $5m^3$ (EKG-5A) are still commonly used.

As for rope shovels, hydraulic excavators have seen recent bucket capacity increases in the past two decades, but the creation a large hydraulic excavator is limited for a number of reasons. The main reason is that technological advantages of hydraulic machines such as mobility and selective excavation decrease with size increase. Therefore, hydraulic excavators have capped at a bucket capacity limit of $42m^3$ [8].

Depending on dumping methods, buckets can be classified as those with a free-falling pendulum doors, jaw-like buckets, and buckets unloaded by tilteling. The first class is commonly used on rope shovels, because of its comparatively rapid dumping. The second class is used when a lower dump height is needed for hydraulic front shovels. The third is mainly applied at hydraulic backhoes.

Modern rope shovel dippers usually have a back wall considerably lesser than a front one. The front lip has a flat or a curved shape in order to provide better material pickup and dipper fill. Dippers for hard rock application have higher lip curvatures. Buckets cutting edges are reinforced with high-manganese steel for higher resistance and durability.

Figure 2.4 Rope shovel free-falling pendulum doors dipper with a curved shape front lip (The picture was kindly provided by Dr. Tim Grain Joseph, University of Alberta)

Bucket teeth for surface mining excavators are consumables. Often they have symmetrical shapes along the longitudinal axis. After a tooth has worn, it can be easily chanced in the field.

In terms of metal consumption, the most rational is a multiple-piece tooth configuration with a changeable nose. This configuration has a tooth consisting of several segments, where each of these segments can be changed when it is worn-out.

2.2.5 Rope Shovel Crowding Mechanism

Crowding forces to a rope shovel dipper is generated by a crowding mechanism which is used to raise and lower the bucket. The force created by a crowding mechanism drive is transferred by the rope-and-pulley system or by the rack-and-gear system to the stick traveling in a saddle block.

Siting the crowd mechanism on a boom increases required moment of inertia, the overturning moment of the excavator, as well as the counterweight magnitude. This requires reducing the bucket capacity or the excavating bucket trajectory. A higher dynamic moment of inertia and radius of mass rotating combined with the rope shovel lower works gives rise to inertial loads in the rotating mechanism components. Acceleration and deceleration time increases, which causes increasing increments in cycle time.

2.2.6 Slewing Mechanism and Rotating Support

The slewing mechanism is a turntable with machinery and work equipment. Slewing mechanism of an excavator provides rotary movement of the upper works for digging or dumping.

Modern excavators in open pits have a slewing mechanism with an individual drive consisting of two or more (up to 10) independent assemblages in the upper works operating around a rotating circle fixed to the lower works.

The rotational frequency of a lower works for a heavy single bucket excavator should not exceed 0,02 sec^{-1} (50 seconds for one complete rotation [1]).

Swinging a loaded bucket to a truck and returning it back to the cycle start after dumping are two components that take the most time for a rope shovel or hydraulic excavator duty cycle. Therefore, increasing the rotational speed of the lower works can increase in machine productivity significantly.

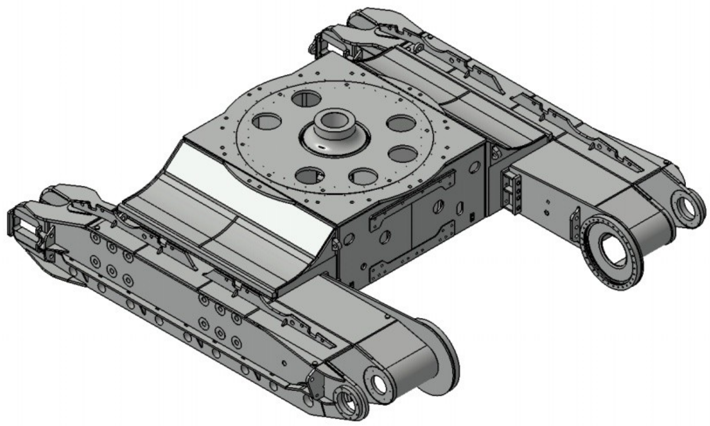

Figure 2.5 Rope shovel lower works (The picture was kindly provided by Dr. Tim Grain Joseph, University of Alberta)

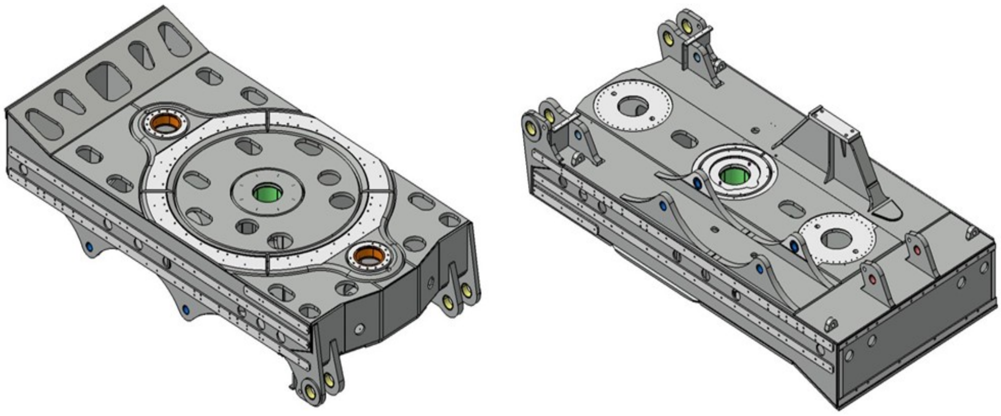

Figure 2.6 Rope shovel upper works - revolving frame (The picture was kindly provided by Dr. Tim Grain Joseph, University of Alberta)

"The cycle time for hydraulic front shovels in normal digging conditions is about 25 to 30 seconds. The "backhoe" configuration cycle time can be rather faster. When an excavator is set up correctly on the upper level and the swing angle is between 20 and 30 degrees the cycles time can be as little as 20 to 23 seconds." "Electric rope shovels with a swing angle of 70 degrees would have the cycle time close to 34 seconds", says Koellner [9].

Rotational support comprises vertical and horizontal components of loads acting on the lower works, transfers these loads (or a portion of them) to the undercarriage frame, provides abutment of the lower works on the undercarriage frame through the slewing ring or rotating circle, and provides minimal resistance between the lower works and the base section during rotating. If a slewing mechanism configuration requires a rotating circle, this rotating circle takes horizontal moments of force.

The majority of single-bucket excavators have slewing mechanisms with loose rollers whose axes are fastened in holders. The rollers have cylindrical or conical shape with one or two bearing ribs. Conical rollers for heavy duty machines create some crowning on the roller path contact surface with the rotating circle. Conical rollers wear slower than cylindrical ones, but they are more difficult to manufacture.

Figure 2.7 Rope shovel rotating circle and cylindrical rollers (The picture was kindly provided by Dr. Tim Grain Joseph, University of Alberta)

2.2.7 Control System and Mechanisms

Modern rope shovels have an attachment manipulation circuit which is part of the electrical automated control system.

Auxiliary mechanisms such as brakes are managed by a pneumatic or hydraulic system. Such systems can be called electro-pneumatic and electro-hydraulic.

Electro-pneumatic systems are distinguished by their insensitivity to ambient temperature changes. These systems are applied for remote brake control of main machine drives (slewing, hoisting, hauling, crowding, etc.); as well as for audible signals, lifting and dropping access ladders, etc.

Hydraulic systems with power cylinders are compact, have high efficiency, independently sited elements, high operating speed, and ability to transfer large wattage. These systems are sensitive to ambient temperatures, which require use of different working fluids in summer and winter periods.

Hydraulic excavators are provided with hydraulic control systems such as pump systems and electro-hydraulic systems. The hydraulic pressure necessary for operational mechanisms activation is created by a pump system. Working fluid flow is directed with control arms through hydraulic distributors.

Electro-hydraulic systems compared to hydraulic systems allow reducing fluid conduit length, simplifying valve controls, and wider application of automatic elements. This system uses valves management through electromagnets in the general electrical control circuit of an excavator.

2.2.8 Undercarriage

The undercarriage is to move an excavator and the basis for supporting all the upper machine parts. Common crawler undercarriage for mining shovels is two parallel crawler mechanisms with linked pads, drive sprockets, bottom and upper (supporting) rollers and idlers. Among the main characteristics required from an undercarriage is: sufficient moving force, speed and maneuverability; ability to handle given grades and inclinations; low weight in addition to providing specific ground force; excavator stability for any position of the center-of-gravity, and lack of detrimental dynamical loads in a machine during traveling; low resistances during machine traveling; minimal number of high-wear parts; operability and durability.

Crawler track type undercarriages are generally used today on electrical rope shovels and heavy hydraulic excavators working on mining sites not requiring frequent or lengthy relocation.

This type of undercarriage provides good stability, ability to handle slopes up to 23°, and low ground pressure. Disadvantages are high weight (with the main frame up to 50% of total weight); high motive force (30% to 40% of the excavator weight); structural complexity and high wear for traveling elements.

Travel speed of excavators in surface mining depends on their power, however it does not normally exceed 3.5 km/h to 4.0 km/h, and rope shovels travel speed is lower (often lower than 1.0 km/h). It should be also noted that hydraulic excavators are smaller and 40% to 60% lighter than rope shovels with the same bucket capacity, and this is what gives them an advantage in mobility and maneuverability.

Travel path slopes usually do not exceed 15°; where maximal generated loads acting on the ground surface can reach 0.9 MPa (130 psi) [1].

Depending on the way load distribution on the ground during duty cycle is invoked, crawlers can be either closely or remotely supported.

“Closely sited supports” means that the ratio of tracks on the ground to the amount of the bottom rollers is less than two In this case individual track links do not sag at all and provide uniform pressure distribution on the ground under the rollers as well as between them. “Remotely sited supports” configuration has the ratio greater than two: individual track links sag easily forming a wavy line. Pressure values under the rollers and between them differ significantly in this case. Because of such differences in pressure distribution configurations of crawler track undercarriages are selected for weak and hard rock application as “close” and “remote”, respectively.

“Remotely sited supports” crawlers sink deeper in ground when used in soils and weak rocks; however, they better bear concentrated loads when used in hard rocks, since they have bigger and stronger rollers. These crawlers are usually provided with four or five large diameter rollers; “closely sited supports” crawlers have six – eight rollers of a relatively small diameter.

Where loose and weak ground rocks are encountered under an excavator drive sprockets and idlers can be raised above the ground level such that the crawler from the front and back rollers to the sprockets and idlers would be inclined 10 to 20 degrees from the horizontal.

Unit power for modern crawler propelling motors applied in open pit excavators (shovels) is approximately 0.18 kW to 0.46kW per ton of machine weight [1].

Maintenance of crawler track type undercarriages includes bolt joint tightening, lubricating, and crawler track chains tensioning.

2.2.9 Upper Works

The metal structure or upper works of a shovel (excavator) is its skeleton, on which all operational equipment drives and control systems are installed. Such metal frames are normally made welded and where necessary they are connected with bolts and pins. Considerable part of excavator metal structure does not carry any load and serves only as machine room frames and to provide safe working conditions for people.

In general, bearing "in contact" metal structures of an excavator include the following components: a boom, a stick, a bucket, upper works and an undercarriage frame (lower works).

Metal structures used in low ambient temperatures require especially careful maintenance. The history of application of mining machines in open pits where temperatures below -30°C dominate gives rise to a large amount of brittle failure during initial operations [10].

For cold temperatures resistance, not only appropriate steel should be used, but correct metal structural design is needed. Since brittle failures occur when component load profiles reach limit resistance of a material, they may give rise to overall locally concentrated stresses. Such local concentrations can cause a change of geometry (abrupt change of the element cross-section, notches, cuts, etc.) and poor fabrication (poor welding, inobservance of the assemblage processes), as well as by locally adverse applied forces [2, 8].

Inability for stress relief for stationary components can significantly decrease cold temperature resistance.

Initial break-in (70 to 100 hours) of upper works with stresses lower than normal working conditions and with temperatures allowing plastic deformations to take place, reduces stress peaks in their concentration zones. This, in turn, increases fatigue resistance of the material and provides better cold temperature resistance.

Wind speed and gustiness can promote cold brittleness. In climatology it is believed that each 1m/sec wind speed enhancement above 7m/sec influences a temperature decline by 2°C. Also each 140m altitude increment translates to an ambient temperature fall by 1°C [2, 10].

It is believed that due to the structural simplicity of electric cable shovels, their use in harsh environments is more effective than the use of hydraulic machines. However, existing experience of hydraulic excavators in Northern Canada (at temperatures of -40°C to -50°C), as well as in Siberia, Russia (where for several months the temperature does not rise above -30˚C and sometimes drops to -50˚C) shows that with correct service and the use of special hydraulic fluids, oils and greases, as well as systems and tools to preheat working fluids, the service life of hydraulic excavators, and productivity and reliability can be superior [8, 13,14].

2.3 Digging Conditions

Both types of surface mining excavator machines can operate in a variety of digging conditions which include different excavated material types, abrasiveness, moisture content, and fragmentation. Although modern mining shovels have higher cutting forces and are often able to dig unblasted rock, they benefit from properly fragmented material attaining better fill factor and lesser machine component fatigue.

It is assumed that hydraulic excavators create higher cutting forces than rope shovels, moreover they can remove material layer by layer starting from the top of a bench. This ability results in comparably less excavated material fragmentation requirement, which in turn reduces drilling and blasting costs.

The inherent heavier weight of rope shovels allows, with better dipper wear protection, working in highly abrasive materials. A heavy duty bucket design for hydraulic excavators leads to a significant decrease of bucket capacity, since these machines are lighter and more sensitive to a bucket weight change.

As for the excavated bench height, both shovel types have comparable indices. However because of hydraulic excavator`s dimensions, its lower boom and stick lengths, it needs to work closer to a digging face, which is not so good from a safety point of view, because of potential rock fall damage. A rope shovel, in turn, has a larger excavating and loading area which allows it to position further from the digging face when operating and requires less machine relocation. Nonetheless, it is recommended to frequently move a shovel to minimize digging beyond a reference vertical line draw from the boom heading block sheave wheel axis. This recommendation is discerned from the fact that working with a large stick handle extension increases the crowding duration, wear of ropes and crowd mechanism, and generates large bending, boom and stick, stresses [8].

2.4 Mining Shovel Productivity

Among others some of the major factors affecting mining shovels productivity are:

- Difficulty of excavation which depends on rock type and state [6]. For instance, when moist clay (or improperly fragmented frozen material in winter) is dug it sticks to the bucket and thus reduces subsequent payload volume as well as increases cycle time due to longer dumping;

- Technical parameters, condition, and reliability of the machine [2];

- Operator`s skill [2, 6];

- Excavation face quality (bench height, rock fragmentation, truck maneuvering path width, illumination, etc.) [6, 11];

- Overall management including truck fleet size, roadways conditions, well-timed fuel supply, spare parts, electricity, consumables supply, etc. [6, 11]

Often with increasing depth of existing open pit mines problems of an increased concentration of mining equipment in a confined area arises. This leads to production decreases as a consequence of delays in truck availability, speed, necessity of power line frequent relocation. In these circumstances use of autonomous and more maneuverable hydraulic excavators is preferable to provide higher production. This type of machine also gives an opportunity for faster mining parameter adjustment in a changing mining environment or for full and qualitative extraction of thin and faulted coal layers to minimize mineral loss.

Failure downtimes are one of the main causes of production decline. A comparison analysis of hydraulic excavators and rope shovels carried out at Muruntau Gold Mine in Uzbekistan indicated that intensity of production declines with working life of a machine, which was significantly higher for hydraulic excavators than for rope shovels [12]. The analysis showed that on the initial stage of exploitation of $15m^3$ Russian EKG rope shovels and $15m^3$ Caterpillar, O&K, and Hitachi hydraulic excavators the average production of the latter was 30% to 35% higher. However, with lifetime augmentation the difference dropped to 10% to 15%. Incremental costs a hydraulic excavators' preventive maintenance and repairs at the same time increased mining prime costs per 1m^3 of excavated rock double that for EKG shovels which had remained constant for several years (Figures 2.8 and 2.9).

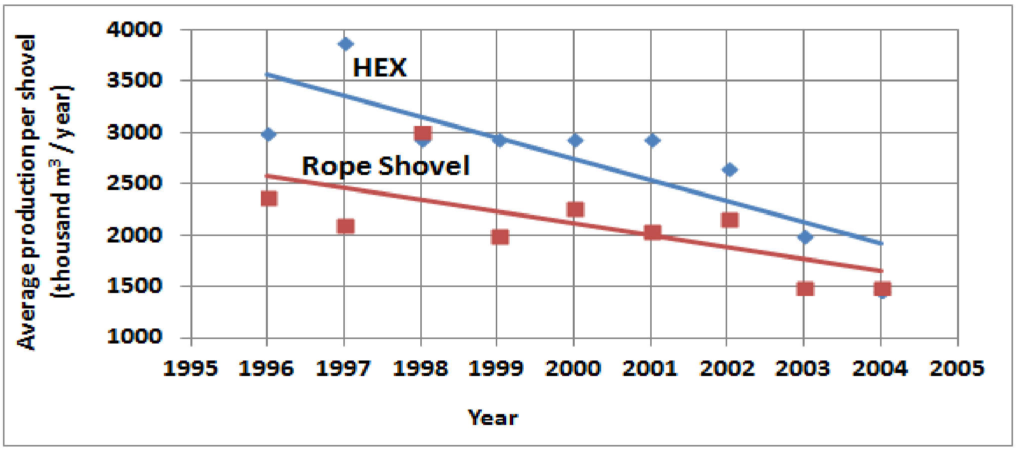

Figure 2.8 Change of the production level with time at Muruntau [12]

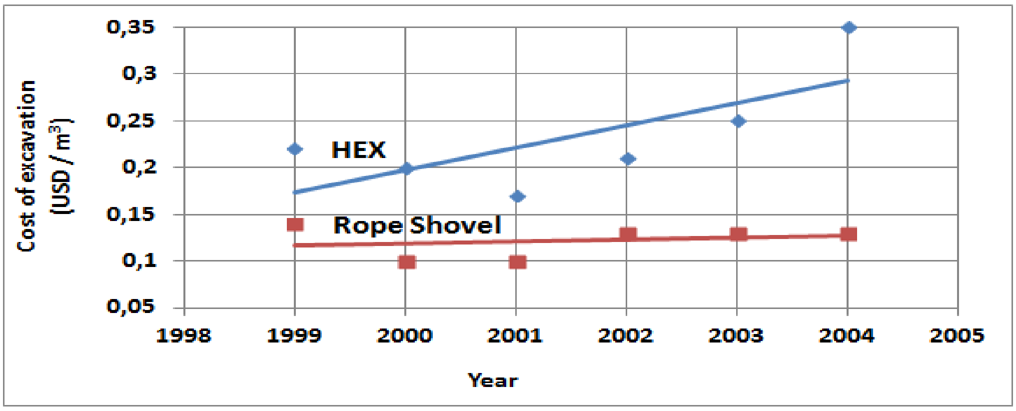

Figure 2.9 Change of the cost of excavation with time at Muruntau [12]

In the case of the Muruntau Mine for the period reviewed, failure downtime of hydraulic excavators increased dramatically, whereas there was no change in average failure downtime for rope shovels (Figure 2.10).

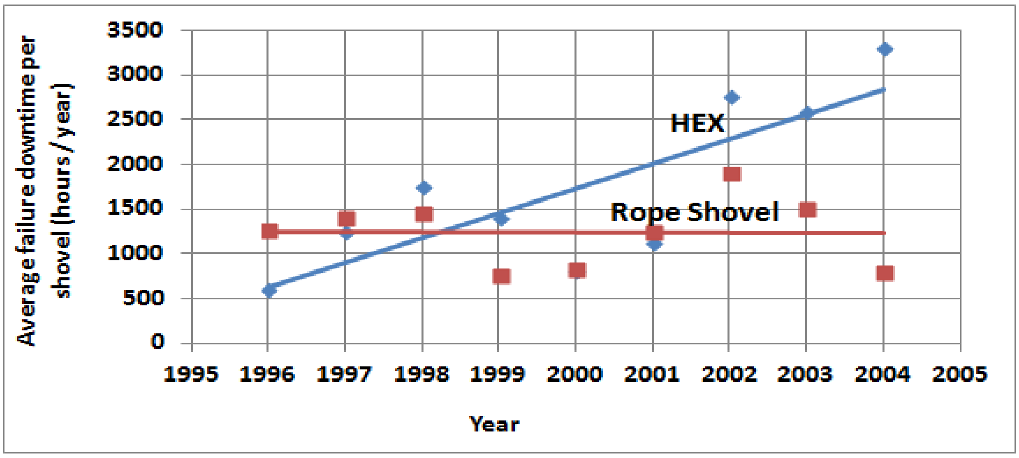

Figure 2.10 Change of shovels failure downtime at Muruntau [12]

This indicates a better repairability for rope shovels, nevertheless, data analysis undertaken 7 years later (in 2011) and at another mining company indicated that in the case of appropriate technical support and equipment maintenance services, the parameters of the actual performance and reliability of hydraulic excavators were not inferior, but maybe superior compared to rope shovels [5]. This was despite the fact that the equipment operated in extreme low temperatures (where for a few months in the operation area the temperature did not rise above -30˚C and sometimes dropped to -50˚C) physical availability and average hourly production of 15m^3 Liebherr R9350 and 15m^3 EKG-15 were, respectively, 95% to 83%, and 670 m^3/h to 523m^3/h (Figure 2.11).

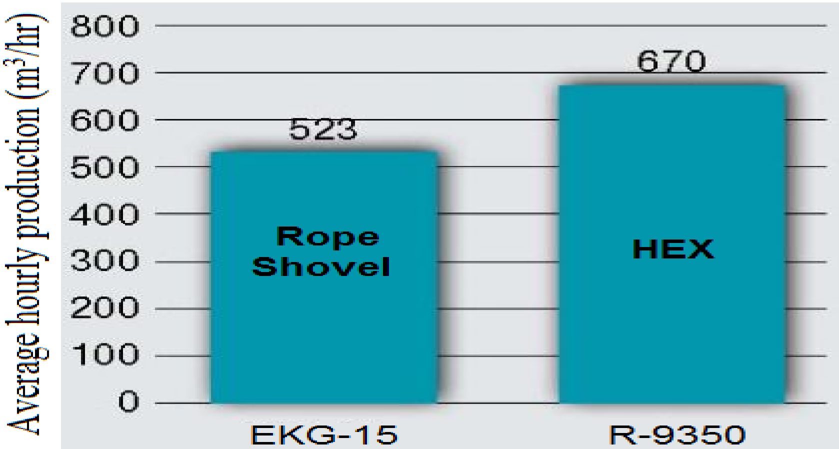

Figure 2.11 Average hourly production (m^3/hr) for R-9350 (a HEX with 3.554 lifetime hours) and EKG-15 (a Rope Shovel with 18.272 hours lifetime) [5]

Among other studies [3] showed that:

- The reliability of a hydraulic drive and thus a hydraulic excavator as a whole depends significantly on the quality of service;

- Components of a hydraulic system and the system in general have high reliability, but low availability;

- Hydraulic system components` resource and reliability is mainly determined by the properties of the working fluid (primarily its cleanness and viscosity).

For productive use of an excavator, a number of operational and technical measures must be undertaken in order to ensure efficient and trouble-free operations.

Properly prepared mining areas promote a long-term, non-stop operation of a machine. Constant operations can be possible if enough sloughing and proper blasting fragmentation is provided.

An excavator path in a pit should be carefully leveled and cleaned from large rock boulders and debris to protect undercarriages from damage. Dozers serve well for these purposes when rope shovels are in use, while the geometry of attachment motion of hydraulic excavators allows them to clean up the mine floor on their own [15]. The mine floor in front of the digging face should be horizontal in order not to overstress slewing mechanisms of a machine.

Keeping excavator uptime largely determines its production capability which is achieved by well-timed and correct maintenance.

2.6 Maintenance Strategies

Maintenance is carried out to maintain the excavator in good functional condition. Maintenance activities may include reactive, preventive, predictive, and proactive approaches. Reactive maintenance implies corrective activities after a failure has occurred. Downtime caused by the failure in such case is unscheduled and leads to unplanned expenses (repair costs as well as production losses). Preventive maintenance is based on an excavator`s required component change schedule based on statistical service life. This strategy keeps scheduled uptime of a machine. The exception is when some component of the machine fails prior to its statistical service life ends. Predictive maintenance is a strategy for minimizing maintenance costs by undertaking corrective activities based on an excavator`s condition. “Routine and complete medical examinations are to the human body as predictive maintenance is to equipment” [16]. Proactive maintenance focuses on determining causes of a failure and providing improved working conditions when those causes are minimized.

Non-observance of maintenance frequency and its poor quality leads to a significant reduction of the working life of any excavator, as well as increase the number of failures, loss of power, increase the cost of operation. Acceptable non-observance of maintenance frequency should be within five to ten percent [10].

Maintenance activities related to the disassembly of diesel engines as an example may be held indoors for protection from dust and dirt in the internal cavity of a diesel engine. Hydraulic system components also have a higher sensitivity to dust. Repair or maintenance of hydraulic excavators requires more careful protection measures against dirt and dust, than for rope excavators.

Shovel maintenance includes: periodic inspection of its active elements (according to a service manual). Well-timed and reliable mechanisms lubrication, periodic adjustment of the wear mechanisms and connections, mechanisms cleaning, and their timely replacement and repairs are all required service strategies.

CHAPTER 3

MINING SHOVELS UNDER THIS INVESTIGATION

In this chapter information about the mining shovels within the scope of this study is given. It includes basic dimensions, main specifications, etc. Furthermore, for the following analysis and correlation between digging conditions and main maintenance issues faced at different mining sites, the chapter also contains description of the sites (location, geology, technological parameters, etc.).

For confidentiality no companies` or mining sites` names are given in the description.

3.1 Komatsu Hydraulic Mining Excavators

3.1.1 Sources and Nature of the Data Collected

In order to improve design, aid to perform adequate service and appropriately update component life expectancy charts, operation and maintenance manuals, etc. Komatsu Mining Germany tries to encourage its customers and distributors to submit monthly reports with detailed failure downtime and performance (availability, mean time between failures, etc.) records for each supplied machine. By collecting the technical problems and related down-times, these reports help to recognize abnormal tendencies of a machine`s work and to provide the impetus to solve problems as early as possible.

According to existing templates all failures occurred should be ranked by failure code: 1-electric; 2-hydraulic; 3-auto lube; 4-air-conditioning; 5-motor; 6-cable drum; 7-bucket/attachment; 8-other. Each of these categories, in turn, has a list of sub-categories. Scheduled breakdowns as well as breakdowns caused by reasons irrelevant to a machine itself (accidents, misoperation, mismaintenance, etc.) should be also included in a report. Consequently, such forms of monitoring allow not only careful track of excavators` performance parameters, but the more important, bring to light weaknesses of a design to permit design improvement.

However, in spite of the existence of forms developed and provided by Komatsu Mining Germany, not all customers and distributors fill in these forms appropriately. Alternatively, they use their own forms (individual for each customer or even each machine) and submit final numbers for availability, mean time between failures and (or) mean time to repair with no qualitative data about technical problems arising during the period under reported. This fact leads to a significant reduction of the data quality that could be used in this study.

Nevertheless, the performance history of one hundred and six items of equipment (8 items of PC 3000, 35 - PC 4000, 34 - PC 5500, 29 - PC 8000) with various degrees of refinement was found acceptable for this analysis. Machines' lifetime period under investigation was decided to be limited to

60,000 hours of operation which is roughly equal to ten years of normal intensive work at a mine site and which is usually declared as a typical service life of a hydraulic excavator by a manufacturer.

For each excavator it was tried to collect as much data per Table 1 as possible. The major portion has received from product marketing & planning, application, service, and parts marketing departments. The other main sources of information were service managers from different parts of the world, who kindly provided necessary data by request.

Table 3.1 List of the estimated parameters and data collected for the comparison study

Parameters to be estimated	Data to be collected
Application Conditions	1. Geological conditions (FACE and UNDERFOOT) 1.1 Rock description (a geological description including rock type, bedding and jointing is desirable) 1.2 Physical and mechanical properties of rock 1.2.1 Density 1.2.2 Uniaxial Compression Strength 1.2.3 Moisture content 1.2.4 Cohesion 1.2.5 Abrasiveness (or scratch hardness by Moh`s scale) 2. Engineering conditions 2.1 Blasting fragmentation 2.2 Travel time 2.3 Swing angle 3. Climatic conditions 3.1 Average annual temperature 3.2 Average annual high temperature 3.3 Average annual low temperature
Availability MTBF MTTR	1. Operation life (total number of hours an excavator has operated) 2. Operating hours (hours a month) 3. Off-schedule repairs hours (hours a month) by categories * ** Use the attached failure codes for help* 4. Number of failures of each failure code (per month) 5. Scheduled services and inspections hours (hours a month) 6. Preventive maintenance hours (hours a month)
Life Cycle Cost	1. A new machine cost 2. Repairs costs 2.1 Spare parts 2.2 Consumables 3. In-service attendance costs 3.1 Fuels and lubricants 3.2 Electricity
Production Rate	1. Tons per hour (for each evaluated month)

3.1.2 General Overview of the Excavators

As one of the main parts of the performance data study for super large hydraulic mining excavators produced by Komatsu Mining Germany (KMG), operating around the globe were collected. Standard bucket capacities of these excavators range from 16 to 42 cubic meters where customers utilize machines from Canada and Russia, where the ambient temperature can drop in winter from -50 to Australia and Africa where the "-" turns to "+" sign. Moreover, these shovels are employed in all types of material and mine a range of commodities from soft coal and kimberlite to metal and uranium ores.

As for design, each model has found implemented as a front shovel or backhoe with alternatively light, standard and heavy duty bucket wear packages to meet abrasiveness of digging materials and mine conditions. Excavators working at different mines were provided with diesel engines or electric motors. This diversity of example designs met in different working environments presented a relevant data set for the comparison study performed here.

PC 3000, PC 4000, PC 5500 and PC 8000 models with front shovel bucket capacities of $16m^3$, $22\ m^3$, $29\ m^3$ and $42\ m^3$, respectively, are the excavator models manufactured and supplied by KMG at present.

3.1.3 PC 3000

Despite of considerable number of PC 3000`s being globally in use the study discussed only eight units were selected with respect to fullness and quality of the available reports containing information about performance. All these shovels are owed by the same company and work in the same conditions. To be more specific, they are involved in coal mining at one of the equatorial regions of the world. They are PC 3000-6 backhoe diesel drive shovels with basic dimensions and main specifications presented on Figure 3.1 and in Table 3.2, respectively.

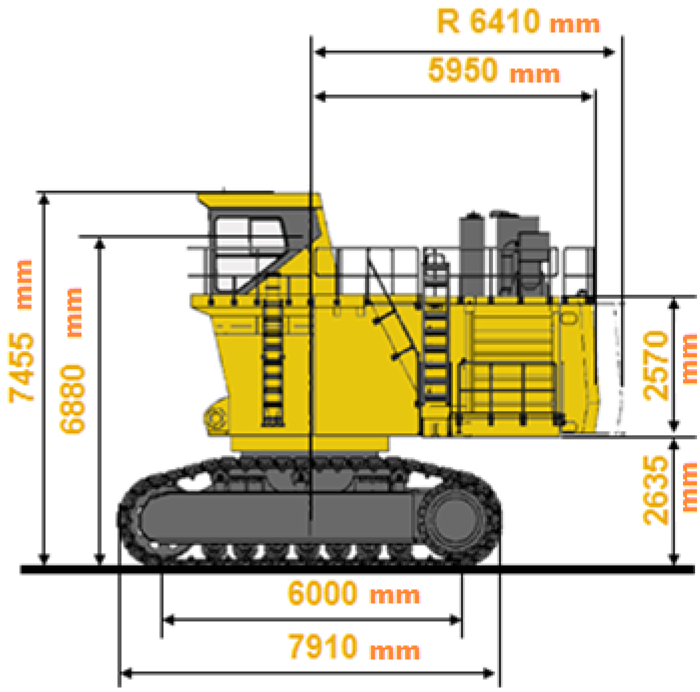

Figure 3.1 PC 3000: Basic dimensions [17]

Table 3.2 PC 3000: Main specifications

Electric	Power Output	KW	900	
	Operating Voltage	V	6000 / 7200	
Undercarriage	Overall Length of Crawler Assembly	mm	7910	
	Crawler Length (Centres)	mm	6000	
	Track Pads Width	mm	1000 / 1200	
Travel	Gradebility	° (%)	29,5 (57)	
	Propel Speed	km/h	2,4	
Attachment			Front Shovel	Backhoe
	Boom Length	m	6,0	8,6
	Stick Length	m	4,3	4,0
	Bucket Capacity (Standard)	m^3	16,0	15,0
	Bucket Capacity (Range)	m^3	12,0 ÷ 16,0	12,0 ÷ 16,5
	Standard Cutting Width	mm	3600	3260
	Crowd / Tear-out Force	kN	1100	800
	Break-out Force	kN	1000	850
	Max.Cutting Height	m	15,1	14,1
	Reach at Ground Level	m	12,7	15,5
	Clean-up Path at Ground Level	m	4,7	-
Weight	Operational Weight	t	250	252
Swing	Swing Speed	rpm	4,6	4,6
	Tail swing	mm	6410	6410
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	56,3	60
	Operating Weight per m^3	t/ m^3	15,6	16,8
Diesel Drive	Engine - Make		KOMATSU	
	Engine - Model		SSA12V159	
	Rated Power (SAE)	kW	940	
	Engine Revolution	rpm	1800	
Hydraulic System	Max. Flow Main Pump	l/min.	3 x 910	
	Hydraulic Pressure Slew	bar	310	
	Max. Flow Slew Pump	l/min.	800	

3.1.4 PC 4000

PC 4000 excavators involved in the study comprised 35 units. Among these machines: five are standard package backhoes working at a coal mining site in a hot alpine environment; eight front shovels and three backhoes at an equatorial region coal mining; five electrically driven machines at African collieries; and ten diesel shovels with predominately Heavy Duty wear packages for metal ore extraction at dry and extremely hot parts of the world.

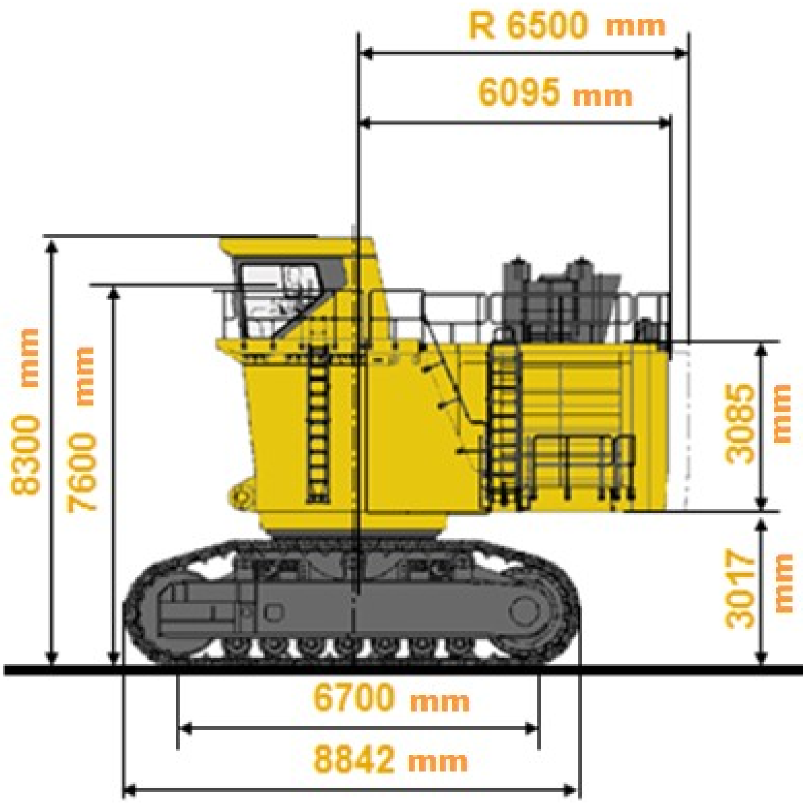

Figure 3.2 PC 4000: Basic dimensions [18]

Table 3.3 PC 4000: Main specifications

Electric	Power Output	KW	1350	
	Operating Voltage	V	6000 / 7200	
Undercarriage	Overall Length of Crawler Assembly	mm	8375	
	Crawler Length (Centres)	mm	6245	
	Track Pads Width	mm	1200 / 1500	
Travel	Gradebility	° (%)	26,5 (50)	
	Propel Speed	km/h	2,1	
Attachment				Backhoe
	Boom Length	m	7,15	9,75
	Stick Length	m	4,9	4,5
	Bucket Capacity (Standard)	m^3	22,0	22,0
	Bucket Capacity (Range)	m^3	19,0 ÷ 24,0	19,0 ÷ 23,0
	Standard Cutting Width	mm	4020	3050
	Crowd / Tear-out Force	kN	1330	1050
	Break-out Force	kN	1250	1155
	Max.Cutting Height	m	17,4	15,0
	Reach at Ground Level	m	14.0	16,5
	Clean-up Path at Ground Level	m	5,7	-
Weight	Operational Weight	t	388	394
Swing	Swing Speed	rpm	4,0	4,0
	Tail swing	mm	6500	6500
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	61.4	61.4
	Operating Weight per m^3	t/ m^3	17,6	17,9
Diesel Drive	Engine - Make		KOMATSU	
	Engine - Model		SDA16V160	
	Rated Power (SAE)	kW	1400	
	Engine Revolution	rpm	1800	
Hydraulic System	Max. Flow Main Pump	l/min.	4 x 1035	
	Hydraulic Pressure Slew	bar	310	
	Max. Flow Slew Pump	l/min.	1035 + 555	

3.1.5 PC 5500

Among the thirty-four pieces of PC 5500 involved in the analysis there are predominately (31 out of 34) excavators operating in ore (copper, iron and uranium) mines. These mines in their turn are located in environmental conditions ranging from a dry and extremely hot (up to + 55C°) to a humid climate with average minimum of -15 C° to -20C° during the winter time. Both "front shovel" and "backhoe" modifications are among these machines and majorly with a diesel drive. Below some of the basic dimensions and main specifications for PC 5500 hydraulic excavator model are presented.

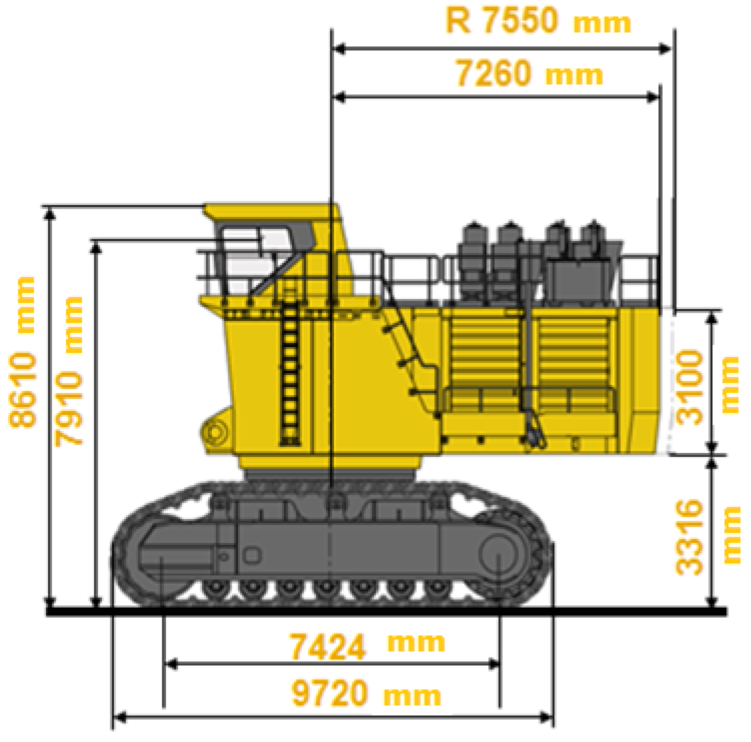

Figure 3.3 PC 5500: Basic dimensions [19]

Table 3.4 PC 5500: Main specifications

Electric	Power Output	KW	2 x 940	
	Operating Voltage	V	6000 / 7200	
Undercarriage	Overall Length of Crawler Assembly	mm	9720	
	Crawler Length (Centres)	mm	7424	
	Track Pads Width	mm	1350 / 1800	
Travel	Gradebility	° (%)	26,5 (50)	
	Propel Speed	km/h	2,2	
Attachment				Backhoe
	Boom Length	m	7,6	11,0
	Stick Length	m	5,6	5,1
	Bucket Capacity (Standard)	m^3	29,0	29,0
	Bucket Capacity (Range)	m^3	21,0 ÷ 29,0	26,0 ÷ 29,0
	Standard Cutting Width	mm	4570	4380
	Crowd / Tear-out Force	kN	1870	1290
	Break-out Force	kN	1865	1450
	Max.Cutting Height	m	19,5	15,5
	Reach at Ground Level	m	15,0	18,7
	Clean-up Path at Ground Level	m	5,6	-
Weight	Operational Weight	t	533	538
Swing	Swing Speed	rpm	3,1	3,1
	Tail swing	mm	7550	7550
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	64,8	64,8
	Operating Weight per m^3	t/ m^3	18,4	18,6
Diesel Drive	Engine - Make		KOMATSU	
	Engine - Model		2 x SDA12V159E-2	
	Rated Power (SAE)	kW	2 x 940	
	Engine Revolution	rpm	1800	
Hydraulic System	Max. Flow Main Pump	l/min.	6 x 700	
	Hydraulic Pressure Slew	bar	310	
	Max. Flow Slew Pump	l/min.	700	

3.1.6 PC 8000

This model is presently the largest hydraulic mining shovel manufactured by KMG. Data used in this study was assumed to be the most comprehensive and reliable. It is largely resulted from the fact that in some cases with purchasing a fleet of several shovels customers get a permanent attendance and service of high level KMG service engineers who not only provide better service but also a higher quality of reports. Twenty-nine front shovels and two backhoes with electric and diesel drives and mostly in copper and coal mines were used in the study.

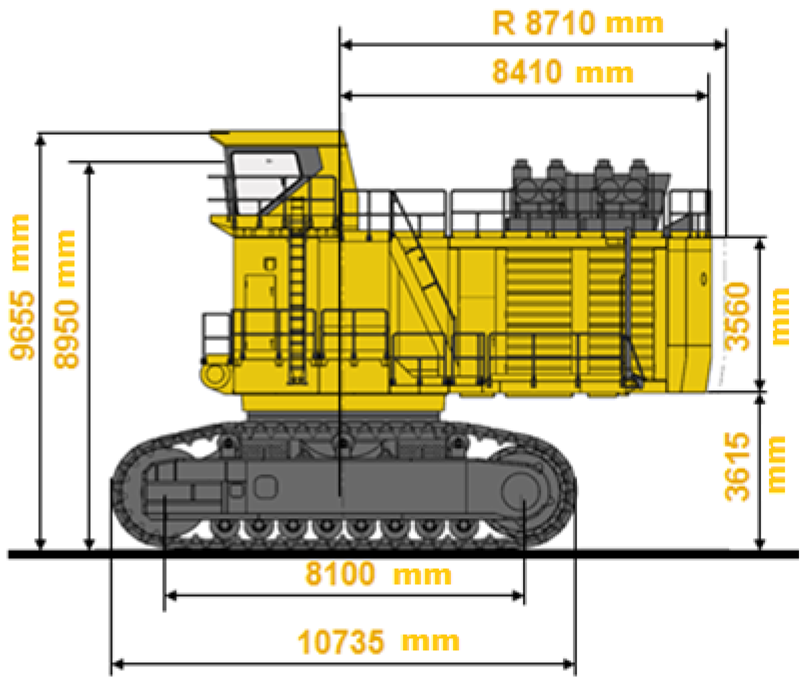

Figure 3.4 PC 8000: Basic dimensions [20]

Table 3.5 PC 8000: Main specifications

Electric	Power Output	KW	2 x 1450	
	Operating Voltage	V	6000 / 7200	
Undercarriage	Overall Length of Crawler Assembly	mm	10735	
	Crawler Length (Centres)	mm	8100	
	Track Pads Width	mm	1500 / 1900	
Travel	Gradebility	° (%)	26,5 (50)	
	Propel Speed	km/h	2,4	
Attachment				Backhoe
	Boom Length	m	8,15	11,5
	Stick Length	m	5,75	5,5
	Bucket Capacity (Standard)	m^3	42,0	42,0
	Bucket Capacity (Range)	m^3	28,0 ÷ 42,0	42,0
	Standard Cutting Width	mm	5375	4575
	Crowd / Tear-out Force	kN	2320	1290
	Break-out Force	kN	2320	1450
	Max.Cutting Height	m	20,9	15,5
	Reach at Ground Level	m	16,3	18,7
	Clean-up Path at Ground Level	m	5,9	-
Weight	Operational Weight	t	752	763
Swing	Swing Speed	rpm	2,7	2,7
	Tail swing	mm	8710	8710
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	69,0	69,0
	Operating Weight per m^3	t/ m^3	17,9	18,1
Diesel Drive	Engine - Make		KOMATSU	
	Engine - Model		2 x SDA16V160E-2	
	Rated Power (SAE)	kW	2 x 1500	
	Engine Revolution	rpm	1800	
Hydraulic System	Max. Flow Main Pump	l/min.	8280	
	Hydraulic Pressure Slew	bar	310	
	Max. Flow Slew Pump	l/min.	2070	

3.2 Data from Industry

3.2.1 Sources and Nature of the Data Collected

As long as the main purpose of the study discussed was to compare electric rope shovels against hydraulic excavators on the basis of a range of parameters it was clear that definite efforts had to be done in order to collect data for cable shovel performance. Moreover, in order to improve reliability of the comparison it was good to have data for different types of machines operating at the same sites. Such an approach would minimize difference in operational environment between compared units. Therefore, it was decided to make an attempt to gather data personally from a coal mining site.

After a month of data collection, the major part of the required information had been received from the company`s geologists, surveyors, mechanical service and operational (processing) departments. The lacking data in regard to production numbers and performance parameters, as well as expenditures related to the possession of a particular shovel were gradually obtained over further months. Just as it was expected getting numbers for spare parts, fuels, lubricants, electricity, consumables and other costs was the most challenging task in the context of cooperating with a mining company.

As a consequence of the above described activities thirty mining shovels were engaged in the analysis. Twenty of them were electrically driven rope shovels with buckets capacities from ten to thirty-three cubic meters. The other ten machines were hydraulic excavators with buckets from ten to twenty-nine cubic meters. A list of RS and HEX (model names, bucket capacities and quantity of units) involved in the study with assistance from a coal mining company is presented in Table 3.6.

Table 3.6 List of mining company shovels involved in the study

Model name		Bucket Capacity (m^3)	Quantity of Items
Rope Shovels	EKG-10 (OMZ)	10,0	3
	EKG-12 (OMZ)	12,0	3
	EKG-12.5 (OMZ)	12,5	1
	EKG-15 (OMZ)	15,0	3
	EKG-20A (OMZ)	20,0	4
	P&H 2300 (Joy)	16,0	2
	P&H 2300XPC (Joy)	16,0	1
	P&H 2300XP (Joy)	20,0	1
	P&H 2800 (Joy)	33,0	2
Hydraulic Excavator	R-994 (Liebherr)	11,0	4
	PC 2000 (KOMATSU)	10,0	4
	PC 4000 (KOMATSU)	22,0	1
	PC 5000 (KOMATSU)	29,0	1

3.2.2 Description of the Site

3.2.2.1 General Overview

The mining site is located at an upland chain elongated along the strike of a coal deposit. The mine is oriented north-west with highest mountain altitude at +610m, to south-east at +580m.

Coal-bearing sediments on site include coal seams with a monoclinal dip of 6° to 15°. The strike of the coal seams is north-east at azimuth 35° to 45°.

Monoclinal layering of sedimentary rock is insignificantly complicated by the presence of minor wavy folding. All folded structures have minor size and rapidly fade. Overburden rocks are mainly presented as sandstone and, to a lesser degree, siltstone and argillite; quaternary sediments are clay and loam.

The climate is continental with long winters and short hot summers. The duration of the winter with snow and low temperatures is 6 to 6.5 months. Maximum temperature is + 35°C (July), the minimum is - 45°C (January). The thickness of snow cover in some years is up to 170cm. The depth of ground frost penetration does not exceed 0.5m. The average annual rainfall is 880mm. The winds have prevailing south-east direction and low speeds of 2 m/sec to 5m/sec. The maximum speed winds have a north-west direction.

3.2.2.2 Stratigraphy and Lithology

The mined formations include twenty coal seams. By thickness they are divided into thin (0.5m to 1.3m), average (1.3m to 3.5m) and thick ones (3.5m and above). The structure of the seams involves 1 to 3 and some up to ten layers of rock. Most of the coal seams are assigned to groups of complex and very complex structure. Interburden layers are sandstones, argillaceous sandstones, siltstones, coaly siltstones, argillites and conglomerates. Often interburden layers have variable lithology and thickness. The thickness changes from 1 to 3m up to 10 to 35m with the maximum value of 40m to 50m. In many cases at the base of these interbeds, thin layers of conglomerates and gravelites can be found. Overall thickness of the set is 370m, the coal percentage is 10.6%. The lithological composition and percentage are presented in Table 3.7. A stratigraphic column is given in Figure 3.5.

Table 3.7 Overall thickness and percentage of host rocks and coal seams set

Overall thickness, m	Conglomerates		Sandstones		Siltstones		Argillites		Coal	
	m	%	m	%	m	%	m	%	m	%
370	1.2	0.3	219.7	59.4	107.0	29.0	2.9	0.7	39.2	10.6

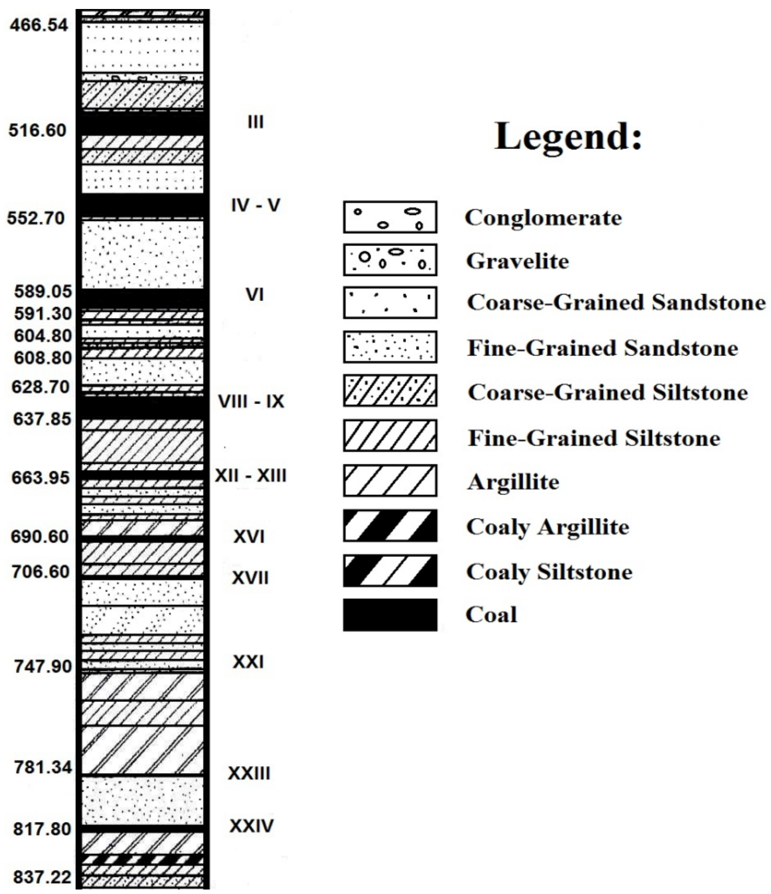

Figure 3.5 Stratigraphic column for Mine “A”

Sandstone is the most prevalent host rock on site. They are presented layers of up to 50m thickness with intrusions of argillaceous sandstone and siltstone. They are fine or medium grained (sparsely coarse-grained) with laminated massive structures. The cement is mainly argillaceous and to a smaller extent carbonaceous or carbonate-argillaceous. The cement composition consist of illite with some sericite, braize, carbonates, and sparse chlorite. The quantity of cement is in the range of 11% to 18%.

Siltstone is less common than sandstone. Mostly liying at the bottom and top of coal seams. The thickness of siltstones reaches 8m to 11m (sparsely at 20m). They have thin-layered of micro-layered texture. The composition and nature of the cement is similar to the sandstone cement. The most common cement is argillaceous at 18% to 30%. The carbonate-argillaceous cement is rarely observed.

Argillites have a limited distribution and lie as interburden and lenticles amongst rocks and on the contacts of coal seams and country rocks. The texture is generally massive and, to a lesser degree laminar. With increase of coal content (to more than 25%) the rock becomes a coaly argillite.

Gravelites and conglomerates are minor distributed and can be found as stringers inside the sandstones. Such detritus material majorly consists of sedimentary rocks. The jointing material is silty and, in many cases carbonized.

In bedrocks, three zones with varying degree of weathering can be noted:

A zone of intense weathering and fracturing is to a depth of 1 to 6 meters. In the upper part, it is characterized by the presence of debris of 0.05m to 0.4m size. The thickness of this layer is 0.5m to 2.0 m. Coal represented as a feasible soot is in the upper portion of the layer. The lower part of the intense weathered zone is characterized by open, clearly visible, assystematic cracks. The strength of the rock is low, permitting excavation without blasting.

A noticeable weathered zone located below the identified zone of intense weathering. Thickness of the zone is from 5 to 8 meters to 10 to 15 meters. Open fractures are more systematic here. Such cracks are particularly well visible in sandstones and form blocks in the rock mass. Rock strength is reasonably high although resistance is lowered. Blasting is required for successful excavation practice.

The third zone is the zone of minor fracturing. It is characterized by an almost complete absence of open cracks; small intervals of fractured rocks are rare. In tectonically quiet carboniferous sediments there are only perpendicular intersecting cracks. Mining is only carried out with drilling and blasting.

3.2.2.3 Hydrogeology

In unconsolidated sediments there are two water tables. The first aquifer presents poorly; it is confined to a light silty loam. It is seasonal and fed by rainfall and meltwater. The filtration coefficient of the loam is 0.01m/day to 0.00035m/day. The second aquifer is confined to the lower part of Quaternary sediments occurring at the contact with bedrock. This horizon is characterized as a permanent regime and is hydraulically connected with the bedrock groundwater. The water inflow does not exceed 0.1 L/sec to 0.3L/sec. Ground water quickly drains and does not affect the water inflow to mine openings. However, despite the low water content in the unconsolidated sediments, even a small presence reduces the bearing capacity of the soil and leads to pit wall instability.

The unpredictable water content of coal-bearing deposits depends on the degree of fracturing, lithology and geomorphology. The deposit is essentially saturated to a depth of 80m. Intrusive rocks are saturated only in upper cracked regions to depths of 40m to 50m from surface. At lower elevations, due to reduction in fracture, they are almost dry.

3.2.2.4 Coal Seams

The main pit has fourteen coal seams with thicknesses from 0.8m to 8.0 m. They have a complex structure, with dip of 6° to 15°. Thickness of rock interburden in coal seams and coal layers varies from site to site. Sudden thickness changes are local progressing to split seams, minor faults, magmatic intrusions and intraformational erosion. The number of intrastratal layers of siderite, siltstone, and sandstones with thickness from 0.01m to 0.25m varies from 2 to 17 layers.

Broken rock and coal are excavated by mining shovels then loaded in trucks. All coal seams are mined with benches of 40 meters width. In cases where the thickness of an intraformational rock layers exceeds 0.4 meters, selective mining of the coal seam is performed.

3.2.2.5 Overburden Operations, Drilling and Blasting

Working levels are developed by hybrid mining methods:

1. Upper levels are developed by rope shovels and hydraulic excavators with loading rock to heavy trucks.
2. At the same time some interlayers are developed by draglines with internal dumping.

Parameters of the principle mining equipment, use of blasting for preparation for overburden excavation, physical and mechanical properties of rock, and opening-up schemes predetermine bench heights of 15 meters.

To reduce the amount of work on road construction on benches, the acceptable bench width is 40 meters, and the operating angle of the slope is 75º.

According to the geological description, 90% of overburden as well as individual coal seams require preliminary fragmentation by drilling and blasting. Given the constituents of the overburden, its physical and mechanical properties and the type of excavation equipment, rotary blasthole drilling is adopted at site. Blastholes are inclined at angles of 75° to 90º and drilled using 216mm rotary roller bits.

The coal is brittle and easy to blast. Thick layers of sandstone interbeds are the least-fractured, strong, and dense and even after blasting can form blocks of $2m^3$ to $3m^3$.

Mining methods require transverse and diagonal blasting layouts providing a minimum width of loosen blasted rock mass with short-delay series of 7 blast holes and inter-hole delays of 20msec to 50msec.

3.2.3 EKG Rope Shovels

3.2.3.1 General Overview of the Shovels

EKG shovels are single bucket, electric, full-circle slewing, crawler mining rope shovels for excavation and loading ore and overburden, including blasted heavy rock.

In the Russian language the abbreviation “EKG” is interpreted as “a crawler excavator for surface mining”. The following figure (e.g. EKG-5) denotes the bucket capacity in cubic meters. The letter code following the figures below indicates options, e.g. an EKG-5U excavator has a 5 m^3 bucket and an attachment for top loadings, and also indicates the manufacturer's code (N - Novokramatorsk Heavy-Machinery Factory (Novokramatorsky Mashinostroitelny Zavod)).

Fourteen EKG machines of different age and dipper capacity from $10m^3$ to $20m^3$ were used in the study.

3.2.3.2 EKG – 10

Crawler mining rope shovel EKG – 10 with a standard bucket capacity of $10m^3$ used for excavation and loading ore and overburden into trucks in surface mines as well as for loading operations at ore storage facilities.

Four units of this model were used in the study. Two had a relatively long operational life of nearly 25 years, and a third which started operating in 2005. The fourth unit (EKG-12,5) is a modified EKG-10. EKG-12,5 was commissioned in 1990.

Some of its basic dimensions and main specifications are presented in Figure 3.5 and Table 3.8, respectively.

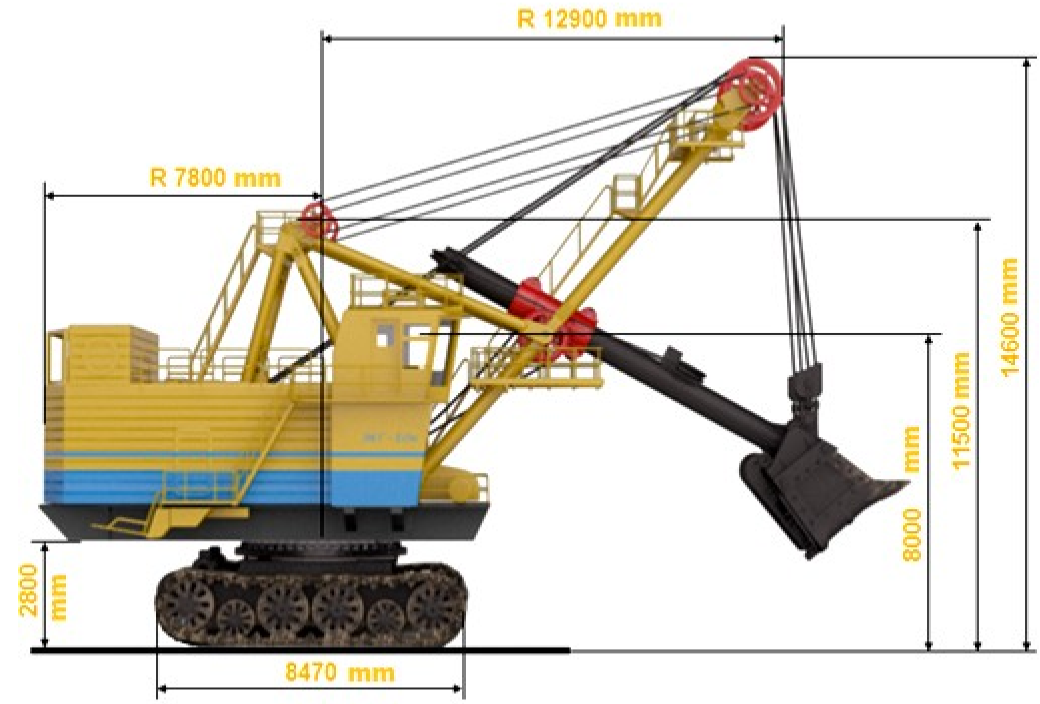

Figure 3.6 EKG-10: Basic dimensions [21]

Table 3.8 EKG-10: Main specifications

Electric	Supply Transformer Power	kVA	800
	Operating Voltage	V	6000
Undercarriage	Overall Length of Crawler Assembly	mm	8470
	Track Pads Width	mm	1100 / 1400
Travel	Gradebility	° (%)	12 (21)
	Propel Speed	km/h	0,7
Attachment	Bucket Capacity (Standard)	m^3	10
	Bucket Capacity (Range)	m^3	5,0 ÷ 12,5
	Max.Cutting Height	m	13,5
	Max.Cutting Radius	m	18,4
	Reach at Ground Level	m	12,6
	Max.Dumping Radius	m	16,3
	Max.Dumping Height	m	8,6
	Crowd Force	kN	500
	Hoist Rope Pull	kN	1000
Weight	Operational Weight	t	410
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	80
	Operating Weight per m^3	t/ m^3	41

3.2.3.3 EKG – 12

Three EKG-12 units were reviewed during the study. All had a standard bucket capacity of $12m^3$ and were commissioned in 2003, 2004 and 2005, respectively. The model is supplied with the rope type crowding mechanism, electric direct current (DC) drive, guy line supported boom and a polyspastless bucket lift mechanism.

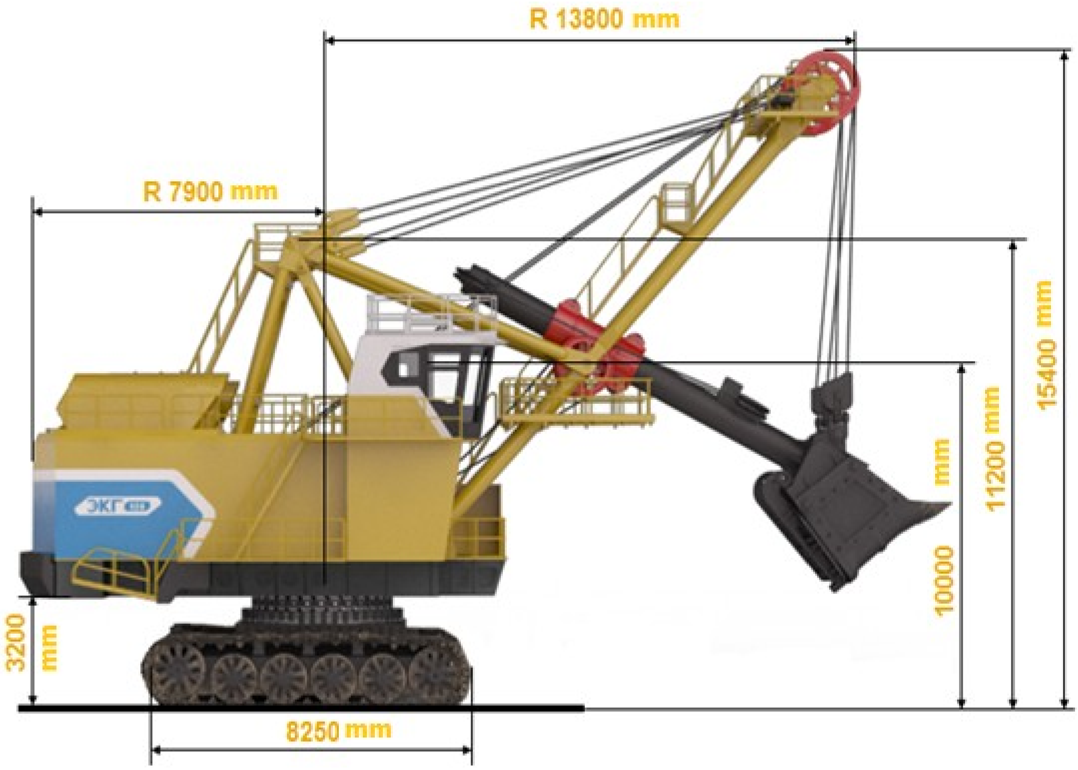

Figure 3.7 EKG-12: Basic dimensions [21]

Table 3.9 EKG-12: Main specifications

Electric	Supply Transformer Power	kVA	1000
	Operating Voltage	V	6000
Undercarriage	Overall Length of Crawler Assembly	mm	8250
	Track Pads Width	mm	1400 / 1800
Travel	Gradebility	° (%)	15 (27)
	Propel Speed	km/h	0,8
Attachment	Bucket Capacity (Standard)	m^3	12
	Bucket Capacity (Range)	m^3	6,3 ÷ 16,0
	Max.Cutting Height	m	15,0
	Max.Cutting Radius	m	18,6
	Reach at Ground Level	m	12,6
	Max.Dumping Radius	m	16,5
	Max.Dumping Height	m	9,0
	Crowd Force	kN	500
	Hoist Rope Pull	kN	1200
Weight	Operational Weight	t	410
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	83,3
	Operating Weight per m^3	t/ m^3	34,2

3.2.3.4 EKG – 15

The operation history for 3 EKG-15 machines was analyzed for the study. All shovels were of different age (10, 15, and 25 years) and were involved in waste rock excavation with only minor coal extraction.

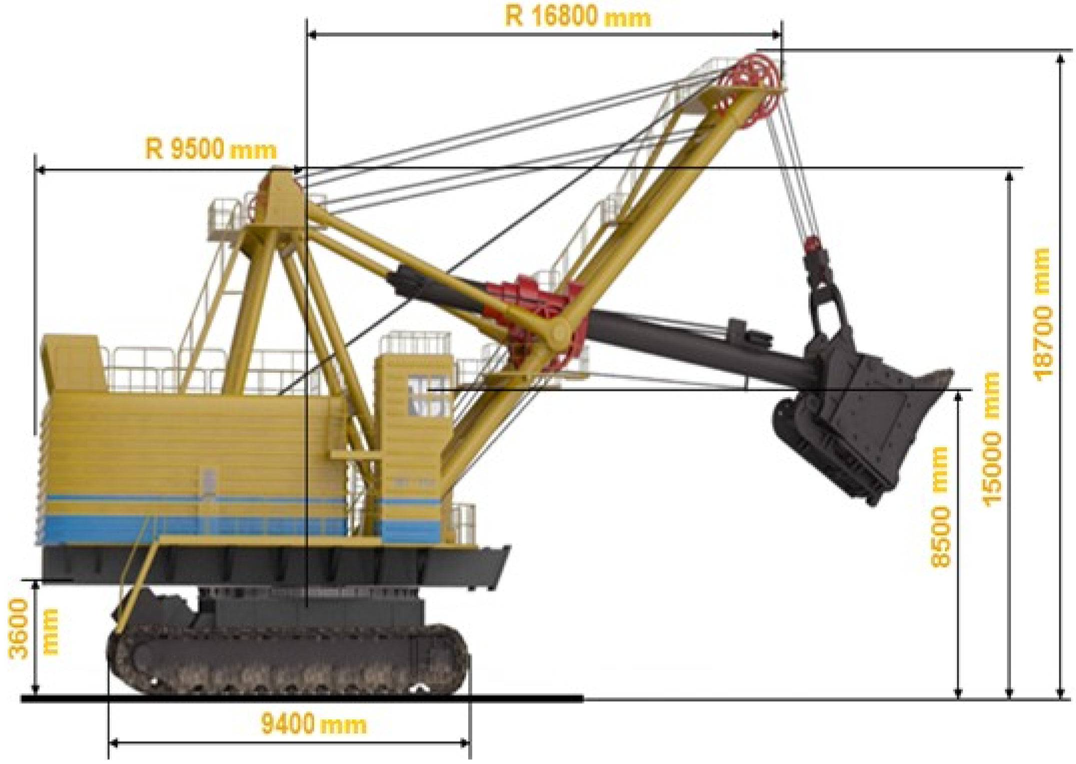

Figure 3.8 EKG-15: Basic dimensions [21]

Table 3.10 EKG-15: Main specifications

Electric	Supply Transformer Power	kVA	1250
	Operating Voltage	V	6000
Undercarriage	Overall Length of Crawler Assembly	mm	9400
	Track Pads Width	mm	1600
Travel	Gradebility	° (%)	12 (21)
	Propel Speed	km/h	0,72
Attachment	Bucket Capacity (Standard)	m^3	15
	Bucket Capacity (Range)	m^3	8,0 ÷ 18,0
	Max.Cutting Height	m	15,8
	Max.Cutting Radius	m	22,6
	Reach at Ground Level	m	15,6
	Max.Dumping Radius	m	19,5
	Max.Dumping Height	m	9,9
	Crowd Force	kN	650
	Hoist Rope Pull	kN	1500
Weight	Operational Weight	t	700
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	83,3
	Operating Weight per m^3	t/ m^3	46,7

3.2.3.5 EKG – 18

A new EKG-18 mining shovel with rack-and-pinion gear crowding mechanism was supplied to the focus mining company recently and started operating in mid-2013. Some of the machine basic dimensions and specifications are presented below.

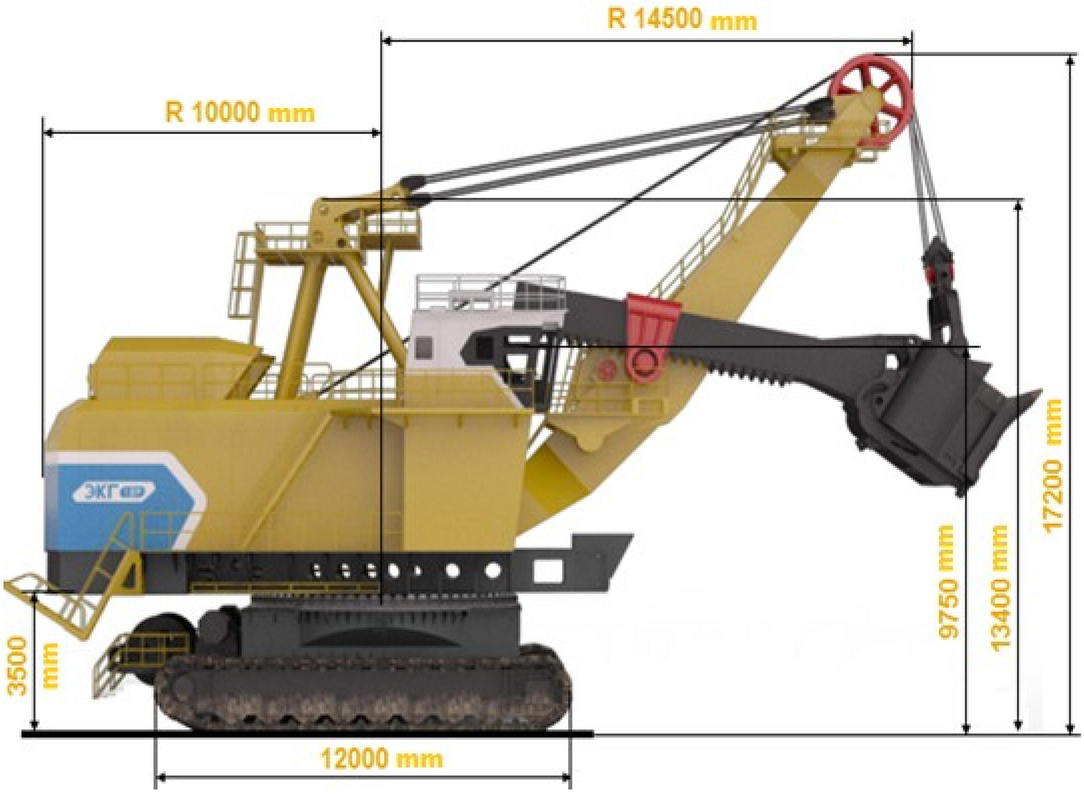

Figure 3.9 EKG-18: Basic dimensions [21]

Table 3.11 EKG-18: Main specifications

Electric	Supply Transformer Power	kVA	1250
	Operating Voltage	V	6000
Undercarriage	Overall Length of Crawler Assembly	mm	12000
	Track Pads Width	mm	1600 / 1800
Travel	Gradebility	° (%)	15 (27)
	Propel Speed	km/h	0,72
Attachment	Bucket Capacity (Standard)	m^3	18
	Bucket Capacity (Range)	m^3	16,0 ÷ 26,0
	Max.Cutting Height	m	16,0
	Max.Cutting Radius	m	21,7
	Reach at Ground Level	m	15,5
	Max.Dumping Radius	m	18,7
	Max.Dumping Height	m	10,2
	Crowd Force	kN	750
	Hoist Rope Pull	kN	1700
Weight	Operational Weight	t	710
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	69,4
	Operating Weight per m^3	t/ m^3	39,4

3.2.3.6 EKG – 20

Among the 4 machines here under consideration two EKGs – 20 started their work life in 1988 whereas another two – in 1990. It is worth noting that three of these pieces of equipment are still in use. They excavate mostly blasted waste rock; predominately 80% to 90% of sandstone and about 10% to 20% of siltstone.

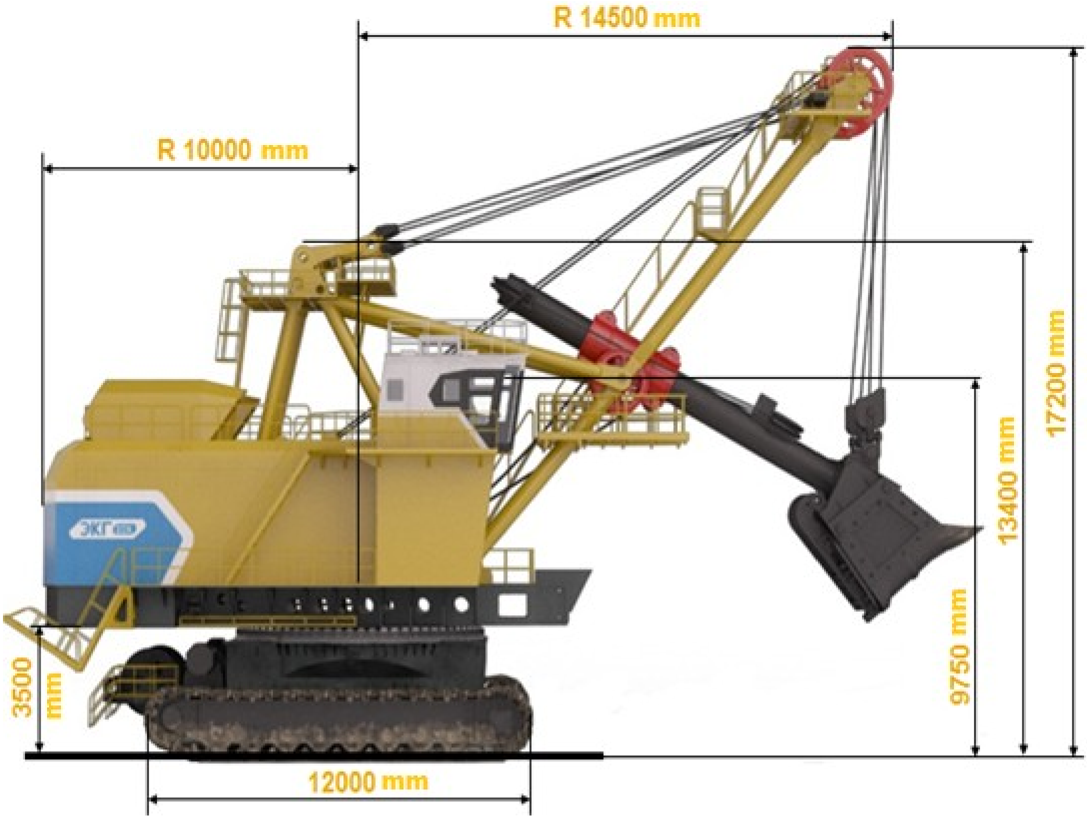

Figure 3.10 EKG-20: Basic dimensions [21]

Table 3.12 EKG-20: Main specifications

Electric	Supply Transformer Power	kVA	1250
	Operating Voltage	V	6000
Undercarriage	Overall Length of Crawler Assembly	mm	12000
	Track Pads Width	mm	1600 / 1800
Travel	Gradebility	° (%)	15 (27)
	Propel Speed	km/h	1,0
Attachment	Bucket Capacity (Standard)	m^3	20
	Bucket Capacity (Range)	m^3	18,0 ÷ 28,0
	Max.Cutting Height	m	17,3
	Max.Cutting Radius	m	22,6
	Reach at Ground Level	m	16,0
	Max.Dumping Radius	m	19,4
	Max.Dumping Height	m	11,2
	Crowd Force	kN	750
	Hoist Rope Pull	kN	1700
Weight	Operational Weight	t	700
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	62,5
	Operating Weight per m^3	t/ m^3	35,0

3.2.4 P&H Rope Shovels

3.2.4.1 General Remarks

For the study six P&H electric cable shovels was used. Bucket capacities of those excavators ranged from $16m^3$ (P&H 2300) to $33m^3$ (P&H 2800). The oldest started operating in 1983, whereas the newest one was commissioned in late 2012. With EKG shovels, P&H shovels are used principally for blasted waste rock excavation.

3.2.4.2 P&H 2300

Four out of six P&H machines studied in this work are modifications of the P&H 2300.

The newest shovel with a bucket of $16m^3$ commissioned in 2012 is the latest variant of the P&H 2300 model – P&H 2300XPC, with a 20m3 dipper. Two P&H 2300 machines started their work life at the mining site between 1983 and late 1984 and were written off with twenty-four and twenty-five years life.

Some of the basic dimensions and main specifications of the model are illustrated below in Figure 3.10 and Table 3.13.

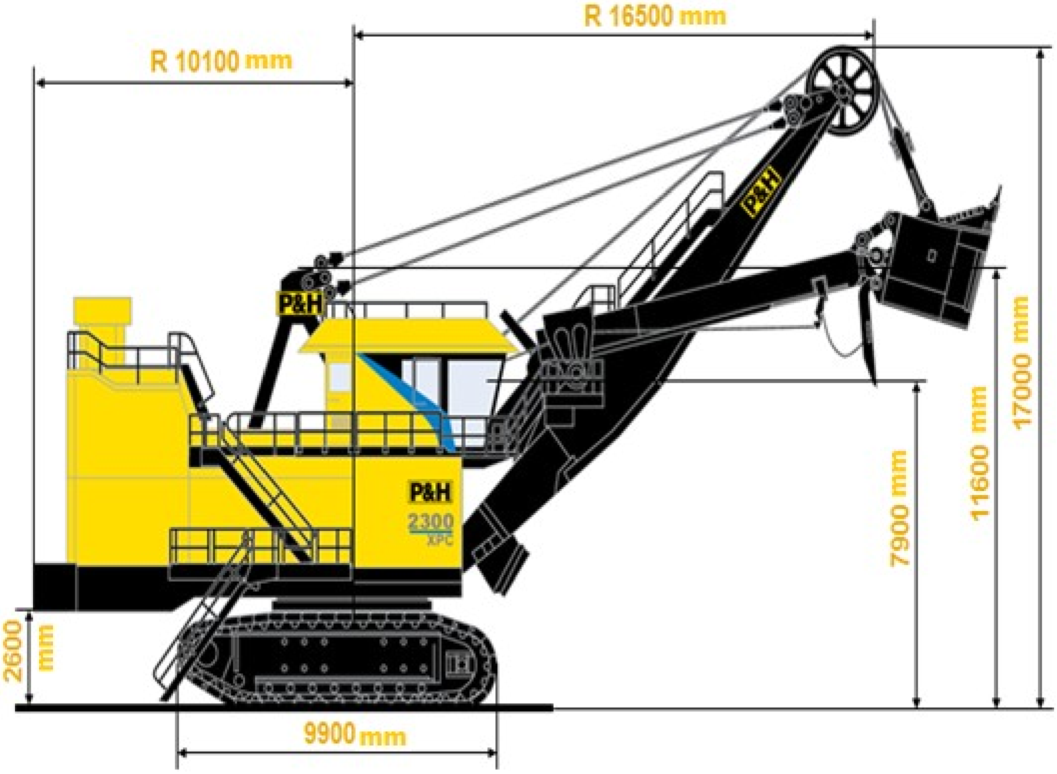

Figure 3.11 P&H 2300: Basic dimensions [22]

Table 3.13 P&H 2300: Main specifications

Electric	Power Output	kW	2 x 1860
	Frequency	Hz	50 / 60
	Operating Voltage	V	3300, 5000, 6000 of 7200 – for 50 Hz 4160 or 6000 – for 60 Hz
Undercarriage	Overall Length of Crawler Assembly	mm	9900
	Track Pads Width	mm	1321 / 1778
Travel	Gradebility	° (%)	10 (17)
	Propel Speed	km/h	1,25
Attachment	Bucket Capacity (Standard)	m^3	25,5
	Bucket Capacity (Range)	m^3	18,3 ÷ 27,8
	Max.Cutting Height	m	13,5
	Max.Cutting Radius	m	21,3
	Reach at Ground Level	m	14,2
	Max.Dumping Radius	m	19,0
	Max.Dumping Height	m	8,5
Weight	Operational Weight	t	744
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	72,9
	Operating Weight per m^3	t/ m^3	30,3

3.2.4.3 P&H 2800

In 2006 two P&H 2800 units were supplied to the mining company. Both these machines are still in use and have an operational life time approaching 50,000 hours. They are equipped with 33m^3 dippers and excavate fine-grained and medium-grained blasted sandstones and, to a lesser extend, siltstones.

The basic dimensions and main specifications of the P&H 2800XPC model are presented in Figure 3.11 and Table 3.14.

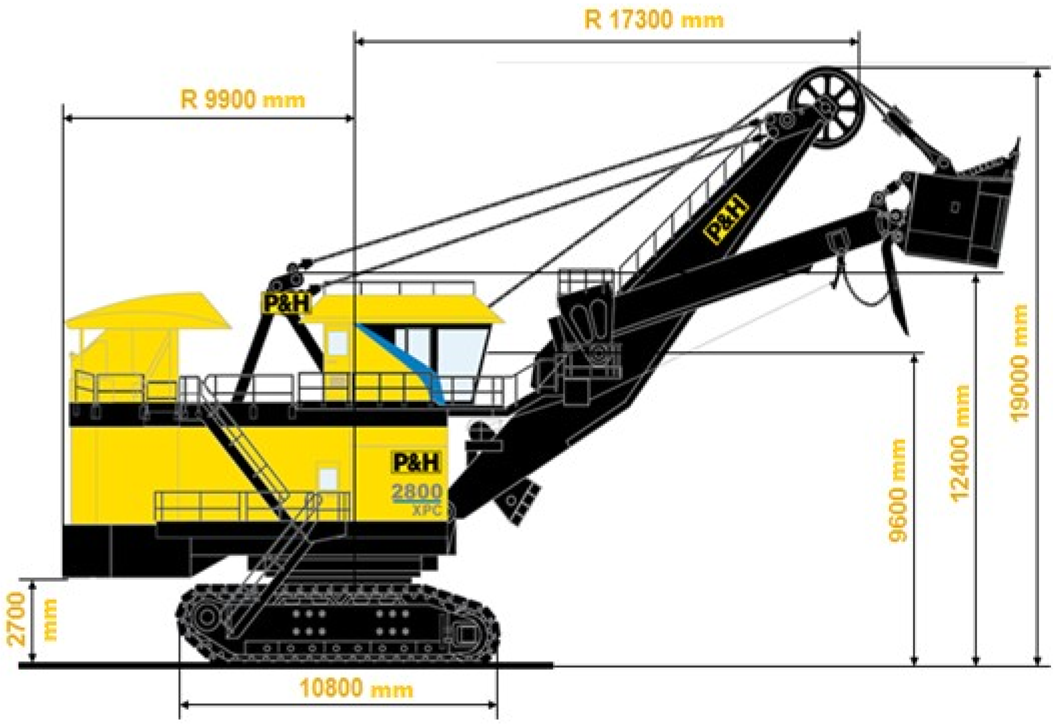

Figure 3.12 P&H 2800: Basic dimensions [23]

Table 3.14 P&H 2800: Main specifications

Electric	Power Output	kW	2 x 1860
	Frequency	Hz	50 / 60
	Operating Voltage	V	5000, 6000 of 7200 – for 50 Hz 4160 or 6000 – for 60 Hz
Undercarriage	Overall Length of Crawler Assembly	mm	10800
	Track Pads Width	mm	1422 / 1829
Travel	Gradebility	° (%)	10 (17)
	Propel Speed	km/h	1,25
Attachment	Bucket Capacity (Standard)	m^3	32,7
	Bucket Capacity (Range)	m^3	26,8 ÷ 36,6
	Max.Cutting Height	m	16,6
	Max.Cutting Radius	m	24,2
	Reach at Ground Level	m	16,2
	Max.Dumping Radius	m	21,8
	Max.Dumping Height	m	9,1
Weight	Operational Weight	t	1079
Comparison Ratio	Electric Motor output per m^3	kW/ m^3	56,8
	Operating Weight per m^3	t/ m^3	32,9

3.2.5 Hydraulic Excavators

3.2.5.1 General Remarks

Ten hydraulic excavators were taken into consideration for the analysis, of which there were four different models from two manufacturers; PC 2000, PC 4000, and PC 5500 from Komatsu and the R 994 from Liebherr. Smaller shovels such as the PC 2000 and R 994 were provided with diesel main drives and excavated waste rock and coal. PC 4000 and PC 5500, however, were electrically driven and were predominately involved in waste rock excavation.

Since an overview of the PC 4000 and PC 5500 has been given earlier, below is information on the Komatsu PC 2000 and Liebherr R 994 only.

3.2.5.2 PC 2000

Four units of this model were operating at the mine site. All were relatively young machines with commissioning dates from late 2011 and 2012 and operational lives of about 14 to 15 and 23 to 24 thousand hours. All machines were equipped with backhoe attachments of bucket capacity $10m^3$. They predominately excavated fragmented coal into heavy trucks.

Some of the basic dimensions and main specifications of this model are given in Figure 3.13 and Table 3.15.

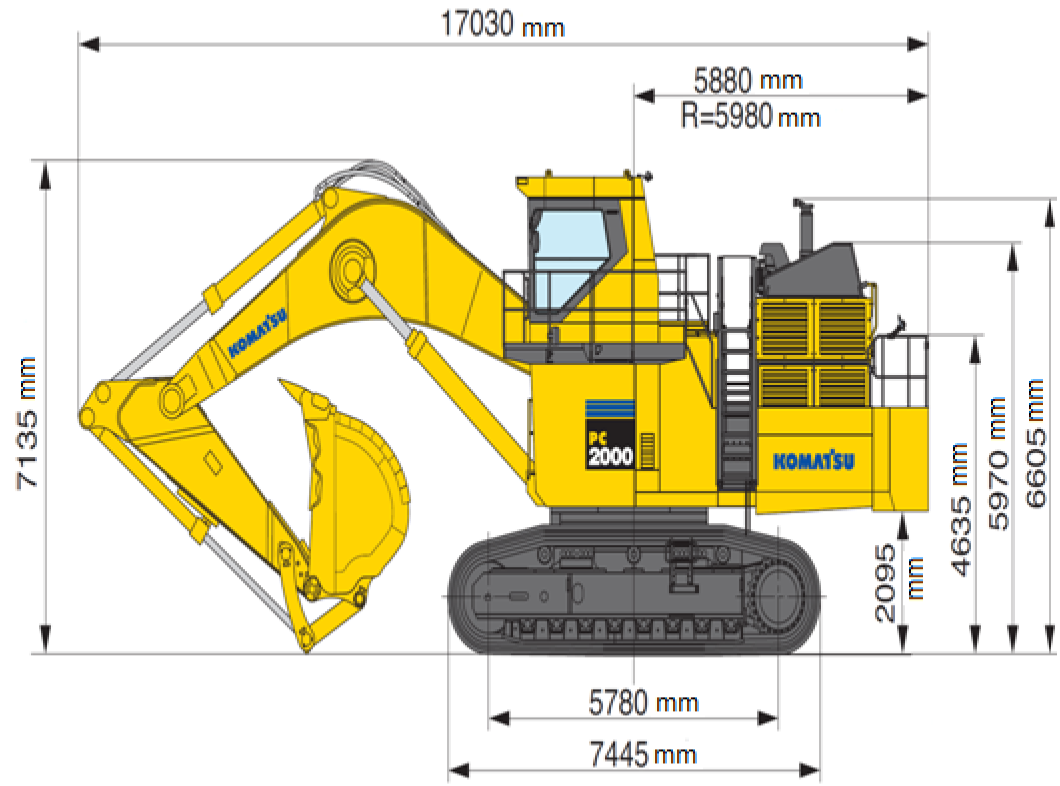

Figure 3.13 PC 2000: Basic dimensions [24]

Table 3.15 PC 2000: Main specifications

Undercarriage	Overall Length of Crawler Assembly	mm	7445	
	Crawler Length (Centres)	mm	5780	
	Track Pads Width	mm	810 / 1010	
Travel	Gradebility	° (%)	33 (65)	
	Propel Speed	km/h	2,7	
Attachment			Front Shovel	Backhoe
	Boom Length	m	5,95	8,7
	Stick Length	m	4,45	3,9
	Bucket Capacity (Standard)	m^3	11,0	12,0
	Standard Cutting Width	mm	3190	2790
	Max.Cutting Height	m	14,5	13,4
	Max.Dumping Height	m	9,7	8,7
	Max.Digging Depth	m	3,2	9,2
	Max.Cutting Reach	m	13,2	15,8
	Reach at Ground Level	m	11,9	15,3
	Min. Crowd Distance	m	7,1	-
Weight	Operational Weight	t	195	200
Swing	Swing Speed	rpm	4,8	
	Tail swing	mm	5980	
Comparison Ratio	Operating Weight per m^3	t/ m^3	17,7	16,6
Diesel Drive	Engine - Make		KOMATSU	
	Engine - Model		SSA12V140E-3	
	Rated Power (SAE)	kW	728	
	Engine Revolution	rpm	1800	
Hydraulic System	Max. Flow – attachment, swing, travel	l/min.	2317	
	Max. Flow – fan drive	l/min	324	

3.2.5.3 R 994

Four R 994 backhoes started operating at the mine site in 2007. All the machines had buckets of $11m^3$ and excavated loosened coal.

In Figure 3.13 and Table 3.16 the basic dimensions and main specifications of the R 994 are shown.

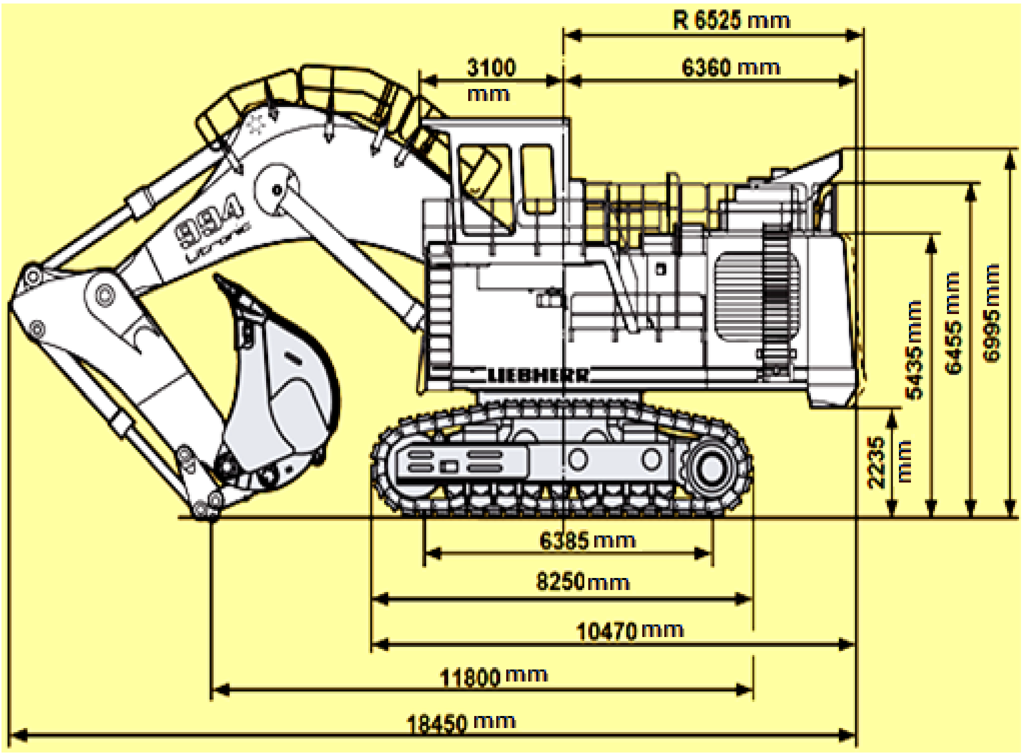

Figure 3.14 R 994: Basic dimensions [25]

Table 3.16 R 994: Main specifications

Undercarriage	Overall Length of Crawler Assembly	mm	8250	
	Crawler Length (Centres)	mm	6385	
	Track Pads Width	mm	850	
Travel	Gradebility	° (%)	n/a	
	Propel Speed	km/h	3,0	
Attachment			Front Shovel	Backhoe
	Bucket Capacity (Standard)	m^3	18,0	18,0
	Bucket Capacity Range	m^3	15,3÷18.0	15,3÷18.0
	Standard Cutting Width	mm	4100	3400
	Max.Cutting Height	m	17,0	15,4
	Max.Dumping Height	m	11,2	10,2
	Max.Digging Depth	m	3,6	9,5
	Max.Cutting Reach	m	14,5	17,0
	Reach at Ground Level	m	13,75	16,3
	Crowd / Tear-out Force	kN	1300	880
	Break-out Force	kN	1060	1020
Weight	Operational Weight	t	300	296
Swing	Swing Speed	rpm	3,7	
	Tail swing	mm	6525	
Comparison Ratio	Operating Weight per m^3	t/ m^3	16,6	16,4
Engine	Engine - Model		QSK45	
	Rated Power (SAE)	kW	1120	
	Engine Revolution	rpm	1800	
Hydraulic System	Max. Flow – attachment	l/min.	4 x 754	
	Max. hydraulic pressure – attachment	bar	320	
	Max. Flow – swing	l/min.	2 x 390	
	Max. hydraulic pressure – swing	bar	350	

CHAPTER 4

COMPARISON PARAMETERS APPLIED TO THE DISCUSSED MINING SHOVELS

4.1 Introduction

In this chapter mining shovels discussed earlier are compared on the base of a range of performance parameters as well as estimated cost of possession of a machine in regards to its productivity. Among the performance parameters ones of the greatest interests for the study are as follows: physical availability; productivity; and expenditures related to the possession and servicing of a machine.

During the analysis the total amount of 4,731 monthly records (which are equal to about 3,400,000 calendar hours of operation history) in regards to performance of 136 pieces of HEXs' and RSs' were revised. All the electric cable shovels under the examination operates at a coal mine, whereas application distribution among the hydraulic excavators is as it is shown in Figure 4.1

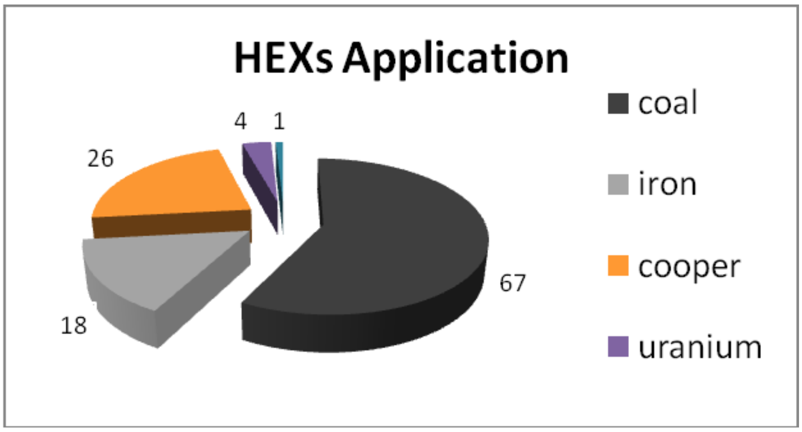

Figure 4.1 Proportion of examined hydraulic excavators by ore mined

The above parameters were determined. For each shovel model by application (ore or coal) and attachment design (“front shovel” (FS) or “backhoe” (BH)), average values for shovels were calculated. As a next step, the arithmetic “mean” for BH and FS hydraulic excavators as well as for rope shovels were computed for each machine type regardless of number of shovels and shovel manufacturer. The “backhoe average” and the “front shovel average” were finally taken to count a hydraulic excavators’ “grand average”.

In this study such performance parameters as physical availability and production were analyzed on a monthly basis and results presented as average monthly values.

4.2 Investigated Parameters

4.2.1 Physical Availability

“Availability is a performance criterion for systems not removed from operations for maintenance purposes, which accounts for both the reliability and maintainability properties of a component or system. Availability can be defined as “a percentage measure of the degree to which machinery and equipment is in an operable state at the point in time when it is needed.” [26]

Availability has different meanings and can be calculated in various ways. In this study, however, mining shovel availability was calculated using the following formula and definition adopted by Komatsu Mining Germany (KMG) [27]:

$$\boldsymbol{Machine\ availability} = \frac{(\boldsymbol{Hours\ worked} - \boldsymbol{Hours\ down\ for\ repair})}{\boldsymbol{Hours\ worked}} * \mathbf{100\%} \quad (4.1)$$

“Hours worked” and “Hours down for repair” are defined as follows:

“Hours worked” is equal to total calendar hours, unless lesser work hours had been scheduled by a mine.

“Hours down for repair” includes:

a. Scheduled preventive maintenance and servicing

b. Mechanical repairs

c. Electrical repairs

This term calculation results in a "physical availability" (PA), a term which the author finds reasonable and uses in this thesis.

Based the calculations, an average physical availability for hydraulic excavators in coal mining at different locations around the globe changes from 95.8 to 66.1 per cent with a total global mean of 89.4% for operational lives of 60,000 hours.

Rope shovels within an operating period of 60,000 hours indicate lower indices which constitute a PA global mean value of 80.3%. However, since all rope shovels investigated operate in a single coal mine location, it was decided to compare these figures with ones belonging to the 10 large hydraulic excavators operating at the same site. The gap between RS and HEX working at the same mine was small. With a maximal operational life of 48,000 hours hydraulic excavators indicated an average physical availability of 83.7%, whereas cable shovels had a value of 81.6% for the same period.

All data are reflected in tables 4.1 to 4.3. Actual values obtained for each individual piece of equipment are given in Appendix A.

Table 4.1 Hydraulic excavators' common physical availability values

HMR (Thousand hours)

BH HEXs 0 6 12 18 24 30 36 42 48 54 60

Make		Physical Availability (%)									
		HEXs - backhoe									
Liebherr	R994	92,2	91,7	86,9	77,3	82,6	82,5	80,3	76,1		
KOMATSU	PC 2000	94,5	89,7	88,5	87,6						
	PC 3000	97,3	96,2	95,1	92,6	92,8	88,1				
	PC 4000	95,0	90,6	89,3	89,1	89,8	90,8	91,0	93,2		
	PC 5500	95,8	93,4	90,4	94,9		88,9	90,8	91,0	92,6	
KOMATSU Average		*95,7*	*92,5*	*90,8*	*91,1*	*91,3*	*89,3*	*90,9*	*92,1*	*92,6*	
Backhoes Average		*95,0*	*92,3*	*90,0*	*88,3*	*88,4*	*87,6*	*87,4*	*86,8*	*92,6*	
FS HEXs											
		HEXs - front shovel									
KOMATSU	PC 4000	95,7	91,6	81,5	73,7	66,1	86,7				
	PC 5500	94,5	92,7	78,0	76,1						
	PC 8000	95,0	91,4	90,9	90,4	89,3	89,4	89,7	89,2	88,6	91,0
Front Shovels Average		*95,1*	*91,9*	*89,8*	*88,5*	*81,8*	*83,3*	*89,7*	*89,2*	*88,6*	*91,0*
GRAND AVERAGE		95,0	92,1	89,9	88,4	85,1	85,4	88,5	88,0	90,6	91,0
CUMULATIVE AVERAGE		95,0	93,6	92,3	91,4	90,1	89,3	89,2	89,1	89,2	89,4

Table 4.2 Rope shovels' physical availability values

HMR (Thousand hours)

RS 0 6 12 18 24 30 36 42 48 54 60

Make		Physical Availability (%)									
		RSs									
OMZ	EKG-10		86,2	87,3	91,7	79,5	85,7	85,2	82,6	75,7	
	EKG-12			82,3	86,8	82,0	80,3	74,6	75,0	76,1	69,2
	EKG-15				84,0	81,9	75,5	74,0	64,6	86,1	
	EKG-18	86,6	87,0								
OMZ Average		*86,6*	*86,6*	*84,8*	*87,5*	*81,1*	*80,5*	*77,9*	*74,1*	*79,3*	*69,2*
JOY	P&H 2300 XP			73,9	67,7	65,3	59,3				
	P&H 2300 XPC	91,8	88,4	81,9							
	P&H 2800	91,8	88,1	86,6	84,3	83,9	86,5	82,0	80,8	82,4	
JOY Average		*91,8*	*88,3*	*80,8*	*76,0*	*74,6*	*72,9*	*82,0*	*80,8*	*82,4*	
GRAND AVERAGE		90,5	87,6	82,1	81,8	77,9	76,7	79,6	76,8	80,5	69,2
CUMULATIVE AVERAGE		90,5	89,0	86,7	85,5	84,0	82,8	82,3	81,6	81,5	80,3

Table 4.3 Physical availability values of hydraulic excavators working at the site “A”

HMR

HEXs (Same mine as RSs) 0 6 12 18 24 30 36 42 48 54 60

Make	Physical Availability (%)									
	HEXs (Same mine as RSs)									
Liebherr R994	92,2	91,7	86,9	77,3	82,6	82,5	80,3	76,1		
KOMATSU PC 2000	94,5	89,7	88,5	87,6						
PC 4000	95,7	91,6	81,5	73,7	66,1	86,7				
PC 5500	94,5	92,7	78,0	76,1						
KOMATSU Average	*94,9*	*91,3*	*82,7*	*79,1*	*66,1*	*86,7*				
GRAND AVERAGE	94,2	91,4	83,7	80,9	79,3	83,3	80,3	76,1		
CUMULATIVE AVERAGE	94,2	92,8	89,8	87,6	85,9	85,5	84,8	83,7	0,0	0,0

In addition to the units of equipment at the coal mining site, there as information for 10 rope shovels with an operational lifespan of 60,000 to 150,000 hours. Physical availability values for those machines are given in Table 4.4 and the cumulative average availability changes for all categories of shovel shown in Figure 4.2.

Table 4.4 Physical availability of rope shovels with operational lifespan exceeding 60.000 hours

HMR (Thousand hours)

RS HMR > 60.000 hrs		60	66	72	78	84	90	96	102	108	114	120	126	132	138	144	150
Make		**Physical Availability (%)**															
		RSs															
OMZ	**EKG-10**								**83,6**	**80,8**	**77,1**	**69,6**	**82,2**	**77,0**	**73,2**	**80,1**	
	EKG-12	**82,3**															
	EKG-12,5						**71,4**	**87,0**	**86,7**	**79,0**	**83,2**	**69,3**	**83,6**				
	EKG-15					**82,0**	**78,8**	**81,5**	**84,5**	**86,1**	**84,4**	**78,0**					
	EKG-20			**77,8**	**77,8**	**80,1**	**72,1**	**71,0**	**76,0**	**72,7**	**76,6**	**81,1**	**71,1**	**85,3**			
OMZ Average				***77,8***	***77,8***	***81,1***	***74,1***	***79,8***	***82,7***	***79,7***	***80,3***	***74,5***	***79,0***	***81,2***	***73,2***	***80,1***	
JOY	**P&H 2300**												**73,0**	**74,1**	**72,4**	**61,1**	
GRAND AVERAGE		82,3		77,8	77,8	81,1	74,1	79,8	82,7	79,7	80,3	74,5	76,6	77,6	72,7	67,4	
CUMULATIVE AVERAGE		**80,4**	**80,4**	**80,2**	**80,0**	**80,1**	**79,7**	**79,7**	**79,9**	**79,9**	**79,9**	**79,6**	**79,5**	**79,4**	**79,1**	**78,6**	

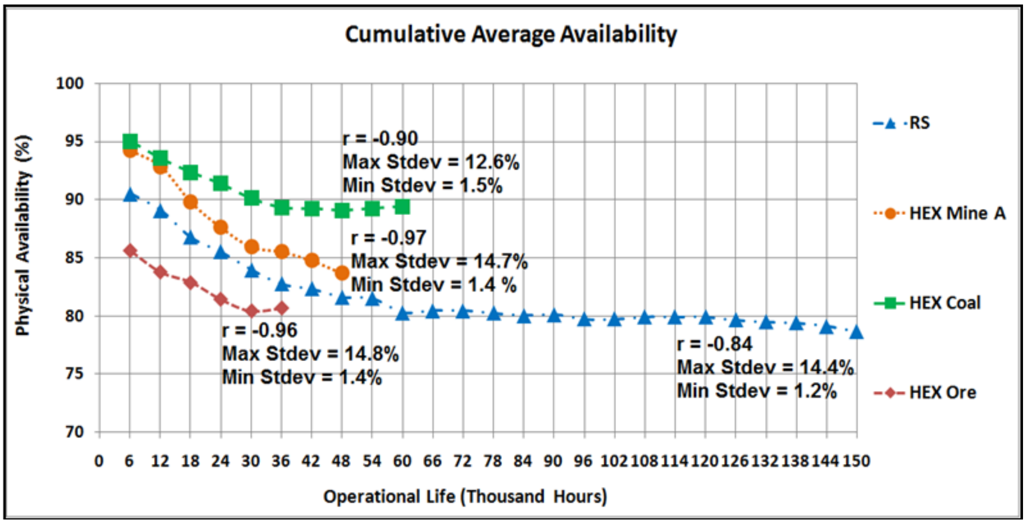

Figure 4.2 Cumulative average physical availability change of mining shovels in relation to their operation lifetime.

It is worth noticing that, although cumulative average physical availability values differ for all the examined groups of mining shovels, their regression trends up to 30,000 hours are similar (see Figures 4.2 to 4.3 and Tables 4.1 to 4.5). During the initial 5 years of operation cumulative average physical availability decrease by 1.6 per cent annually for all groups. After 30,000 hours hydraulic excavators from ore and coal mines (except of Mine A) indicate stabilization of cumulative average physical availability, whereas excavation equipment (both HEX and RS) from Mine A continues to display a slow decline of 0.8 per cent annually in cumulative average physical availability.

Availability of the hydraulic machines in iron ore and cooper mining are essentially 5 to 6 per cent less than those working in coal mines; however, cumulative average availability change with time is similar (Figure 4.3).

Detailed information in regard to PA values of shovels from metal mines is summarized in Table 4.5.

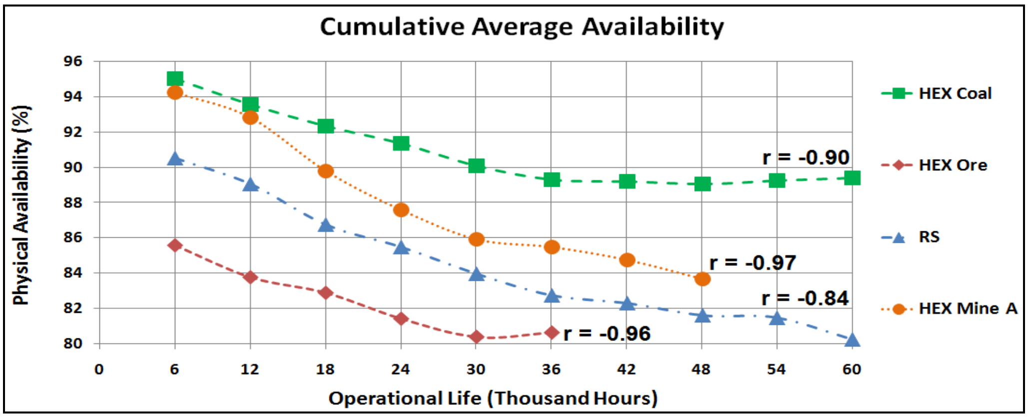

Figure 4.3 Cumulative average physical availability changes of RSs and HEXs in coal and metal mines in relation to their operation lifetime.

Table 4.5 Physical availability values of hydraulic excavators working in metal mines.

	HMR (Thousand hours)										
BH HEXs	0	6	12	18	24	30	36	42	48	54	60
Make	Physical Availability (%)										
	HEXs - backhoe										
KOMATSU PC 4000	90,9	81,0	87,2								
PC 5500	82,7	80,9	79,6	80,8	71,3	75,3					
PC 8000	84,4										
Backhoes Average	*86,0*	*81,0*	*83,4*	*80,8*	*71,3*	*75,3*					
FS HEXs											
	HEXs - front shovel										
KOMATSU PC 4000	79,4	81,3	81,6								
PC 5500	88,8	84,4	82,2	83,7	81,2	88,7	82,8	92,2	90,6	89,4	
PC 8000	87,2	83,2	72,6	62,7							
Front Shovels Average	*85,1*	*83,0*	*78,8*	*73,2*	*81,2*	*88,7*	*82,8*	*92,2*	*90,6*	*89,4*	
GRAND AVERAGE	85,6	82,0	81,1	77,0	76,3	82,0	82,8	92,2	90,6	89,4	
CUMULATIVE AVERAGE	85,6	83,8	82,9	81,4	80,4	80,6	81,0	82,4	83,3	83,9	

4.2.2 Production

In order to determine and compare productivity of mining shovels, a production history of 41 hydraulic excavators and 10 rope shovels of various size and bucket capacity and of operational age up to 60,000 working hours was compiled. This history includes 2,060 monthly records of different HEXs and 921 records of RSs. Additionally, 587 records for ten older rope shovels (with operational life more than 60,000 hours) were included in the analysis.

In some design practices at surface mines a specific index representing proportion of volume of material annually excavated by a mining shovel to one cubic meter of its bucket capacity (m^3 per year / $1m^3$ of bucket capacity) was used [29]. This indicator allows performing a productivity comparison between all types of excavators regardless of bucket size. For this study, however, the average volume of material excavated monthly had used in the calculation (m^3 per month / $1m^3$ of bucket capacity).

Results of these calculations indicate an average excavated target by hydraulic excavator bucket capacity fluctuates from $9,595m^3$ to $22,954m^3$. The cumulative average for the total period is $16,760m^3$. The cumulative average monthly hours are 532. These numbers yield $31.5m^3$ per hour per $1m^3$ of bucket capacity as the cumulative average production rate during the 60,000 hour period.

The equivalent rope shovels analysis shows that the productivity mean is $14,383m^3$ ($4,623m^3$ to $25,588m^3$). The average monthly available hours for rope shovels is somewhat less than hydraulic machines at 467 hours. Or 30.8m^3 per hour per 1m^3 of bucket capacity.

It should be noted here that to calculate a "GRAND AVERAGE" value between 18,000 and 36,000 for PC 4000 and PC 5500 working in Mine "A" a weighted mean depending of the number of units representing each HEX model was used. The decision mentioned above was made in order to avoid an overestimation of low indices (which are likely to be a consequence of contradictory information provided in reports) in the overall assessment and because there were only single pieces of equipment representing each model.

All data is presented more closely below in Tables 4.6 to 4.8. Actual values obtained for each individual piece of equipment are given in Appendix B.

Cumulative average production (for 30,000 operational hours) of hydraulic front shovels in iron ore is 9% less than ones from collieries (Table 4.9).

Table 4.6 Hydraulic excavators' common productivity

BH HEXs		HMR (Thousand hours) 0	6	12	18	24	30	36	42	48	54	60
Make		Production (m3 per month / 1m3 of bucket capacity)										
HEXs - backhoe												
Liebherr	R994	17139	14913	16210	15041	16009	15096	15865	13561			
	uptime hours	595	514	551	508	546	506	515	445			
KOMATSU	PC 2000	22954	21041	20928	19924							
	uptime hours	606	588	573	571							
	PC 4000	18027	17251	15204	16407	14896	15592	13521	14378			
	uptime hours	598	607	557	586	574	565	498	514			
	PC 5500		15469									
	uptime hours		558									
KOMATSU Average		*20491*	*17920*	*18066*	*18166*	*14896*	*15592*	*13521*	*14378*			
	uptime hours	*602*	*584*	*565*	*578*	*574*	*565*	*498*	*514*			
Backhoes Average		*19373*	*17168*	*17447*	*17124*	*15453*	*15344*	*14693*	*13970*			
	uptime hours	*599*	*566*	*560*	*555*	*560*	*536*	*506*	*479*			
FS HEXs												
HEXs - front shovel												
KOMATSU	PC 4000	17881	11820	19584	10461	7331	4015					
	uptime hours	484	475	441	389	338	343					
	PC 5500	13315	15097	9595	6264							
	uptime hours	589	586	415	293							
	PC 8000	21289	20522	19499	18609	18398	17180	17030	15291	18000	16468	
	uptime hours	578	552	546	569	555	520	515	485	538	490	
Front Shovels Average		*17495*	*15813*	*18983*	*17242*	*17607*	*16239*	*17030*	*15291*	*18000*	*16468*	
	uptime hours	*550*	*538*	*534*	*545*	*540*	*507*	*515*	*485*	*538*	*490*	
GRAND AVERAGE		18434	16491	18215	17183	16530	15792	15862	14630	18000	16468	
	uptime hours	575	552	547	550	550	521	511	482	538	490	
CUMULATIVE AVERAGE		18434	17462	17713	17581	17371	17107	16930	16642	16793	16760	
	uptime hours	575	563	558	556	555	549	544	536	536	532	

In addition to the shovels mentioned above, information concerning production of 10 rope shovels with operational life between 60,000 and 150,000 hours was also studied with the results summarized in Table 4.10.

Table 4.7 Rope shovels' productivity

HMR (Thousand hours)

RS 0 6 12 18 24 30 36 42 48 54 60

Make		Production (m3 per month / 1m3 of bucket capacity)									
		RSs									
OMZ	**EKG-10**	**14350**	**14720**	**16955**	**17306**	**16510**	**19316**	**18441**	**14021**	**12049**	
	uptime hours	549	510	563	595	522	591	549	534	452	
	EKG-12	**13505**	**18208**	**17473**	**19319**	**16228**	**17624**	**14040**	**16705**	**16460**	**13048**
	uptime hours	451	546	519	562	481	504	434	495	490	390
	EKG-15	**12422**	**15372**	**12928**	**11774**	**11389**	**11365**	**10570**	**9307**	**4222**	**14149**
	uptime hours	438	504	462	495	402	436	440	348	381	385
	EKG-18	**13514**	**13583**								
	uptime hours	471	537								
	EKG-20								**4623**	**10665**	**10683**
	uptime hours								214	439	422
OMZ Average		*13448*	*15471*	*15785*	*16133*	*14709*	*16102*	*14350*	*11164*	*10849*	*12627*
	uptime hours	*477*	*524*	*515*	*551*	*468*	*510*	*474*	*398*	*440*	*399*
JOY	**P&H 2300 XP**	**15758**	**19892**	**10153**	**7462**	**8197**	**8733**				
	uptime hours	481	503	430	383	395	362				
	P&H 2300 XPC	**25588**	**21604**	**13854**							
	uptime hours	561	495	447							
	P&H 2800	**19603**	**21027**	**17395**	**16973**	**19007**	**19409**	**18734**	**13548**	**11791**	
	uptime hours	573	549	482	484	528	526	502	391	425	
JOY Average		*20316*	*20841*	*13801*	*12217*	*13602*	*14071*	*18734*	*13548*	*11791*	
	uptime hours	*538*	*515*	*453*	*433*	*462*	*444*	*502*	*391*	*425*	
GRAND AVERAGE		**16391**	**17772**	**14793**	**14567**	**14266**	**15289**	**15446**	**11641**	**11037**	**12627**
	uptime hours	**503**	**521**	**484**	**504**	**466**	**484**	**481**	**396**	**437**	**399**
CUMULATIVE AVERAGE		**16391**	**17082**	**16319**	**15881**	**15558**	**15513**	**15504**	**15021**	**14578**	**14383**
	uptime hours	**503**	**512**	**503**	**503**	**495**	**493**	**492**	**480**	**475**	**467**

Table 4.8 Productivity of hydraulic excavators operating at site “A”

HMR

HEXs (Same mine as RSs)		0–6	6–12	12–18	18–24	24–30	30–36	36–42	42–48	48–54	54–60
Make		Production (m3 per month / 1m3 of bucket capacity)									
HEXs (Same mine as RSs)											
Liebherr	**R994**	**17139**	**14913**	**16210**	**15041**	**16009**	**15096**	**15865**	**13561**		
	uptime hours	595	514	551	508	546	506	515	445		
KOMATSU	**PC 2000**	**22954**	**21041**	**20928**	**19924**						
	uptime hours	606	588	573	571						
	PC 4000	**11792**	**11820**	**8873**	**10461**	**7331**	**4015**				
	uptime hours	484	475	441	389	338	343				
	PC 5500	**13315**	**15097**	**9595**	**6264**						
	uptime hours	589	586	415	293						
KOMATSU Average		*16020*	*15986*	*17030*	*16070*	*7331*	*4015*				
	uptime hours	*1679*	*1649*	*1430*	*1253*	*338*	*343*				
GRAND AVERAGE		16300	15718	16702	15658	14273	12880	15865	13561		
	uptime hours	568	541	495	440	442	425	515	445		
CUMULATIVE AVERAGE		16300	16009	16240	16094	15730	15255	15342	15120		
	uptime hours	568	554	535	511	497	485	489	484		

Table 4.9 Productivity of hydraulic excavators operating at an iron ore mine

HMR (Thousand hours)

FS HEXs	0–6	6–12	12–18	18–24	24–30	30–36	36–42	42–48	48–54	54–60
Make	Production (m3 per month / 1m3 of bucket capacity)									
HEXs -front shovel										
KOMATSU PC 5500	17329	16734	16312	14537	15572					
CUMULATIVE AVERAGE	17329	17031	16792	16228	16097					

Table 4.10 Productivity of rope shovels with operational lifespan exceeding 60.000 hours

HMR (Thousand hours)

RS HMR > 60.000 hrs		60	66	72	78	84	90	96	102	108	114	120	126	132	138	144	150
Make				Production (m3 per month / 1m3 of bucket capacity)													
RSs																	
OMZ	EKG-10							10600	14970	13093	12339	11854	15498	13322	14092	13511	
	uptime hours							434	544	494	455	483	519	508	471	527	
	EKG-12	15847															
	uptime hours	475															
	EKG-12,5						12000	14436	9134	17126	17674	13623	10817				
	uptime hours						447	461	334	473	473	419	344				
	EKG-15	11139	11431	11467	10739	10077	9604	5267	11547	12506	8742	8420					
	uptime hours	409	408	462	412	410	384	340	444	491	377	355					
	EKG-20	10596	12483	12281	11289	11106	12310	11680	10375	10250	14318	13096	9393	10378			
	uptime hours	357	424	450	426	424	463	438	409	433	505	504	428	482			
OMZ Average		*12527*	*11957*	*11874*	*11014*	*10592*	*11305*	*10496*	*11506*	*13244*	*13268*	*11748*	*11903*	*11850*	*14092*	*13511*	
	uptime hours	*414*	*416*	*456*	*419*	*417*	*432*	*418*	*433*	*473*	*452*	*440*	*430*	*495*	*471*	*527*	
JOY	P&H 2300						9469	9983	9108	9947	9920	12252	11651	11739	15695	12594	
	uptime hours						447	436	440	458	413	464	408	387	451	372	
GRAND AVERAGE		12527	11957	11874	11014	10592	10846	10393	11027	12585	12599	11849	11840	11813	14894	13053	
	uptime hours	414	416	456	419	417	435	422	434	470	445	445	425	459	461	449	
CUMULATIVE AVERAGE		14214	14026	13861	13657	13453	13290	13120	13003	12981	12962	12909	12860	12815	12902	12908	
	uptime hours	463	459	459	456	453	452	450	449	450	450	450	449	449	450	450	

In order to track and compare average production levels variability with shovel life, a cumulative average production plot (Figure 4.4) was prepared. It can be seen from the plot that although there is a difference in production values for the analyzed equipment from coal mines, regression trends for cumulative average production of all of them are essentially the same and can be described by the following equation:

$$\textbf{\textit{Production}} = \textbf{\textit{-29.2*a + b}} \qquad (4.2)$$

where:

Production – amount of monthly excavated material per 1 cubic meter of bucket capacity (m^3 per month / 1 m^3)

a – prediction operational lifetime (thousands hours);

b – cumulative average production after 6,000 hours of operation (m^3 per month / $1m^3$)

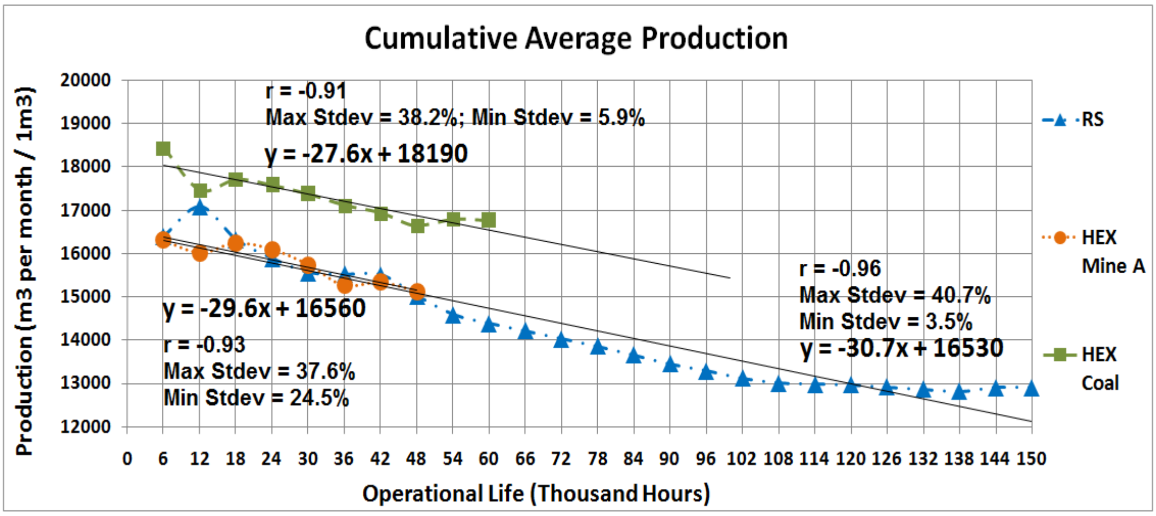

Figure 4.4 Cumulative average production change of mining shovels in relation to their operation lifetime.

4.2.3 Correlation between Availability and Production

It is commonly assumed that performance of a mining machine, its production numbers among other factors, depends majorly on the availability of the machine [30]. In other words, high availability provides high uptime-hours, which in turn provides (with invariable hourly production) better productivity.

Relations between cumulative average values of availability and production by category of equipment are presented in Figure 4.5 and can be expressed as follows.

Rope shovels in coal mines (from the coal mine “A”):

$$\textit{Production} = 384.5 * \textit{Availability} - 17186 \quad (4.3)$$

Hydraulic excavators in coal mines:

$$\textit{Production} = 234.8 * \textit{Availability} - 4056 \quad (4.4)$$

Hydraulic excavators in metal mines:

$$\textit{Production} = 255.1 * \textit{Availability} - 4429 \quad (4.5)$$

The correlation for HEX operating at coal mine site “A” was expected to vary from the slope for machines evaluated in coal mining. Indeed, the correlation for this category was found to be:

$$\textit{Production} = 101.9 * \textit{Availability} + 6787 \quad (4.6)$$

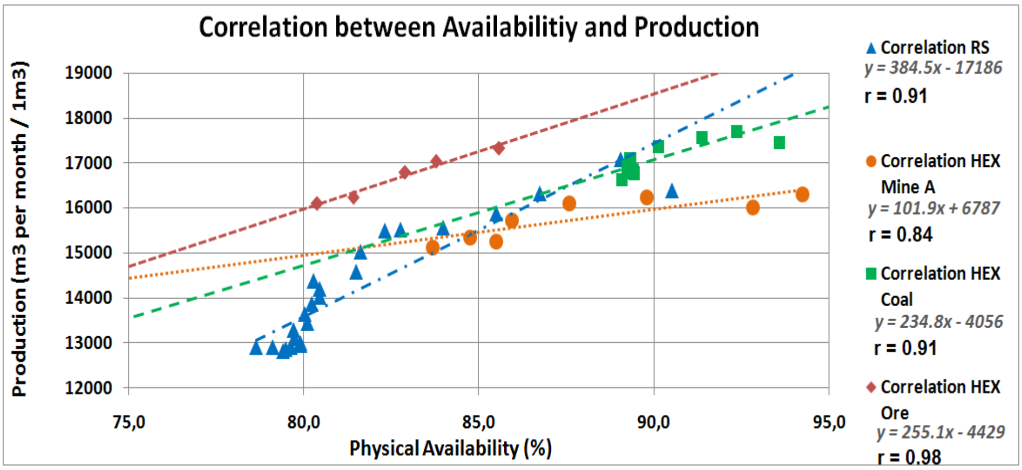

Figure 4.5 Correlations between Availability and Production cumulative average values

4.2.4 Operational Cost

Expenditure cost for mine "A" was related to the cost for 30 mining shovels of varying age and size over 8 years (2008 to 2014). Of 10 hydraulic excavators 8 were diesel and 2 larger were electric motor driven.

The expenditures used did not include labor costs but lease costs were included to partially take into account purchasing costs for new pieces of equipment.

Operational costs were assessed as the cost incurred by mine "A" for excavating $1m^3$ of material (CAD/$1m^3$). For convenience, operational costs were translated in Canadian Dollars (CAD).

According to the calculations performed on operational life of machines less than 60,000 hours, the maximal cost of excavation for rope shovels was 2.06 CAD per $1m^3$ (P&H 2300XPC between 6,000 and 12,000 operation hours), whereas the minimal cost was 0.06 CAD per $1m^3$ (EKG-12 between 18,000 and 24,000 operation hours). Hydraulic excavators indicate the maximum and minimum of 1.09 CAD/$1m^3$ (PC 5500) and 0.18 CAD per $1m^3$ (PC 4000), respectively.

Despite these figures being strongly dependable on lease conditions and payments made by a mining company to a lessor by year, cumulative average expenditure costs seem to be a more relevant indicator than independent average values for any of the periods. Cumulative average expenditures show that for a period of 48,000 operational hours or about 8 calendar years, 1 m^3 of material excavated by rope shovels was equivalent to 0.38 CAD, whereas HEX excavation reached 0.48 CAD/$1m^3$, corresponding to being 25% more expensive.

To further investigate the parameter for RS, it was seen that at 150,000 hours operation (25 years of operation) expenditure costs decreased gradually, converging on 0.24 CAD per m^3 of excavation.

All data has been provided in Tables 4.11 through 4.13. Actual values obtained for each individual piece of equipment are given in Appendix C.

Table 4.11 Rope shovels' operational costs (lease included)

HMR (Thousand hours)

RS 0 6 12 18 24 30 36 42 48 54 60

Make		Expenditures (CAD / m3)									
RSs											
OMZ	EKG-10				0,13	0,18	0,18	0,21	0,38	0,54	
	EKG-12				0,06	0,14	0,12	0,36	0,24	0,24	0,30
	EKG-15					0,15	0,10	0,24	0,12		
	EKG-18	0,49									
OMZ Average		*0,49*			*0,10*	*0,16*	*0,13*	*0,27*	*0,24*	*0,39*	*0,30*
JOY	P&H 2300 XP				0,23	0,26	0,26				
	P&H 2300 XPC	0,69	2,06								
	P&H 2800		0,15	0,31	0,23	0,23	0,21	0,22	0,34	0,44	
JOY Average		*0,69*	*1,11*	*0,31*	*0,23*	*0,25*	*0,23*	*0,22*	*0,34*	*0,44*	
GRAND AVERAGE		0,59	1,11	0,31	0,16	0,19	0,17	0,26	0,27	0,41	0,30
CUMULATIVE AVERAGE		0,59	0,85	0,67	0,54	0,47	0,42	0,40	0,38	0,39	0,38

Table 4.12 Hydraulic excavators' operational costs (lease included)

HMR (Thousand hours)

HEXs (Same mine as RSs) 0 6 12 18 24 30 36 42 48

Make		Expenditures (CAD / m3)							
HEXs									
Liebherr	R994	0,29	0,30	0,30	0,53	0,72	0,47	0,57	0,36
KOMATSU	PC 2000	0,44	0,53	0,45	0,40				
	PC 4000	0,18	0,31	0,61	0,49	0,63			
	PC 5500	0,21	0,49	1,09					
KOMATSU Average		*0,28*	*0,44*	*0,72*	*0,44*	*0,63*			
GRAND AVERAGE		0,28	0,41	0,61	0,47	0,68	0,47	0,57	0,36
CUMULATIVE AVERAGE		0,28	0,34	0,43	0,44	0,49	0,49	0,50	0,48

Table 4.13 Operational costs of rope shovels with operational lifespan exceeding 60,000 hours (lease included)

RS HMR > 60.000 hrs		60	66	72	78	84	90	96	102	108	114	120	126	132	138	144	150
Make				Expenditures (CAD / m3)													
RSs																	
OMZ	EKG-10									0,09	0,06	0,21	0,10	0,18	0,12	0,17	
	EKG-12	0,16															
	EKG-12,5						0,04	0,04	0,07	0,07	0,14	0,05	0,07				
	EKG-15					0,06	0,07			0,04	0,05	0,07					
	EKG-20			0,23	0,16	0,09	0,19	0,16	0,20	0,23	0,23	0,21	0,36				
	OMZ Average	*0,16*		*0,23*	*0,16*	*0,07*	*0,10*	*0,10*	*0,14*	*0,11*	*0,12*	*0,14*	*0,18*	*0,18*	*0,12*	*0,17*	
JOY	P&H 2300												0,15	0,15	0,18	0,16	
GRAND AVERAGE		0,16		0,23	0,16	0,07	0,10	0,10	0,14	0,11	0,12	0,14	0,17	0,17	0,15	0,17	
CUMULATIVE AVERAGE		0,36	0,36	0,35	0,33	0,31	0,30	0,29	0,28	0,27	0,26	0,26	0,25	0,25	0,24	0,24	

In order to assess poor correlation in service expenditures, the average cost of excavation were recalculated excluding lease costs. Only such things as consumables (teeth, ropes, electric cables, hoses, etc.), fuel, lubricants, electricity, etc. were included. It was found out that the cumulative average excavation costs were as follows. For a period of 48,000 operational hours the cost of excavation by a rope shovel was equivalent to 0.14 CAD/1m^3, whereas cost of excavation by a hydraulic machine reached 0.31 CAD/1m^3, corresponding to being 116% more expensive.

The results of the calculation are summarized a Tables 4.14 through 4.16 and Figures 4.6 through 4.7.

To determine major contributors for such a significant excavation cost discrepancy between rope shovels and hydraulic excavators, a more thorough analysis was made. The analysis comprised the following items of service expenditures:

- routine maintenance and repairs;
- major overhauls;
- fuel;
- electricity;
- lubricants;
- consumables.

Comparison of costs for each of these categories showed that servicing of HEX is from 11% (routine maintenance) to 180% (major overhaul) more expensive. Moreover, if to compare cost of electricity required to excavate 1m^3 by RS versus cost of diesel fuel required to excavate 1m^3 by HEX, the difference would constitute 322%. Details are given in figure 4.8.

Table 4.14 Rope shovels' operational costs (lease excluded)

RS		0	6	12	18	24	30	36	42	48	54	60
Make		Expenditures (CAD / m3)										
RSs												
OMZ	EKG-10				0,06	0,10	0,11	0,12	0,29	0,23		
	EKG-12				0,02	0,09	0,07	0,29	0,18	0,18	0,21	
	EKG-15					0,14	0,09	0,23	0,11			
	EKG-18	0,06										
OMZ Average		*0,06*			*0,04*	*0,11*	*0,09*	*0,22*	*0,19*	*0,20*	*0,21*	
JOY	P&H 2300 XP				0,15	0,18	0,20					
	P&H 2300 XPC	0,11	0,14									
	P&H 2800		0,08	0,22	0,12	0,15	0,13	0,14	0,14	0,18		
JOY Average		*0,11*	*0,11*	*0,22*	*0,14*	*0,17*	*0,17*	*0,14*	*0,14*	*0,18*		
GRAND AVERAGE		0,09	0,11	0,22	0,09	0,13	0,12	0,20	0,18	0,20	0,21	
CUMULATIVE AVERAGE		0,09	0,10	0,14	0,13	0,13	0,13	0,14	0,14	0,15	0,15	

Table 4.15 Hydraulic excavators' operational costs (lease excluded)

HEXs (Same mine as RSs)		HMR (Thousand hours) 0	6	12	18	24	30	36	42	48
Make		Expenditures (CAD / m3)								
HEXs										
Liebherr	R994	0,21	0,20	0,21	0,43	0,62	0,37	0,45	0,25	
KOMATSU	PC 2000	0,13	0,20	0,26	0,20					
	PC 4000	0,07	0,17	0,45	0,34	0,31				
	PC 5500	0,11	0,12	0,23						
KOMATSU Average		*0,10*	*0,16*	*0,31*	*0,27*	*0,31*				
GRAND AVERAGE		0,13	0,17	0,29	0,32	0,47	0,37	0,45	0,25	
CUMULATIVE AVERAGE		0,13	0,15	0,20	0,23	0,28	0,29	0,31	0,31	

Table 4.16 Operation costs of rope shovels with operational lifespan exceeding 60,000 hours (lease excluded)

HMR (Thousand hours)

RS HMR > 60.000 hrs		60	66	72	78	84	90	96	102	108	114	120	126	132	138	144	150
Make				Expenditures (CAD / m3)													
RSs																	
OMZ	EKG-10									0,07	0,06	0,21	0,10	0,18	0,12	0,17	
	EKG-12	0,09															
	EKG-12,5						0,04	0,04	0,07	0,07	0,14	0,05	0,07				
	EKG-15					0,06	0,07			0,04	0,05	0,07					
	EKG-20			0,21	0,14	0,08	0,18	0,15	0,18	0,21	0,18	0,16	0,27				
	OMZ Average	*0,1*		*0,21*	*0,14*	*0,07*	*0,10*	*0,10*	*0,13*	*0,10*	*0,11*	*0,12*	*0,15*	*0,18*	*0,12*	*0,17*	
JOY	P&H 2300												0,15	0,15	0,18	0,16	
GRAND AVERAGE		0,09		0,21	0,14	0,07	0,10	0,10	0,13	0,10	0,11	0,12	0,15	0,17	0,15	0,17	
CUMULATIVE AVERAGE		0,15	0,15	0,15	0,15	0,15	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	

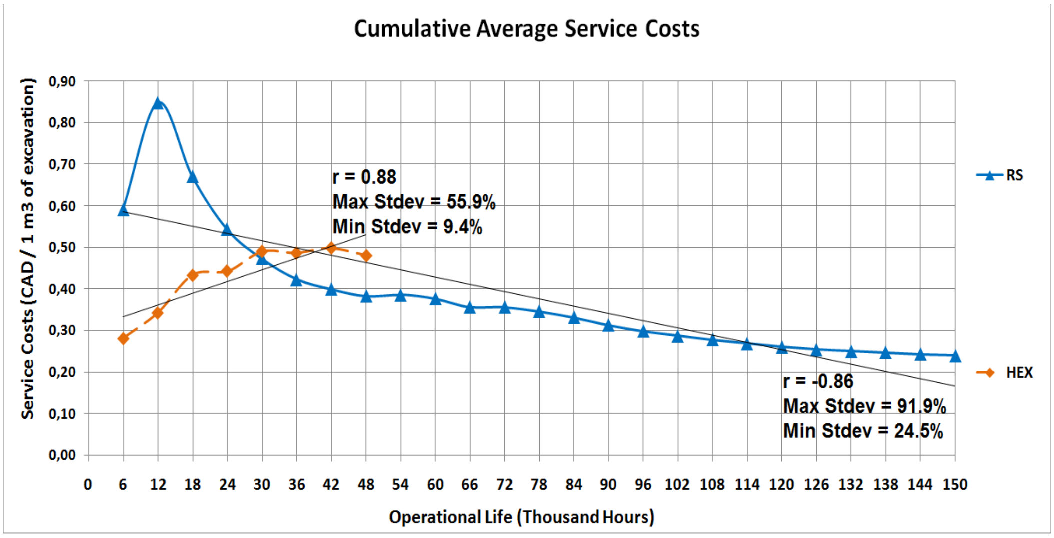

Figure 4.6 Cumulative average excavation costs change (including lease) in relation to shovels' operational lifetime.

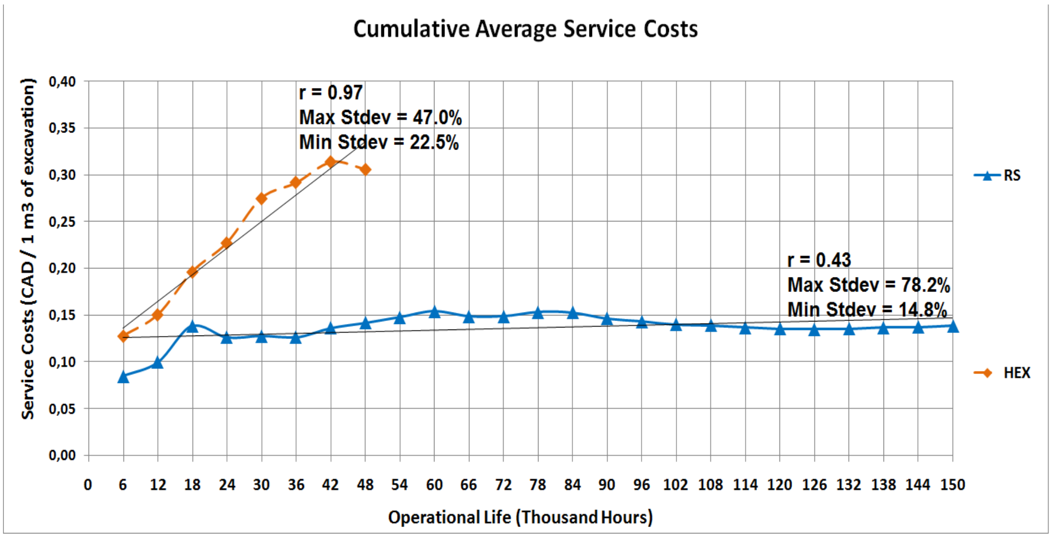

Figure 4.7 Cumulative average excavation costs change (excluding lease) in relation to shovels' operational lifetime.

	Consumables	Electricity	Fuel	Lubricants	Major Overhaul	Routine Maintenance
Hydraulic Excavators	0,142 (CAD/m³)	0,068 (CAD/m³)	0,145 (CAD/m³)	0,007(CAD/m³)	0,013 (CAD/m³)	0,039 (CAD/m³)
Difference (%)	140	99	322	173	180	11
Rope Shovels	0,059 (CAD/m³)	0,034 (CAD/m³)		0,020 (CAD/m³)	0,004 (CAD/m³)	0,035 (CAD/m³)

Figure 4.8 Hydraulic excavators and rope shovels excavation costs related to servicing categories.

4.3 Discussion

For each mining shovel analyzed in this study all the available information with respect to design, application, commissioning date, machine-hours, performance indicators and cost of operation were combined and taken into consideration. The results of this investigation are presented in Appendices A, B, and C. Also the summary results of the analyzed parameters are tabulated below in Table 4.17.

A comparison of physical availability (PA) and trends for mining rope shovels and hydraulic excavators suggests that Mine A has relatively poor maintenance practices for HEX. Such an assumption is supported by comparatively lower physical availability values for machines working in the mine to the average values of 67 analyzed coal mining HEX units. Moreover, decreasing physical availability trends are distinctly different for these two groups of excavators. All coal mining HEX have cumulative average PA stabilized after 30,000 operational hours, whereas, Mine A HEX availability decreases constantly over a 48,000 hours period.

Availability (and subsequent production) differences of hydraulic machines excavating coal and ones dealing with ore should likely to be explained by various types of digging environment. Coal is assumed to be an easy excavated material; it is not abrasive and comparatively soft. Coal typical host rocks (sandstone, argillite, siltstone, shale) are also not as hard and abrasive as metal ores and related rocks (e.g. granite). Thus, a carried out failures analysis shows that more severe digging conditions in ore mines lead to more frequent wear of buckets, their teeth, protective lips and strips. Moreover, average monthly amount of hours spent for undercarriage repairs is about 8 times more for ore mining HEX than for coal mining HEX. This means that digging conditions (coal mines, metal mines, oil sands, phosphate, etc.) greatly influence on the durability and performance of a machine.

The analysis indicated that an hour of productivity for mining shovels normalized to $1m^3$ of a bucket capacity does not depend on the life-time of a machine regardless of natural or technological conditions. Therefore, the degree of excavation executed by a piece of equipment is highly dependent on the machine uptime hours during a reviewed period. This finding is also supported by previous studies for electrical rope shovels with operation life of 18 to 22 years [31].

Table 4.17 Summary of the compared parameters

				HMR (Thousand hours) 0–6	6–12	12–18	18–24	24–30	30–36	36–42	42–48	48–54	54–60	TOTAL MEAN
Coal	All HEX	Availability (%)		95,0	92,1	89,9	88,4	85,1	85,4	88,5	88,0	90,6	91,0	89,4
Coal	All HEX	Poroduction (m3 monthly / 1m3)		18434	16491	18215	17183	16530	15792	15862	14630	18000	16468	16760
Coal	RS	Availability (%)		90,5	87,6	82,1	81,8	77,9	76,7	79,6	76,8	80,5	69,2	80,3
Coal	RS	Poroduction (m3 monthly / 1m3)		16391	17772	14793	14567	14266	15289	15446	11641	11037	12627	14383
Coal	RS	Expenditures (CAD/ 1m3)	with leasing	0,59	1,11	0,31	0,16	0,19	0,17	0,26	0,27	0,41	0,30	0,38
Coal	RS	Expenditures (CAD/ 1m3)	no leasing	0,09	0,11	0,22	0,09	0,13	0,12	0,20	0,18	0,20	0,21	0,15
Coal	HEX Mine "A"	Availability (%)		94,2	91,4	83,7	80,9	79,3	83,3	80,3	76,1	-	-	83,7
Coal	HEX Mine "A"	Poroduction (m3 monthly / 1m3)		16300	15718	16702	15658	14273	12880	15865	13561	-	-	15120
Coal	HEX Mine "A"	Expenditures (CAD/ 1m3)	with leasing	0,28	0,41	0,61	0,47	0,68	0,47	0,57	0,36			0,48
Coal	HEX Mine "A"	Expenditures (CAD/ 1m3)	no leasing	0,13	0,17	0,29	0,32	0,47	0,37	0,45	0,25			0,31
Metal Ore	HEX	Availability (%)		85,6	82,0	81,1	77,0	76,3	82,0	82,8	92,2	90,6	89,4	83,9
Metal Ore	HEX	Poroduction (m3 monthly / 1m3)		17329	16734	16312	14537	15572	-	-	-	-	-	16097

				HMR (Thousand hours) 60–66	66–72	72–78	78–84	84–90	90–96	96–102	102–108	108–114	114–120	120–126	126–132	132–138	138–144	144–150	TOTAL MEAN
Coal	RS > 60.000 Hrs	Availability (%)		82,3	-	77,8	77,8	81,1	74,1	79,8	82,7	79,7	80,3	74,5	76,6	77,6	72,7	67,4	78,6
Coal	RS > 60.000 Hrs	Poroduction (m3 monthly / 1m3)		12527	11957	11874	11014	10592	10846	10393	11027	12585	12599	11849	11840	11813	14894	13053	12908
Coal	RS > 60.000 Hrs	Expenditures (CAD/ 1m3)	with leasing	0,16		0,23	0,16	0,07	0,10	0,10	0,14	0,11	0,12	0,14	0,17	0,17	0,15	0,17	0,09
Coal	RS > 60.000 Hrs	Expenditures (CAD/ 1m3)	no leasing	0,09		0,21	0,14	0,07	0,10	0,10	0,13	0,10	0,11	0,12	0,15	0,17	0,15	0,17	0,08

Production variations are often related not only to operational hours, but result from many other factors. Whereas uptime hours and availability may have high indices, production values may suffer from, for example, operator's proficiency and tactics [32, 33], inherent properties of the excavated material or blast quality [34]. Moreover, for the equipment at mine "A", utilization (or the time when a machine excavates) is often cut by such things as: absence of spare parts (especially for HEXs), loss of electrical supply, climatic conditions, lack of service crew availability, lack of truck fleet, etc.

The analysis shows that hydraulic excavators demonstrate, generally, 15% higher production indicators. Comparatively low production levels of machines working at the same location, such as cable shovels is a consequence of poor data for the PC 4000 and PC 5500. However, these machines consist only 3% of the overall quantity of HEX analyzed, dealing with coal extraction, so their influence on the final assessment should not be overestimated.

With better production parameters hydraulic shovels (even those ones provided with high maintenance practices) by 60,000 hours of operation lose 10% of their cumulative average production. During the same period rope shovels display a decrease of 12 %.

As mentioned previously, in order to assess the actual difference of life cycle cost for the loading machine types in the context of mine "A", equipment lease was included in the expenditures. However, lease by case may have different agreement conditions between a customer and a supplier [35, 36]. Therefore an additional effort has been undertaken to compare that influence of the initial capital cost of rope shovels on their life cycle cost and to compare service expenditures for HEX and RS.

Basic prices for OMZ rope shovels and Komatsu hydraulic excavators with comparable bucket capacities have been evaluated. It has been found that average price for a new EKG rope shovel is about 71.5% higher than for a new Komatsu PC excavator. However, it should be mentioned that the durability normally guaranteed by hydraulic excavator manufacturers is 60.000 hours of operation or 10 years, whereas mining rope shovels usually extends to 18 to 23 years.

It is clearly seen from Figures 4.6 and 4.7 that a rope shovel ownership requires considerably greater expenditure during the initial 30.000 hours (5 years) of operation. However, by that point the cumulative average cost of excavation decreases to 0.47 CAD per 1 m^3 of excavation, and reaches the point where operational cost of hydraulic machines start to exceed (0.49 CAD/1m^3). The cumulative average cost of excavation for hydraulic shovels reaches a plateau of 0.49 CAD/1m^3; this magnitude fluctuates between 30,000 and 48,000 operational hours from 0.48 CAD/1m^3 to 0.50 CAD/1m^3.

Such a rapid fall of excavation cost for RS and simultaneously a rise for HEX both can be explained with help from Figure 4.7 showing service cost (not taking into account the amount of money spent for purchasing a new pieces of equipment) change in time. Whereas support for cable shovels remains constant (nearly 0.14 CAD/1m^3), after the third year of utilization, cumulative average service cost of a hydraulic machine indicates a firm increase and by 48,000 hours of operation exceeds more than twice the cumulative service costs for competitors – 0.31 CAD/1m^3 in comparison to 0.14 CAD/1m^3.

Moreover, a carried out analysis of categorized service costs indicates that hydraulic machines versus rope shovels are significantly more expensive in each category. For excavation expenditures in "consumables", "major overhaul" and "routine maintenance" the difference can be explained by import taxes for spare parts and consumables supplied from abroad for all HEX, whereas for a predominant portion of RS they are supplied from local manufacturers (except of JOY shovels).

It is worth noticing that spare parts and consumables manufactured and supplied by domestic companies often require less time to be delivered when necessary (more available). This fact in turn influences equipment physical availability and consequently productivity.

Nevertheless, expenditures for fuel and lubricants, as well as electricity costs do not depend on import taxes; therefore they are of high interest.

Although only two electrically driven hydraulic excavators were involved in the study, the data analysis displays that for 1m^3 of excavation by a HEX twice more electricity is required than with use of a RS. Comparison of fuel and electricity costs for 8 diesel hydraulic and 20 electric rope shovels, respectively, resulted to a finding that electricity was by 322% more efficient than diesel fuel.

Expenditures for lubricants included in 1m^3 excavation costs were found to be 173% higher for hydraulic excavators than for cable shovels.

Thus, due to the contribution of service costs differences, considerably higher initial investments for purchasing rope shovels, in comparison to hydraulic machines, led to lower cumulative expenditure costs for company "A" by the end of the fifth year of utilization.

It should be noted that the behavior and proportions of productivity and servicing cost indices of HEX and RS obtained during the study are very similar to ones detected at Muruntau gold mine in 2004 [12] (see Chapter 2). By the end of an eight year period of operation for hydraulic excavators (by Caterpillar, Orenstein & Koppel, Hitachi) and electrical rope EKG-15, they determined almost the same trends and differences of production and service cost values as defined in this study.

Despite such disadvantages for hydraulic excavators, in reality they can be partially a consequence of improper service, low experience of engineers and technicians in operating maintenance of hydraulic machines. On the contrary, EKG shovels had been used extensively in post-Soviet territory for several decades and rich maintenance experience had been gained. Moreover, absence of high-precision connections in rope shovels, absence of high requirements of machining accuracy as for hydraulic systems, and old-fashioned design allowed repairing EKG components (even producing spare parts) in Mine "A" maintenance and repair shops.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The main purpose of this study was to implement an effectiveness evaluation of hydraulic excavators versus rope shovels in surface coal mining. The results of the study can serve as additional arguments for selecting the appropriate excavation-loading equipment for a coal mine as well as a tool for predicting changes in the parameters affecting a shovels' lifetime.

Physical availability, productiveness, and possession expenditures for mining shovels of different sizes and designs operating all the way around the globe were examined, with an operational history of 3,400,000 calendar hours investigated.

5.1 Conclusions

Based on the investigations carried out with the scope of the study the following can be concluded:

1. From physical availability, hydraulic excavators demonstrate larger values in comparison to electric cable shovels. Total average mean values for a period of 60,000 hours were 89.4% for hydraulic excavators and 80.3% for rope shovels. It can be noted that from 36,000 hours of operation cumulative average availability of HEX in coal mining remains

almost unchanged, whereas RS indicator undergoes a gradual decrease until 60,000 operational hours, where it is plateaued and remains stable almost by 150,000 hours. It is noticeable that although hydraulic excavators in coal mines have 5 to 6 per cent higher cumulative average availability, than those in metal ore and granite, and 11 per cent higher than cable shovels dealing with coal and coal overburden, their parameters change little.

2. Monthly production analysis of 41 hydraulic excavators and 20 rope shovels resulted in finding that the average cumulative volume of excavation normalized to $1m^3$ of bucket capacity is about 16.5% higher for coal mining HEX than for RS. Production differences between hydraulic shovels in coal mining and those in metal mining were found to be 3% (only two pieces of iron ore mining machines were involved in the assessment).

   Cumulative average production of the analyzed coal mining shovels groups has very similar regression trends. It allows predicting productivity of equipment at different stages of life using an integrated regression trend:

$$\textbf{\textit{Production}} = -\ 29.2 * a + b \qquad (4.2)$$

   where:

   a - prediction operational lifetime (thousands hours);

b - average monthly production (normalized to $1m^3$ of bucket capacity) after 6,000 hours of operation.

Having an empirical background the equation could become a valuable tool for the industry in predicting production change in time for a particular shovel. With more data available in regard to performance of mining shovels dealing with different excavated materials the same approach could be utilized not only for coal mining but for any type of commodity.

3. Correlation between physical availabilities of excavators and their productivities have been detected and are as follows:

Rope shovels in coal mines (from the coal mine “A”):

$$\textit{Production} = 384.5 * \textit{Availability} - 17186 \quad (4.3)$$

Hydraulic excavators in coal mines:

$$\textit{Production} = 234.8 * \textit{Availability} - 4056 \quad (4.4)$$

Hydraulic excavators in metal mines:

$$\textit{Production} = 255.1 * \textit{Availability} - 4429 \quad (4.5)$$

Hydraulic excavators in coal mine “A”:

$$\textit{Production} = 101.9 * \textit{Availability} + 6787 \quad (4.6)$$

4. Cumulative average expenses related to the possession of a hydraulic excavator after 48,000 operational hours exceeds ones related to the

possession of a rope shovel by 25%. Whereas initial cost of a cable shovel is considerably higher (e.g. between KMG excavators and OMZ shovels differ by 71.5%) than a hydraulic machine of comparable capacity, for 30,000 operational hours the integral average cost of excavation equalizes for both mining machine types. This is a result of much higher service expenditures of hydraulic excavators, including cost of spare parts, consumables, fuel, lubricants, etc. However, from 30,000 to 48,000 operational hours cumulative average cost of excavation by HEX stabilizes and displays only a slight year-on-year fluctuation.

Service costs normalized to $1m^3$ of excavation for cable shovels increases gradually by about 30% during the initial 18,000 hours of life (roughly 3 years) and after that remains almost unchanged up to 150,000 hours (around 25 years), while the same indicator for hydraulic equipment displays a gradual rise with no stabilization in the analyzed period. Consequently, the cumulative average servicing expenditures related to one cubic meter of excavation for 48,000 operational hours at 2.15 times higher for HEX versus RS.

5. Comparatively low availability and productivity numbers of HEX operating in Mine A versus common HEX indicators are likely to be a result of rather poor culture of utilization and maintenance of this type of equipment existing in the region where HEX came into a mining extensive use only about 20 years ago.

6. All the data and analysis obtained and discussed above indicate that the RS's main advantages over HEX are lower cost of excavation and longer

expected life. HEX, in turn, are significantly cheaper, technologically more flexible, and provide larger production numbers, although they require higher-quality maintenance and servicing.

Nevertheless, it should be emphasized that the life cycle cost of equipment was evaluated here on the basis of information from only one mining company (Mine “A” in this thesis). Taking into consideration that availability and productivity parameters for Mine “A” are considerably lower compared to global indices calculated for all coal mining excavators in the study, it can be concluded that expenditure cost trends may also differ in other mines. Therefore, further efforts need to be made in order to receive data from industry and improve the reliability of the data and outcomes obtained in this study.

It is believed by the author that the results of the study discussed provide a decent picture of hydraulic excavators and rope shovels performance and costs differences. However, inclusion of new pieces of information about shovels operating in various working conditions around the globe may consequently provide better understanding of what to expect from a particular excavation equipment unit on a particular mining site.

5.2 Recommendations for Future Studies

1. In this study the information, regarding performance and life cycle cost for 136 mining shovels, predominately involved in coal mining, was

examined. In future studies more items of equipment of various manufacturers and capacities dealing with different types of excavated material and for alternative climatic and technological environments should be included.

2. For further studies, key maintenance issues for hydraulic excavators and rope shovels should be determined. Relationships between problematic components, failures occurrence frequency and average duration of repairs; together with the associated expenditures and comprehensive information about operating conditions should be investigated. Such connections would become an additional clue for the excavation equipment selection in surface mining.

3. As an ultimate goal of such a high level investigation, a template for excavation equipment selection in surface mining can be created. The template based on empirical relationships between application conditions, mine design, and mining shovels effectiveness would require input of base data (e.g. underfoot and digging face materials, blast fragmentation, bench height and width, etc.). With base data input and after following a precise algorithm, the template would provide forecast productions and extraction cost numbers for different mining shovels relative to the determined working conditions.

   Having an empirical background and being constantly updated such a template would become a highly valuable tool for the industry.

REFERENCES

1. Poderny R., 2007. Mechanical equipment for surface mining. Publised by Moscow State Mining University, Moscow.

2. Trubetskoy K.; Potapov M.; Vinitsky K.; Melnikov N., 1994. Surface mining. Reference manual. Mining desk, 590p.

3. Burt C., Caccetta L., 2014. Equipment Selection for Surface Mining: A Review, Interfaces, 44(2), pp. 143-162

4. P&H Mining Equipment, 2007. Electric versus hydraulic. Mining Magazine. Pp. 42-51

5. Horeshok A., Kudrevatyh A., 2011. Comparison analysis of electrical rope shovels and hydraulic backhoes performance at coal mines of “KuzbassRazrezUgol Mining Company”. Coal of Kuzbass, 3 (Published on-line).

6. Frimpong S., Hu Y., 2010. Parametric simulation of shovel oil sands interactions during excavation. International Journal of Surface Mining (Published on-line Aug. 9, 2010)

7. RH40-E Hydraulic mining excavator. TEREX / O&K, brochure.

8. Kelsh H., 2008. Parameters of hydraulic mining excavators for successful rope shovels replacement in low ambient temperatures. Mining informational and analytical bulletin, 11, pp. 76-79

9. Fiscor S., 2007. Productivity Considerations for Shovels and Excavators. Engineering & Mining Journal, 208, p.38.

10. Saponenko U., 2007. Single-bucket shovel operator. Publised by "Academia", Moscow

11. Karpuz C., Ceylanoglu. A., Pasamehmetoglu A.G., 1992. An investigation on the influence of depth of cut and blasting on shovel digging performance. International Journal of Surface Mining and Reclamation, 6, pp. 161-167

12. Shemetov P., Rubtsov C., Shlylov A., 2005. Exploitation of rope shovels and hydraulic excavators at Muruntau open pit. Mining Industry, 5 (Published on-line).

13. Merzlyakov V., Slesarev B., Shteinzayg W., 2013. Exploitation of Komatsu Mining Germany hydraulic excavators at mining sites in Russia. Equipment and Electromechanics. 5.

14. Jovanović V., Janošević D., Petrović N., 2014. Analysis of slewing bearing load of a rotating platform drive in hydraulic excavators. Technical Gazette, 21, pp. 263-270

15. P&H Mining Equipment, 2007. Peak performance practices – excavator selection (Edited summary). Mining Magazine, pp. 42-51

16. Ritzel T., Lenz M., 1997. Shovel maintenance at Sierrita. Mining Engineering, 49, pp. 29-34

17. PC 3000-6 Hydraulic excavator. Komatsu, brochure. 2013 Komatsu printed in Germany

18. PC 4000-6 Hydraulic excavator. Komatsu, brochure. 2013 Komatsu printed in Germany

19. PC 5500-6 Hydraulic excavator. Komatsu, brochure. 2013 Komatsu printed in Germany

20. PC 8000-6 Hydraulic excavator. Komatsu, brochure. 2013 Komatsu printed in Germany

21. EKG IZ KARTEX, http://www.iz-kartex.com/new-product-line/ (accessed March 15, 2015)

22. P&H 2300XPC Electric mining shovel – DC Drive. Product overview. Joy Global / P&H, brochure. 2012 Joy Global Inc.

23. P&H 2800XPC Electric mining shovel – AC Drive. Product overview. Joy Global / P&H, brochure. 2012 Joy Global Inc.

24. PC 2000-8 Hydraulic excavator. Komatsu, brochure. 2008 Komatsu printed in USA

25. R 994 B Hydraulic excavator. Technical description. Liebherr. Brochure. 2004 Printed in Germany by Eberl

26. Vamshi K. Katukoori "Standardizing Availability Definition", University of New Orleans (www.plant-maintenance.com/articles/Availability_Definition.pdf downloaded on March 6, 2015)

27. KMG Back-to-Back Availability Guarantee

28. Tomlingson, Paul D., 2010. Equipment management: Key to equipment reliability and productivity in mining. Society for Mining, Metallurgy, and Exploration, Littleton, USA, 317p.

29. Borsch-Komponiets V.I., 1996. One method for prompt evaluation of mining shovels efficiency. Mining Industry, 1, pp. 29 -37

30. Samanta B., Sankar B., Mukherjee S.K., 2001. Reliability analysis of shovel machines used in an open cast coal mine. Mineral Resources Engineering, 10(2) pp. 219-231

31. Anistratov, K., Konopelko, S., 2009. Optimal service life of electric mining shovels. Mining (www.gornoe-delo.ru/articles/detail.php?ID=7512 downloaded on March 2, 2015)

32. Hendricks C, Scoble M., Peck J., 1989. Performance monitoring of electric mining shovels. Transactions of the Institute of Mining and Metallurgy, 98, p. A151-A159

33. Patnayak S., Tannant D.D., Parsons I., Del Valle V., Wong J. 2008. Operator and dipper tooth influence on electric shovel performance during oil sands mining. International Journal of Mining, Reclamation and Environment, 22(2), pp. 120-145

34. Mol O.,Danell R., Leung L., 1987. Studies of rock fragmentation by drilling and blasting in open cut mines. Rock Fragmentation by Blasting, Second International Symposium, pp. 381-392

35. O'Sullivan A., Steven M., 2003. Economics: Principles in action. Pearson Prentice Hall, New Jersey, 541p.

36. Gazman V., 2008. Financial leasing and factoring. Higher School of Economics, Moscow, 342p.

APPENDIX A

INDIVIDUAL PHYSICAL AVAILABILITY VALUES

Table A.1 Physical Availability: PC 3000

									Operation Hours									
Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 3000	Asia	2009	Coal/OVB	BH	15,0	Komatsu Diesel Engine	**37.419**	Jan 15					91,4	92,9				
PC 3000	Asia	2010	Coal/OVB	BH	15,0	Komatsu Diesel Engine	**32.526**	Jan 15				91,3	92,8	90,9				
PC 3000	Asia	2010	Coal/OVB	BH	15,0	Komatsu Diesel Engine	**31.764**	Jan 15				92,3	94	89,4				
PC 3000	Asia	2010	Coal/OVB	BH	15,0	Komatsu Diesel Engine	**32.239**	Feb 15				94,3	93	75,3				
PC 3000	Asia	2012	Coal/OVB	BH	15,0	Komatsu Diesel Engine	17.971	Jan 15	95,0	97,2	95,1							
PC 3000	Asia	2013	Coal/OVB	BH	15,0	Komatsu Diesel Engine	11.859	Jan 15	98,6	95								
PC 3000	Asia	2013	Coal/OVB	BH	15,0	Komatsu Diesel Engine	**10.451**	Jan 15	98,3	96,3								
PC 3000	Asia	2009	Coal/OVB	BH	15,0	Komatsu Diesel Engine	**37.787**	Jan 15					92,6	91,8				

Table A.2 Physical Availability: PC 4000

									Operation Hours										
Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 4000	Latin America	2006	Coal/OVB	BH	23,0	Komatsu Diesel Engine	45.544	Mar 14	93,3	88,7	86,5	88,9	86,8	88,9	90	92,7		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	48.167	Mar 14	95,3	87,2	88	89,7	91,4	91,6	92,1	92,7		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	**49.980**	Oct 14	94,1	90,3	91,1	90,7	92,1	90,4	92,8	93,8		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	**41.329**	Oct 14	94,5	92	88,1	87,4	90,2	90,1	89	94		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	**45.975**	Oct 14	94,2	90	90,2	88,4	90,4	93,1	90,9	92,8		
PC 4000	Europe	2008	Coal/OVB	FS	22,0	Electric Motor	**30.862**	Jan 15	95,7	91,6	81,5	73,7	66,1	86,7				
PC 4000	Asia	2010	Coal/OVB	BH	22,0	Komatsu Diesel Engine	**29.140**	Jan 15			91,8	89,4	87,8					
PC 4000	Asia	2011	Coal/OVB	FS	22,0	Komatsu Diesel Engine	**20.819**	Feb 15		92	91,9							
PC 4000	Asia	2011	Coal/OVB	FS	22,0	Komatsu Diesel Engine	**19.786**	Feb 15		92,5	91,7							
PC 4000	Asia	2012	Coal/OVB	FS	24,0	Komatsu Diesel Engine	**12.898**	Jan 15	95,2	94								
PC 4000	Asia	2014	Coal/OVB	FS	24,0	Komatsu Diesel Engine	**5.776**	Jan 15	95,1									
PC 4000	Asia	2012	Coal/OVB	FS	22,0	Komatsu Diesel Engine	**16.805**	Dec 14	90,5	89,7	88,6							
PC 4000	Asia	2012	Coal/OVB	FS	22,0	Komatsu Diesel Engine	**16.222**	Jan 15	91,7	88,9	92,7							
PC 4000	Africa	2010	Coal/OVB	FS	22,0	Electric Motor	**23.366**	Feb 15				89,2						
PC 4000	Africa	2011	Coal/OVB	FS	26,0	Electric Motor	**15.970**	Feb 15		96,5	94							
PC 4000	Africa	2012	Coal/OVB	FS	22,0	Electric Motor	**15.109**	Feb 15		90,7	94							
PC 4000	Africa	2013	Coal/OVB	BH	22,0	Electric Motor	**9.368**	Feb 15	96,2	95,5								
PC 4000	Africa		Coal/OVB	FS	22,0	Electric Motor	**8.700**	Feb 15	95	95								

Table A.2 Continued

PC 4000	Asia		Coal/OVB	FS	24,0	Komatsu Diesel Engine	**17.360**	Jan 15	99,6		89,4							
PC 4000	Asia	2012	Coal/OVB	FS	24,0	Komatsu Diesel Engine	**15.374**	Jan 15	91,8									
PC 4000	Asia	2012	Coal/OVB	BH	24,0	Komatsu Diesel Engine	**16.516**	Feb 15	97,5									
PC 4000	Australia		Coal/OVB	BH	22,0	Komatsu Diesel Engine	**15.753**	Jan 15			83,2							
PC 4000	Asia	2005	Coal/OVB	FS	22,0	Komatsu Diesel Engine	**51.161**	Jan 15							86	88,7		
PC 4000	Asia	2005	Coal/OVB	FS	22,0	Komatsu Diesel Engine	**51.100**	Feb 15							83,3	92,4		
PC 4000	Asia	2005	Coal/OVB	FS	24,0	Komatsu Diesel Engine	44.522	Feb 14							86,7	81,9		
PC 4000	Asia	2006	Coal/OVB	FS	24,0	Komatsu Diesel Engine	**48.549**	Dec 14							90,6	89,3		
PC 4000	Australia		Iron Ore/OV	FS	22,0	Komatsu Diesel Engine	**10.642**	Jan 15	81	77,2								
PC 4000	Australia		Iron Ore/OV	FS	19,0	Komatsu Diesel Engine	**12.552**	Feb 15	76,6	82,2								
PC 4000	Australia		Iron Ore/OV	FS	19,0	Komatsu Diesel Engine	**10.158**	Jan 15	82,2	81,5								
PC 4000	Australia		Iron Ore/OV	FS	19,0	Komatsu Diesel Engine	**9.514**	Feb 15	78,9	79,4								
PC 4000	Australia		Iron Ore/OV	FS	19,0	Komatsu Diesel Engine	**9.979**	Jan 15	87,4	72,5								
PC 4000	Africa		Iron Ore/OV	FS	22,0	Komatsu Diesel Engine	**15.162**	Jan 15		83,3	91,2							
PC 4000	Africa		Iron Ore/OV	FS	15,0	Komatsu Diesel Engine	**13.973**	Jan 15		88,4	92							
PC 4000	Africa		Iron Ore/OV	FS	15,0	Komatsu Diesel Engine	**10.975**	Jan 15	67	88,5								
PC 4000	Africa		Iron Ore/OV	FS	15,0	Komatsu Diesel Engine	**10.094**	Jan 15	83	78,9								
PC 4000	Latin America	2011	Copper/OVE	BH	19,0	Komatsu Tier 2 Diesel Engine	**21.292**	Feb 15	90,9	81	87,2							

Table A.3 Physical Availability: PC 5500

									Operation Hours									
Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 5500	Europe	2011	Coal/OVB	FS	29,0	2 x Electric Motor	21.106	Nov 14	94,5	92,7	78	76,1						
PC 5500	Australia		Coal/OVB	BH	34,0	2 x Komatsu Diesel Engines	12.895	Feb 15		93,4								
PC 5500	USA	2004	Coal/OVB	BH	28,0	2 x Komatsu Diesel Engines	50.322	Sep 14	95,8	93,4	90,4	94,9		91,4	90,4	89,4	90,9	
PC 5500	USA	2006	Coal/OVB	BH	28,0	2 x Komatsu Diesel Engines	49.095	Sep 14						86,3	91,1	92,5	94,2	
PC 5500	Australia		Iron Ore/OVB	BH	26,0	2 x Komatsu Diesel Engines	34.012	Jan 15					76,8	77,9				
PC 5500	Australia	2012	Iron Ore/OVB	BH	25,0	2 x Komatsu Diesel Engines	15.648	Jan 15	82,1	72,5	81,5							
PC 5500	Australia	2012	Iron Ore/OVB	BH	26,0	2 x Komatsu Diesel Engines	11.341	Jan 15	78	79,1								
PC 5500	Australia	2012	Iron Ore/OVB	BH	26,0	2 x Komatsu Diesel Engines	12.570	Jan 15	75,7	76,4								
PC 5500	Australia	2012	Iron Ore/OVB	BH	26,0	2 x Komatsu Diesel Engines	11.570	Jan 15	82,5	81,7								
PC 5500	Latin America	2007	Copper/OVE	FS	28,0	2 x Komatsu Diesel Engines	44.756	Jan 15		75,8	76,4		67,4					
PC 5500	Latin America	2008	Copper/OVE	FS	28,0	2 x Komatsu Diesel Engine	41.392	Jan 15				76,2	72,1	79,5				
PC 5500	Latin America	2008	Copper/OVE	BH	28,0	2 x Komatsu Diesel Engine	35.158	Mar 14			79,1	81,6						
PC 5500	Latin America	2010	Copper/OV B	BH	29,0	2 x Komatsu Diesel Engines	22.514	Aug 14	89,7									
PC 5500	Latin America	2010	Copper/OV B	BH	29,0	2 x Komatsu Diesel Engines	24.049	Jan 15	87,7	85,8	80,5							
PC 5500	Latin America	2012	Copper/OV B	FS	29,0	2 x Komatsu Diesel Engine	14.401	Feb 15	88,5	82,5								
PC 5500	Latin America		Copper/OV B	FS	29,0	2 x Komatsu Diesel Engine	5.537	Jan 15	87,4									
PC 5500	Latin America	2010	Copper/OV B	FS	29,0	2 x Komatsu Diesel Engine	18.206	Feb 15	87,8	82,1	81,7							
PC 5500	Africa	2011	Iron Ore/OV	FS	24,0	2 x Komatsu Diesel Engines	14.629	Aug 14			78,8							

Table A.3 Continued

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours									
									0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 5500	Africa	2011	Iron Ore/OV	FS	24,0	2 x Komatsu Diesel Engines	13.539	Aug 14		81,6	76,3							
PC 5500	Latin America	2007	Copper/OVB	BH	28,0	2 x Komatsu Diesel Engines	**38.979**	Feb 15					65,8	72,6				
PC 5500	Latin America	2010	Copper/OVB	BH	29,0	2 x Komatsu Diesel Engines	**26.686**	Jan 15		85,3	81,5							
PC 5500	Latin America	2011	Copper/OVB	BH	29,0	2 x Komatsu Diesel Engines	**25.471**	Feb 15		85,3	75,3	79,9						
PC 5500	Latin America	2005	Copper/OVB	FS	29,0	2 x Electric Motor	**62.570**	Feb 15					81,4	84,7	82,8	84,6	87,9	85,5
PC 5500	Latin America	2005	Copper/OVB	FS	29,0	2 x Electric Motor	**58.807**	Feb 15			80,5							
PC 5500	Latin America	2005	Copper/OVB	FS	29,0	2 x Electric Motor	**60.580**	Feb 15		87,1								
PC 5500	Latin America	2008	Copper/OVB	FS	28,0	2 x Komatsu Diesel Engine	**42.005**	Jan 15			84,5	84,8	82,1	91,8				
PC 5500	Latin America	2010	Copper/OVB	FS	29,0	2 x Komatsu Diesel Engine	**28.345**	Jan 15		87,7	89,2							
PC 5500	Latin America		Copper/OVB	FS	28,0	2 x Electric Motor	33.293	Dec 13		89,4	88,7	90,7						
PC 5500	Africa	2008	Phosphate	FS	22,0	2 x Electric Motor	**34.140**	Feb 15					95	95				
PC 5500	Africa		Uranium Ore/ Granite/OV	FS	25,0	2 x Komatsu Diesel Engines	**35.130**	Jan 15						92,4				
PC 5500	Africa	2006	Uranium Ore/ Granite/OV	FS	25,0	2 x Electric Motor	**53.656**	Jan 15									93,3	93,3
PC 5500	Africa	2007	Uranium Ore/ Granite/OV	FS	25,0	2 x Electric Motor	**48.501**	Jan 15								96,9		
PC 5500	Africa	2007	Uranium Ore/ Granite/OV	FS	25,0	2 x Electric Motor	**48.011**	Jan 15								95		
PC 5500	Europe	2011	Iron Ore/OVB	FS	26,0	2 x Electric Motor	**28.982**	Feb 15			84,1	83,1	88,9					
PC 5500	Europe	2013	Iron Ore/OVB	FS	26,0	2 x Electric Motor	**12.631**	Jan 15	91,3	89,2								

Table A.4 Physical Availability: PC 8000

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours									
									0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 8000	Latin America	2004	Coal/OVB	FS	42,0	Electric 2 x ABB	65.338	Oct 14	92,7	93,2	92,7	89,8	89,5	88,2	86	89,5	87,9	86,9
PC 8000	Latin America	2005	Coal/OVB	FS	42,0	Electric 2 x ABB	56.632	Mar 14	93,5	89,8	86,7	90,1	87,9	86,2	89,1	88,4	87,2	92,1
PC 8000	Latin America	2005	Coal/OVB	FS	42,0	Electric 2 x ABB	51.785	Apr 14	94	91	87,8	88,2	87,8	85,7	87,5	87,9	90,7	93,9
PC 8000	Latin America	2007	Coal/OVB	FS	42,0	Electric 2 x ABB	44.239	Jan 15	92,8	88,9	85,1	86,7	89,1	88	89,7	91		
PC 8000	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	40.445	Dec 14	93,6	89,1	88,4	88,7	87	89,5	88,9			
PC 8000	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	41.287	Mar 14	92,9	84,5	87,9	88,5	89,3	90,2	91			
PC 8000	Latin America	2013	Copper/OVB	FS	42,0	2 x Komatsu Diesel Engine	6.799	Jan 15	90,9									
PC 8000	Latin America	2009	Copper/OVB	FS	42,0	Diesel 2 x Komatsu	30.122	Dec 14	90,6	71,4	64,2	66						
PC 8000	Latin America	2010	Copper/OVE	FS	42,0	2 x Komatsu Diesel Engine	25.940	Feb 15	81,6	84,7	80,9	59,4						
PC 8000	Latin America	2013	Copper/OVE	FS	42,0	2 x Komatsu Diesel Engine	8.088	Feb 15	82,9									
PC 8000	Latin America	2013	Copper/OVE	BH	42,0	2 x Komatsu Diesel Engine	4.690	Feb 15	82,7									
PC 8000	Latin America	2013	Copper/OVE	BH	42,0	2 x Komatsu Diesel Engine	7.638	Jan 15	86									
PC 8000	Latin America	2012	Copper/OVE	FS	40,0	Electric 2 x ABB	15.071	Feb 15	86,7	89,5								
PC 8000	Latin America		Copper/OVE	FS	42,0	Electric 2 x ABB	9.295	Jan 15	90,4	87,2								
PC 8000	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	43.223	Feb 15	97,1	92,7	90,3	94,9	91,3	91,3	89,4			
PC 8000	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	42.247	Feb 15	95,6	94	91,3	95,9	91,7	91,1	92,5			
PC 8000	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	38.957	Feb 15	97,3	90,9	92,5	92,8	90,7	88,7	92,9			
PC 8000	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	38.190	Feb 15		89,1	95,2	91,7	88	88,8				

Table A.4 Continued

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours									
									0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 8000	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	**34.795**	Feb 15		91	95,7	90,9	86,8	92,2				
PC 8000	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	**34.568**	Feb 15		90,5	93,6	90,5	90,2	89,7				
PC 8000	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	**33.865**	Feb 15		93,4	94,4	92,8	91,3	91,9				
PC 8000	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	**18.754**	Feb 15	95,2	89,7	90,1							
PC 8000	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	**18.431**	Feb 15	95,3	93,5	91,4							
PC 8000	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	**17.409**	Feb 15	96,7	92,9	92,4							
PC 8000	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	**15.960**	Feb 15	96,2	93,5	93,4							
PC 8000	Latin America	2013	Coal/OVB	FS	42,0	Electric 2 x ABB	**11.934**	Feb 15	94,5	93,2								
PC 8000	Latin America	2013	Coal/OVB	FS	42,0	Electric 2 x ABB	**10.506**	Feb 15	96,8	96								
PC 8000	Africa		Coal/OVB	FS	42,0	Electric 2 x ABB	**21.682**	Feb 15			80,3	84,7						
PC 8000	Africa	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	12.625	Aug 14		91,5	98,5							

Table A.5 Physical Availability: PC 2000 and R 994

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours: 0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel Engine	23.379	Dec 14	96,6	93,5	88,2	91,3						
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel Engine	21.878	Dec 14	96,4	79,7	85,4	83,8						
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel Engine	15.669	Dec 14	94,6	91	87,5							
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel Engine	15.667	Dec 14	90,2	94,5	92,7							
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	**47.933**	Dec 14	92,2	96,7	91	75	84,5	91,9	81,5	82,9		
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	45.807	Dec 14	93,3	94,2	85,7	82,1	87,4	81,7	83,8	71,8		
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	42.999	Jun 14	89,9	90,2	87,1	77,4	78,6	79,9	75,5	73,5		
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	34.276	Dec 14	93,4	85,8	83,8	74,5	79,8	76,3				

Table A.6 Physical Availability: Rope Shovels 0 ÷ 60.000 Operation Hours

Type	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours 0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
EKG-10	2005	Coal/OVB	FS	10,0	Electric Motor	53.060	Dec 14		86,2	87,3	91,7	79,5	85,7	85,2	82,6	75,7	
EKG-12	2003	Coal/OVB	FS	12,0	Electric Motor	65.795	Oct 14					79,1	80,2	86,1	70,8	73,6	68,9
EKG-12	2005	Coal/OVB	FS	12,0	Electric Motor	59.056	Dec 14			86,1	87,9	86,1	83,6	64,8	83,3	80,8	67,5
EKG-12	2004	Coal/OVB	FS	12,0	Electric Motor	55.356	Dec 14			78,4	85,7	80,9	77,2	72,8	70,9	73,9	71,3
EKG-15	2003	Coal/OVB	FS	15,0	Electric Motor	48.992	May 13				84,0	81,9	75,5	74,0	64,6	86,1	
EKG-18	2013	Coal/OVB	FS	18,0	Electric Motor	8.313	Dec 14	86,6	87,0								
P&H 2300X	2005	Coal/OVB	FS	20,0	Electric Motor	35.535	Dec 14			73,9	67,7	65,3	59,3				
P&H 2300X	2012	Coal/OVB	FS	16,0	Electric Motor	13.296	Dec 14	91,8	88,4	81,9							
P&H 2800	2006	Coal/OVB	FS	33,0	Electric Motor	52.617	Dec 14		86,9	87,8	89,8	84,2	89,4	82,8	83,5	82,4	
P&H 2800	2006	Coal/OVB	FS	33,0	Electric Motor	45.170	Dec 14	91,8	89,2	85,4	78,7	83,6	83,5	81,1	78,0		

Table A.7 Physical Availability: Rope Shovels 60.000 ÷ 150.000 Operation Hours

Type	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours														
								60000 - 66000	66000 - 72000	72000 - 78000	78000 - 84000	84000 - 90000	90000 - 96000	96000 - 102000	102000 - 108000	108000 - 114000	114000 - 120000	120000 - 126000	126000 - 132000	132000 - 138000	138000 - 144000	144000 - 150000
EKG-10	1990	Coal/OVB	FS	10,0	Electric Motor	>100.000	Dec 14								82,9	79,9	75,6	77,2	81,1	71,6	65,7	80,1
EKG-10	1991	Coal/OVB	FS	10,0	Electric Motor	>100.000	Dec 14								84,2	81,7	78,5	61,9	83,3	82,4	80,7	
EKG-12	2003	Coal/OVB	FS	12,0	Electric Motor	65.795	Oct 14	82,3														
EKG-12,5	1990	Coal/OVB	FS	12,5	Electric Motor	>100.000	Dec 14						71,4	87,0	86,7	79,0	83,2	69,3	83,6			
EKG-15	1985	Coal/OVB	FS	15,0	Electric Motor	>100.000	Aug 10								84,5	86,1	84,4	78,0				
EKG-15	1991	Coal/OVB	FS	15,0	Electric Motor	>100.000	Dec 14					82,0	78,8	81,5								
EKG-20	1988	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14			82,2	78,5	80,4	60,7	74,3	66,2	69,0						
EKG-20	1990	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14						73,2	70,6	85,8	76,4	76,6	81,1	71,1	85,3		
EKG-20	1990	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14			73,3	77,0	79,8	82,3	68,2	75,9							
P&H 2300	1984	Coal/OVB	FS	16,0	Electric Motor	>100.000	Dec 14												71,9	74,1	72,4	61,1
P&H 2300	1984	Coal/OVB	FS	16,0	Electric Motor	>100.000	Dec 14												74,1			

APPENDIX B

INDIVIDUAL PRODUCTIVITY VALUES

Table B.1 Production: PC 4000

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Operation Hours 0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 4000	Latin America	2006	Coal/OVB	BH	23,0	Komatsu Diesel Engine	45.544	17234	15826	13228	16720	12761	14085	12693	14465		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	48.167	19092	15718	14252	16553	15946	14897	13837	13847		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	49.980	17382	18701	18202	16788	16856	18894	15586	13937		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	41.329	18279	19669	16527	15917	13808	13874	11642	15401		
PC 4000	Latin America	2007	Coal/OVB	BH	23,0	Komatsu Diesel Engine	45.975	18148	16340	17861	16059	15111	16211	13847	14239		
PC 4000 E	Europe	2008	Coal/OVB	FS	22,0	Electric Motor	30.862	11792	11820	8873	10461	7331	4015				
PC 4000	Asia	2011	Coal/OVB	FS	22,0	Komatsu Diesel Engine	20.819			24275							
PC 4000	Asia	2011	Coal/OVB	FS	22,0	Komatsu Diesel Engine	19.786			25603							
PC 4000	Asia	2014	Coal/OVB	FS	24,0	Komatsu Diesel Engine	5.776	23971									
PC 4000	Australia		Coal/OVB	BH	22,0	Komatsu Diesel Engine	15.753			11156							

Table B.2 Production: PC 5500

								Operation Hours									
Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 5500 E	Europe	2011	Coal/OVB	FS	29,0	2 x Electric	21.106	13315	15097	9595	6264						
PC 5500	Australia		Coal/OVB	BH	34,0	2 x Komatsu Diesel Engines	12.895		15469								
PC 5500 E	Europe	2011	Iron Ore/O'	FS	26,0	2 x Electric Motor	28.982			65247	130829	109005					
PC 5500 E	Europe	2013	Iron Ore/O'	FS	26,0	2 x Electric Motor	12.631	155959	150605								

Table B.3 Production: PC 8000

								Operation Hours									
Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 8000 E	Latin America	2004	Coal/OVB	FS	42,0	Electric 2 x ABB	65.338	19628	23341	18448	16088	20278	17287	20046	17354	16739	17306
PC 8000 E	Latin America	2005	Coal/OVB	FS	42,0	Electric 2 x ABB	56.632	20584	18643	16652	18922	20199	18612	17944	18106	21189	17394
PC 8000 E	Latin America	2005	Coal/OVB	FS	42,0	Electric 2 x ABB	51.785	22069	20212	17346	16812	18502	16738	17883	17526	16073	14703
PC 8000 E	Latin America	2007	Coal/OVB	FS	42,0	Electric 2 x ABB	44.239	23502	22097	20464	20357	22212	21024	17516	8177		
PC 8000 E	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	40.445	23976	23483	21298	18567	19841	20639	14974			
PC 8000 E	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	41.287	23931	22181	24165	20702	22610	19580	19569			
PC 8000 E	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	43.223	22690	22611	20484	20555	18700	16026	16336			
PC 8000 E	Latin America	2008	Coal/OVB	FS	42,0	Electric 2 x ABB	42.247	24274	22433	18071	19434	18219	15968	17190			
PC 8000 E	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	38.957	20405	19905	19788	21145	16245	14655	11815			
PC 8000 E	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	38.190		19952	17513	19859	15523	16380				
PC 8000 E	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	34.795		18841	19552	16992	14623	16468				
PC 8000 E	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	34.568		20095	20071	16500	16625	15543				
PC 8000 E	Latin America	2009	Coal/OVB	FS	42,0	Electric 2 x ABB	33.865		19116	20198	15978	15595	14415				
PC 8000 E	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	18.754	20610	19310	21973							
PC 8000 E	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	18.431	22859	21532	24221							
PC 8000 E	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	17.409	20448	15712	16615							
PC 8000 E	Latin America	2012	Coal/OVB	FS	42,0	Electric 2 x ABB	15.960	17200	17945	14629							
PC 8000 E	Latin America	2013	Coal/OVB	FS	42,0	Electric 2 x ABB	11.934	17992	19871								
PC 8000 E	Latin America	2013	Coal/OVB	FS	42,0	Electric 2 x ABB	10.506	19167	22637								

Table B.4 Production: PC 2000 and R 994

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Operation Hours 0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel	23.379	23814	23689	22315	19963						
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel	21.878	24047	20185	21900	19886						
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel	15.669	22891	19000	20096							
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel	15.667	21064	21289	19400							
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	47.933	17471	14459	15751	12913	15291	15727	15546	13795		
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	45.807	19071	15501	15763	15673	16338	14816	15876	13525		
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	42.999	16102	17342	18088	16880	16036	16152	16175	13364		
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	34.276	15913	12351	15237	14696	16371	13691				

Table B.5 Production: Rope Shovels 0 ÷ 60.000 Operation Hours

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours: 0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
EKG-10	Europe	2005	Coal/OVB	FS	10,0	Electric Motor	53.060	Dec 14	14350	14720	16955	17306	16510	19316	18441	14021	12049	
EKG-12	Europe	2003	Coal/OVB	FS	12,0	Electric Motor	65.795	Oct 14	11652	16083	17792	17050	15287	15966	9961	15408	17489	14190
EKG-12	Europe	2005	Coal/OVB	FS	12,0	Electric Motor	59.056	Dec 14	15358	20333	19759	23050	17122	19288	15731	17492	14420	13938
EKG-12	Europe	2004	Coal/OVB	FS	12,0	Electric Motor	55.356	Dec 14			14870	17856	16274	17619	16427	17214	17470	11017
EKG-15	Europe	2003	Coal/OVB	FS	15,0	Electric Motor	48.992	May 13	12422	15372	12928	11774	11389	11365	10570	9307	4222	
EKG-15	Europe	1991	Coal/OVB	FS	15,0	Electric Motor	>100.000	Dec 14										14149
EKG-18	Europe	2013	Coal/OVB	FS	18,0	Electric Motor	8.313	Dec 14	13514	13583								
EKG-20	Europe	1988	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14								7879	12842	10183
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14										14983
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14								1367	8488	6883
P&H 2300X	Europe	2005	Coal/OVB	FS	20,0	Electric Motor	35.535	Dec 14	15758	19892	10153	7462	8197	8733				
P&H 2300X	Europe	2012	Coal/OVB	FS	16,0	Electric Motor	13.296	Dec 14	25588	21604	13854							
P&H 2800	Europe	2006	Coal/OVB	FS	33,0	Electric Motor	52.617	Dec 14	18727	18357	20736	17644	19146	20441	19475	18038	11791	
P&H 2800	Europe	2006	Coal/OVB	FS	33,0	Electric Motor	45.170	Dec 14	20478	23698	14055	16301	18868	18376	17993	9058		

Table B.6 Production: Rope Shovels 60.000 ÷ 150.000 Operation Hours

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	Last update	Operation Hours 60000 - 66000	66000 - 72000	72000 - 78000	78000 - 84000	84000 - 90000	90000 - 96000	96000 - 102000	102000 - 108000	108000 - 114000	114000 - 120000	120000 - 126000	126000 - 132000	132000 - 138000	138000 - 144000	144000 - 150000
EKG-10	Europe	1990	Coal/OVB	FS	10,0	Electric Motor	>100.000	Dec 14								15406	13125	11638	13012	16448	12298	12731	13511
EKG-10	Europe	1991	Coal/OVB	FS	10,0	Electric Motor	>100.000	Dec 14							10600	14534	13062	13041	10696	14549	14346	15454	
EKG-12	Europe	2003	Coal/OVB	FS	12,0	Electric Motor	65.795	Oct 14	15847														
EKG-12,5	Europe	1990	Coal/OVB	FS	12,5	Electric Motor	>100.000	Dec 14						12000	14436	9134	17126	17674	13623	10817			
EKG-15	Europe	1985	Coal/OVB	FS	15,0	Electric Motor	>100.000	Aug 10								11547	12506	8742	8420				
EKG-15	Europe	1991	Coal/OVB	FS	15,0	Electric Motor	>100.000	Dec 14	11139	11431	11467	10739	10077	9604	5267								
EKG-20	Europe	1988	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14			13952	12909	11279	11038	12790	10258	7208						
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14	10596	12483	12538	12794	10329	12337	11472	12447	13292	14318	13096	9393	10378		
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100.000	Dec 14			10355	8164	11710	13555	10778	8421							
P&H 2300	Europe	1983	Coal/OVB	FS	16,0	Electric Motor	>100.000	Dec 14							10266	10599	10042	11057	12813	12688	10089		
P&H 2300	Europe	1984	Coal/OVB	FS	16,0	Electric Motor	>100.000	Dec 14						8891	7229	8380	10667	13490	13958	12554	13390	15695	12594
P&H 2300	Europe	1984	Coal/OVB	FS	16,0	Electric Motor	>100.000	Dec 14						10047	12453	8344	9133	5214	9984	9712			

APPENDIX C

INDIVIDUAL EXPENDITURE COST VALUES

Table C.1 Expenditure Costs (lease is included): Hydraulic excavators

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000
PC 4000 E	Europe	2008	Coal/OVB	FS	22,0	Electric Motor	**30 862**	0,18	0,31	0,61	0,49	0,63			
PC 5500 E	Europe	2011	Coal/OVB	FS	29,0	2 x Electric	21 106	0,21	0,49	1,09					
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel	23 379	0,24	0,36	0,39	0,40				
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel	21 878	0,53	0,53	0,51					
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel	15 669	0,43	0,74						
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel	15 667	0,56	0,50						
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	**47 933**		0,30	0,22	0,45	0,89	0,40	0,89	0,36
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	45 807	0,29	0,33	0,39	0,50	0,61	0,40	0,37	
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	42 999		0,31	0,30	0,68	0,47	0,59	0,71	
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel	34 276		0,24		0,49	0,93	0,49	0,29	

Table C.2 Expenditure Costs (lease is excluded): Hydraulic excavators

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000
PC 4000 E	Europe	2008	Coal/OVB	FS	22,0	Electric Motor	**30 862**	0,07	0,17	0,45	0,34	0,31			
PC 5500 E	Europe	2011	Coal/OVB	FS	29,0	2 x Electric Motor	21 106	0,11	0,12	0,23					
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel Engine	23 379	0,01	0,15	0,20	0,20				
PC 2000	Europe	2011	Coal/OVB	BH	10,0	Komatsu Diesel Engine	21 878	0,15	0,20	0,32					
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel Engine	15 669	0,17	0,25						
PC 2000	Europe	2012	Coal/OVB	BH	10,0	Komatsu Diesel Engine	15 667	0,19	0,21						
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	**47 933**		0,20	0,12	0,34	0,79	0,30	0,79	0,25
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	45 807	0,21	0,23	0,29	0,40	0,51	0,30	0,26	
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	42 999		0,23	0,22	0,59	0,37	0,50	0,55	
R 994	Europe	2007	Coal/OVB	BH	11,0	Diesel Engine	34 276		0,14		0,39	0,82	0,40	0,18	

Table C.3 Expenditure Costs (lease is included): Rope shovels 0 ÷ 60.000 Operation Hours

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
EKG-10	Europe	2005	Coal/OVB	FS	10,0	Electric Motor	53 060				0,13	0,18	0,18	0,21	0,38	0,54	
EKG-12	Europe	2003	Coal/OVB	FS	12,0	Electric Motor	65 795						0,10	0,27	0,21	0,22	0,29
EKG-12	Europe	2005	Coal/OVB	FS	12,0	Electric Motor	59 056				0,06	0,14	0,14	0,50	0,22	0,27	0,24
EKG-12	Europe	2004	Coal/OVB	FS	12,0	Electric Motor	55 356					0,14	0,13	0,31	0,27	0,23	0,37
EKG-15	Europe	2003	Coal/OVB	FS	15,0	Electric Motor	48 992					0,15	0,10	0,24	0,12		
P&H 2300XP	Europe	2005	Coal/OVB	FS	20,0	Electric Motor					0,23	0,26	0,26				
P&H 2300XPC	Europe	2012	Coal/OVB	FS	16,0	Electric Motor		0,69	2,06								
P&H 2800	Europe	2006	Coal/OVB	FS	33,0	Electric Motor				0,23	0,24	0,21	0,17	0,22	0,22	0,44	
P&H 2800	Europe	2006	Coal/OVB	FS	33,0	Electric Motor			0,15	0,40	0,22	0,25	0,24	0,22	0,46		

Table C.4 Expenditure Costs (lease is excluded): Rope shovels 0 ÷ 60.000 Operation Hours

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	0 - 6000	6000 - 12000	12000 - 18000	18000 - 24000	24000 - 30000	30000 - 36000	36000 - 42000	42000 - 48000	48000 - 54000	54000 - 60000
EKG-10	Europe	2005	Coal/OVB	FS	10,0	Electric Motor	53 060				0,06	0,10	0,11	0,12	0,29	0,23	
EKG-12	Europe	2003	Coal/OVB	FS	12,0	Electric Motor	65 795						0,04	0,19	0,15	0,16	0,22
EKG-12	Europe	2005	Coal/OVB	FS	12,0	Electric Motor	59 056				0,02	0,08	0,09	0,42	0,16	0,20	0,16
EKG-12	Europe	2004	Coal/OVB	FS	12,0	Electric Motor	55 356					0,09	0,09	0,26	0,23	0,18	0,25
EKG-15	Europe	2003	Coal/OVB	FS	15,0	Electric Motor	48 992					0,14	0,09	0,23	0,11		
P&H 2300XP	Europe	2005	Coal/OVB	FS	20,0	Electric Motor					0,15	0,18	0,20				
P&H 2300XP	Europe	2012	Coal/OVB	FS	16,0	Electric Motor		0,11	0,14								
P&H 2800	Europe	2006	Coal/OVB	FS	33,0	Electric Motor				0,16	0,12	0,14	0,10	0,14	0,14	0,18	
P&H 2800	Europe	2006	Coal/OVB	FS	33,0	Electric Motor			0,08	0,27	0,13	0,17	0,16	0,14	0,14		

Table C.5 Expenditure Costs (lease is included): Rope shovels 60.000 ÷ 150.000 Operation Hours

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	60000 - 66000	660001- 72000	72000 - 78000	78000 - 84000	84000 - 90000	90000 - 96000	96000 - 102000	102000 - 108000	108000 - 114000	114000 - 120000	120000 - 126000	126000 - 132000	132000 - 138000	138000 - 144000	144000 - 150000
EKG-10	Europe	1990	Coal/OVB	FS	10,0	Electric Motor	>100000									0,08	0,06	0,07	0,11	0,28	0,11	0,17
EKG-10	Europe	1991	Coal/OVB	FS	10,0	Electric Motor	>100000									0,10	0,07	0,35	0,08	0,08	0,13	
EKG-12	Europe	2003	Coal/OVB	FS	12,0	Electric Motor	65 795	0,16														
EKG-12,5	Europe	1990	Coal/OVB	FS	12,5	Electric Motor	>100000						0,04	0,04	0,07	0,07	0,14	0,05	0,07			
EKG-15	Europe	1985	Coal/OVB	FS	15,0	Electric Motor	>100000									0,04	0,05	0,07				
EKG-15	Europe	1991	Coal/OVB	FS	15,0	Electric Motor	>100000					0,06	0,07									
EKG-18	Europe	2013	Coal/OVB	FS	18,0	Electric Motor	8 313															
EKG-20	Europe	1988	Coal/OVB	FS	20,0	Electric Motor	>100000					0,03	0,25	0,14	0,23	0,25						
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100000						0,17	0,16	0,12	0,21	0,23	0,21	0,36			
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100000			0,23	0,16	0,14	0,16	0,19	0,25							
P&H 2300	Europe	1984	Coal/OVB	FS	16,0	Electric Motor														0,15	0,19	0,16
P&H 2300	Europe	1984	Coal/OVB	FS	16,0	Electric Motor													0,16			

Table C.6 Expenditure Costs (lease is excluded): Rope shovels 60.000 ÷ 150.000 Operation Hours

Type	Area	Commissioning Year	Material	Attachment Type	Bucket (cum)	Main Drive	Machine Hours	60000 - 66000	660001- 72000	72000 - 78000	78000 - 84000	84000 - 90000	90000 - 96000	96000 - 102000	102000 - 108000	108000 - 114000	114000 - 120000	120000 - 126000	126000 - 132000	132000 - 138000	138000 - 144000	144000 - 150000
EKG-10	Europe	1990	Coal/OVB	FS	10,0	Electric Motor	>100000									0,08	0,06	0,07	0,11	0,28	0,11	0,17
EKG-10	Europe	1991	Coal/OVB	FS	10,0	Electric Motor	>100000									0,06	0,06	0,35	0,08	0,08	0,13	
EKG-12	Europe	2003	Coal/OVB	FS	12,0	Electric Motor	65 795	0,09														
EKG-12,5	Europe	1990	Coal/OVB	FS	12,5	Electric Motor	>100000						0,04	0,04	0,07	0,07	0,14	0,05	0,07			
EKG-15	Europe	1985	Coal/OVB	FS	15,0	Electric Motor	>100000									0,04	0,05	0,07				
EKG-15	Europe	1991	Coal/OVB	FS	15,0	Electric Motor	>100000					0,06	0,07									
EKG-20	Europe	1988	Coal/OVB	FS	20,0	Electric Motor	>100000					0,03	0,24	0,14	0,23	0,25						
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100000						0,14	0,13	0,10	0,17	0,18	0,16	0,27			
EKG-20	Europe	1990	Coal/OVB	FS	20,0	Electric Motor	>100000			0,21	0,14	0,13	0,15	0,18	0,22							
P&H 2300	Europe	1984	Coal/OVB	FS	16,0	Electric Motor														0,15	0,18	0,16
P&H 2300	Europe	1984	Coal/OVB	FS	16,0	Electric Motor													0,15			