Condition Monitoring of Large-Scale Slew Bearings in Bucket-Wheel Boom-Type Reclaimers

A Diploma Thesis

by

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June 2016

To the ones I care about most.

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Acknowledgements

First of all, I want to thank Professor Paul O'Leary for his dedicated supervision, for the fruitful discussions, for his endurance throughout the course of the work done for this thesis, and for introducing me to the concept of *welcome everything, push away nothing.* I also want to thank everyone at the Chair of Automation who supported me in my work.

At Sandvik Mining Systems, I want to address my thanks to my former manager Frank Feger, who was one of the few who believed in our initial idea for this thesis from day one and whose mentorship I valued. Many thanks as well to my supportive colleagues, especially to Gottfried Poier, Gordon Ziske, Joachim Vorauer and Thomas Kaltenberger for their critical input, for their encouraging colleagueship, and for supporting me in my professional training and development during my daily work at Sandvik Mining Systems. Thank you, Gordon, for reviewing my calculations done for this thesis.

My uttermost thanks go to my closest family, who supported me throughout the process of developing this thesis. At this point I am glad to honour my father Josef, who gifted me with invaluable memories before passing away. You are missed by everyone. My honest gratitude goes to my mother Ingrid, who did everything to raise my sister and me with the most honest values so we have become open-minded and kind persons who pursue their goals with passion. A big thank you to my sister Anita for always supporting me and for being a role model of integrity and business understanding. I address my boundless gratitude to my beloved significant other Kerstin, who inspires me since the day we met. Apart from giving me motivation for my work every day, she supported me with careful proofreading and addressed my almost endless questions regarding linguistic matters. Thank you for coping with my many flaws. Last but not least, I want to thank my dear friend Andreas for his supportive mentorship.

Words alone cannot express my gratitude for my fortune of having such lovely and inspiring people around me.

Abstract

This thesis examines solutions for condition monitoring of slew bearings, which are main components of bucket-wheel boom-type reclaimers. A detailed overview of the function of this type of reclaimer is given and the characteristics of slew bearings are described. A sample design calculation of a slew bearing is performed to illustrate influencing factors. Extensive studies on failure modes and their probable causes are discussed. Established as well as potential ways of monitoring the condition of slew bearings are outlined. These methods of monitoring are based solely on observing the effects of wear and damage on slew bearings. The concept of *data mining* is introduced to assess the causes of excessive wear and damage of slew bearings. Historical operational sensor data of reclaimers is analysed using physical models. These models correspond to inverse problems that are solved by using Linear Differential Operators and their inverses. The findings of these analyses are presented in this thesis. Finally, a framework for data mining is suggested, which can be used to describe mechanisms of collecting, storing, analysing, and evaluating sensor data.

Index terms

data mining ; cyber-physical systems ; condition monitoring ; predictive maintenance ; slew bearing ; reclaimer ; operational data ; linear differential operators ; data analytics ; lexical analysis

Kurzfassung

Diese Diplomarbeit befasst sich mit möglichen Ansätzen zur Zustandsüberwachung von Schwenklagern, welche zu den Hauptbauteilen von Schaufelrad-Ausleger-Rückladegeräten zählen. Zunächst wird ein detaillierter Überblick über die Funktionsweise dieser Art von Rückladegeräten gegeben und die Eigenschaften der eingesetzten Schwenklager werden beschrieben. Als Beispiel erfolgt die Dimensionierung eines Schwenklagers um Einflussfaktoren zu verdeutlichen. Umfassende Studien über Fehlermöglichkeiten und deren wahrscheinliche Ursachen werden besprochen. Etablierte wie auch potenzielle Methoden zur Überwachung des Zustandes von Schwenklagern werden umrissen. Diese Monitoring-Methoden basieren ausschließlich auf der Beobachtung der Auswirkungen, die Verschleiß und Beschädigungen auf Schwenklager haben. Um die Ursachen für übermäßigen Verschleiß und starke Beschädigungen an Schwenklagern bestimmen zu können, wird das Konzept *Data Mining* vorgestellt. Historische Betriebsdaten von Sensoren, die auf Rückladegeräten installiert sind, werden mithilfe physikalischer Modelle analysiert. Diese Modelle entsprechen inversen Problemen, die durch die Verwendung von Linear Differential Operators, und deren Umkehrfunktionen, gelöst werden. Die Ergebnisse dieser Analysen werden in der vorliegenden Diplomarbeit präsentiert. Abschließend wird ein Framework für Data Mining vorgeschlagen, das verwendet werden kann, um Abläufe für die Sammlung, Speicherung, Analyse und Auswertung von Sensordaten zu beschreiben.

Schlagwörter

Data Mining ; Cyber-Physical Systems ; Condition Monitoring ; Zustandsüberwachung ; Zustandsorientierte Wartung ; Schwenklager ; Großwälzlager ; Rückladegerät ; Betriebsdaten ; Linear Differential Operators ; Datenanalyse ; Lexical Analysis

Contents

Chapter 1

Introduction

The motivation for this thesis is rooted in the significance of machine availability. As reclaimers are main parts of bulk materials handling processes, shutdowns are bound to high economic risks. For example, a reclaimer has a throughput capacity of 12,400 metric tons per hour. Currently, the price for one dry metric ton of iron ore fines is at approximately 55.13 US dollars[1]. Although the current price level is far below that of the last economic commodity super-cycle, one hour of downtime accumulates to approximately 680,000 US dollars worth of unhandled material. Subsequent processes, such as the loading of vessels, are influenced as well and cause further costs. Such enormous amounts pose serious economic risks for operating companies.

Sophisticated methods for condition monitoring of the main components are key to maintaining a high machine availability and to avoiding unplanned shutdowns and sudden breakdowns. Slew bearings are main components of reclaimers and knowing about the condition of these bearings is crucial to the machines' availability. The aim of this thesis is to generate generic solutions for monitoring the condition of such slew bearings.

[1]Source: `www.finanzen.at/rohstoffe/eisenerz`. Retrieved on 2016-05-27.

Chapter 2

System overview

2.1 Stockyard systems

Stockyards are primarily utilised for the storage of bulk materials. Linear stockyards are more common than circular ones, because circular stockyards have a limited range of use. Highly abrasive materials, such as raw iron ore, lead to severe abrasion of the scraper systems usually designed for reclaiming material from circular stockyards. Furthermore, circular stockyards are commonly designed with an encasing dome. This dome is intended to either protect the bulk material from the environment, e.g., potash, or protect the environment from the bulk material, e.g., loose mill scale.

Linear stockyards are most common for the storage of coal or iron ore. These types of stockyards can be used to store several forms of iron ore, such as pellets or abrasive crushed raw material. As Hinterholzer and Kessler [1] point out, stockyards are also used for material blending and homogenisation of different grades of material beyond general storage purposes. There are several areas of application where stockyards can be necessary. A case example is a complete bulk material handling system from mine to port as illustrated in Figure 2.1.

In this example, material is excavated from the ground in the mine. If the material has a relatively low compressive strength (below 20 MPa), it is considered for mining with soft rock mining equipment, e.g., via a bucket-wheel excavator as shown by Schröder [2] as well as by Bell, Cripps and Culshaw [3]. Soft types of coal, such as lignite, can be excavated using such a machine. Blasting is used to extract harder materials, such as more compact and harder types of coal, e.g., anthracite, or iron ore, out of the ground. After blasting, the loose material can be loaded via ordinary excavators or front-end loaders onto trucks, which deliver the raw material to a crusher. The material is crushed to achieve a more homogeneous grain size distribution. After the crushing process, material is loaded onto a conveyor belt, called yard belt, which conveys the material to a stockyard system. The material is then systematically heaped onto a stockpile via a rail-mounted stacker. Depending on the desired cross section of the stockpile, the stacker has to be: only luffable for a Chevron shape as illustrated in Figure 2.5; or both luffable and slewable for the more advanced Windrow

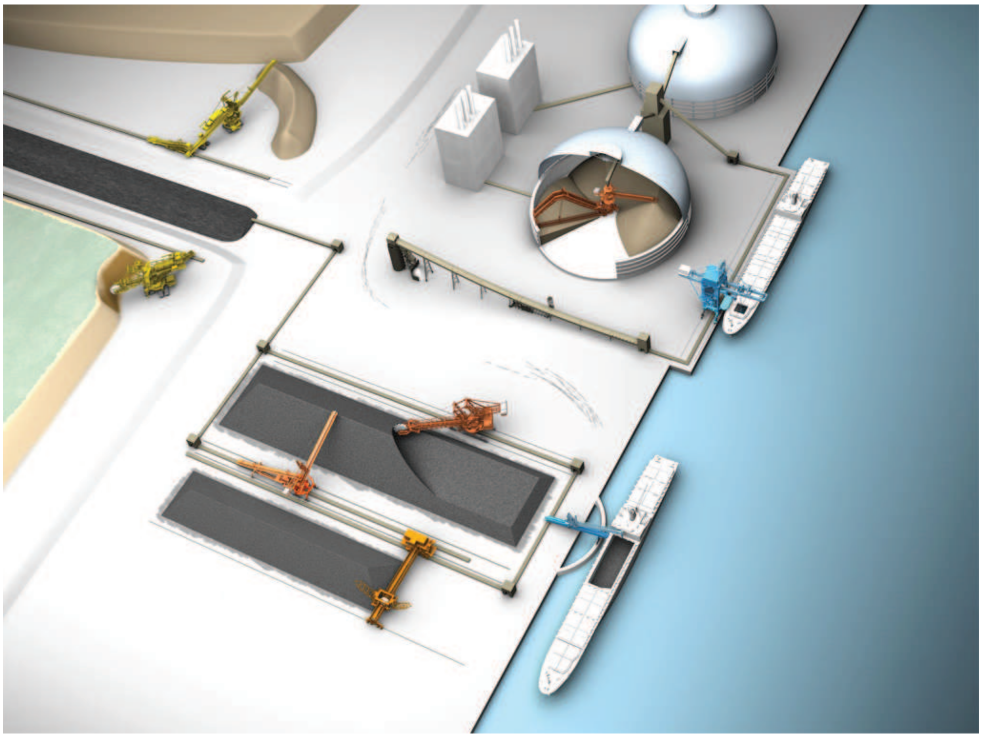


Figure 2.1: Overview of a possible stockyard layout (courtesy of Sandvik)

method of stockpiling as shown in Figure 2.6.

The main advantage of the Windrow method is that a higher level of homogenisation can be achieved, since the different grades of the material are already spread all over the width of the stockpile's cross section. In the case illustrated in Figure 2.1, the stockyard is not only needed for the homogenisation of bulk material, but also acts as a buffer. When a bulk material vessel arrives, it has to be loaded with the material immediately, without having to wait for material to be conveyed directly from the mine. A rail-mounted reclaimer is used for reclaiming the material from the stockyard. The most common type of reclaimer for such a system in iron ore materials handling is a bucket-wheel boom-type reclaimer. This thesis focuses on this particular type of reclaimer.

2.2 Bucket-wheel boom-type reclaimer

2.2.1 Overview

Figure 2.2: Bucket-wheel boom-type reclaimer (courtesy of Sandvik)

A bucket-wheel boom-type reclaimer is shown in Figure 2.2. It is a PR200 reclaimer of Sandvik Mining Systems, which has been in operation for over ten years. This particular machine handles iron ore at a stockyard at a port in Australia. It is designed to deliver iron ore to ship loaders, which load the material through hatches into the holes of bulk vessels. The boom conveyor is equipped with a belt of 1,800 mm width to reach a nominal reclaim capacity of 12,400 metric tons per hour. The boom has a length of 49.5 m when measured from the machine's slewing axis to the axis of the bucket-wheel at the tip of the boom. Multiple such machines are in operation under similar conditions in Australia. This makes this type of reclaimer interesting for detailed research, in particular with respect to fleet management. Throughout this thesis, the term *reclaimer* will be used for bucket-wheel boom-type reclaimers.

2.2.2 Main assembly groups

In general, a reclaimer consists of an undercarriage and a superstructure which are connected by a slewable device. A rotating bucket-wheel mounted on the tip of a luffable boom reclaims material from a stockpile. A conveyor belt mounted on the boom conveys the material to the centre of the reclaimer, where the material falls through a chute onto a yard belt.

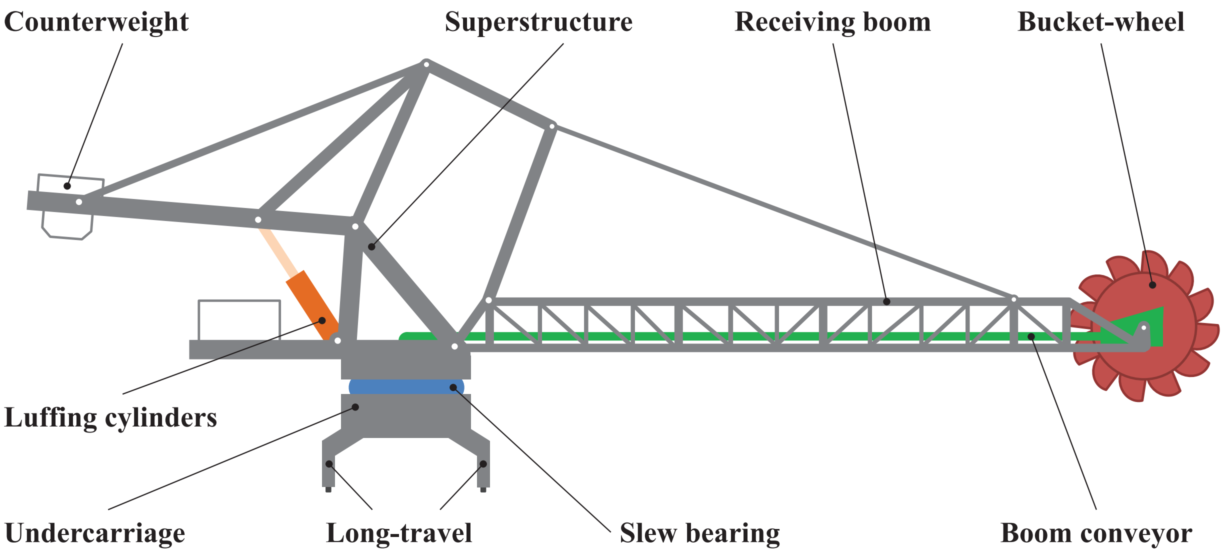


Figure 2.3: Sandvik PR200 reclaimer

2.2.2.1 Long-travel assembly group

This kind of reclaimer is rail-mounted. The rails run alongside the linear stockpile(s) of the stockyard. The yard conveyor belt is located in between the rails. It is used for conveying reclaimed material from the stockpile(s) to the destination, e.g. a ship loading facility. The reclaimer is supported by a system of bogies, which distribute the load of the reclaimer onto multiple wheels. There are driven and non-driven wheel sets. Every driven wheel is powered by a separate motor (long-travel drives). Brakes are mounted on the long-travel drives to ensure control over starting and stopping the reclaimer's movements on the rails. Rail cleaners and rail clamps are also mounted on the long-travel assembly group. The rail clamps are used for locking the reclaimer in position for a longer period of time or in case of a storm.

2.2.2.2 Slewing assembly group

The boom of the reclaimer can be slewed around its centre axis. The superstructure is connected to the undercarriage via a slew bearing. For the described type of reclaimer, a slew bearing consisting of a combination of roller bearing and ball bearing is used. The rollers carry the vertical load of the superstructure while the balls carry the horizontal load as well as uplifting forces caused by a tilting moment.

Teeth are located on the outside of the bearing. The pitch circle diameter of the slew bearing is 6,672 mm [4]. Slew drives are utilised for rotating the superstructure with respect to the undercarriage; this relative movement is called *slewing*. Three separate slew drives are distributed along the circumference of the slew bearing. Each slew drive is mounted on the superstructure. Also, the upper half of the slew bearing is connected to the superstructure using bolts. The slew drives turn the lower half of the slew bearing, where the teeth are mounted. All three slew drives are used to rotate the superstructure at the same time.

2.2.2.3 Luffing assembly group

The design with a counterweight boom ensures that the luffing cylinders do not have to carry the full load of the boom and all the equipment and material on it. The machine is counter-balanced to reduce the load the cylinders have to carry.

Two hydraulic cylinders are used to luff the boom up and down. The reclaimers are designed so that every luffing movement is carried out by both cylinders. In case of a cylinder replacement or an emergency breakdown of one of the cylinders, the reclaimer is capable of holding its position and making rudimentary movements with one cylinder ensuring motional integrity.

2.2.2.4 Bucket-wheel assembly group

The bucket-wheel is located at the tip of the reclaimer's boom. It consists of a rigid wheel with buckets mounted along its circumference. During operation, the bucket-wheel rotates and digs material from the stockpile, which is then loaded onto the boom conveyor. The shaft of the bucket-wheel is connected to a gearbox and the bucket-wheel drive. A fluid coupling and a brake for the drive are also installed. The drive torque is transferred via a torque arm, which connects the bucket-wheel drive and the boom tip's steel structure.

2.2.2.5 Boom conveyor assembly group

A boom conveyor is utilised to convey reclaimed material from the tip of the boom to the centre of the machine, where the centre chute is located. Material falls through the centre chute onto the yard belt so that the material can be conveyed to its destination. To keep the tilting moment of the boom at a modest level, the drive with the gearbox of the boom conveyor is located near the centre chute of the reclaimer, not at the tip of the boom. A tension station at the other end ensures proper operation of the conveyor.

2.2.3 Working methods

2.2.3.1 Layouts of stockpiles

A stockyard usually consists of several stockpiles. Bucket-wheel boom-type reclaimers are designed to serve linear stockpiles within stockyards. Linear stockpiles are heaped up by stackers. The stockpiles are stacked parallel to the long-travel rails of stackers and reclaimers. Depending on the type of stacker, different cross section layouts for stockpiles can be achieved. The most important stockpile structures in conjunction with the use of bucket-wheel boom-type reclaimers are the Chevron and Windrow methods [1], [5]. Combinations of both are also used [6]. The different cross sections of stockpiles enable blending and homogenisation of the different grades of bulk material. Stockpiles are also utilised as buffers for bulk material at ship or train loading facilities or at power plants when coal is the material handled.

Figure 2.4: Longitudinal stockyard (courtesy of Sandvik)

Chevron method

To achieve a Chevron-type stockpile, material is always stacked in the centre of the stockpile. The stacker pours material off the tip of the boom while the stacker travels slowly along the stockyard; a longitudinal heap is created. At the stockpile's end, the stacker luffs up the boom and reverses its long-travel movement, so that material is heaped on top of the bottom layer just created before.

The distance between the tip of the stacker (where material is being poured off the boom conveyor) and the long-travel rails of the stacker stays the same at all times. As the long-travel speed of the stacker and the material flow stay the same during the stacking operation, the separate layers of the stockpile have the same cross sectional area. Hence, the thickness of the different layers decreases with increasing stockpile height. This promotes material segregation. Coarse material glides off the slope of the stockpile while fine material remains at the top. The fine material sticks together and forms conglomerates on the top of the stockpile's front face. This can cause stockpile collapses. As a result, material will fall onto the reclaiming machine causing it to be overloaded. Following the overload detection by the reclaimer (usually when a defined limit of bucket-wheel drive current is reached), the reclaiming operation has to be interrupted by stopping slewing while the bucket-wheel usually continues to rotate. The boom conveyor is not stopped, so that the excessive material already on the boom can be removed.

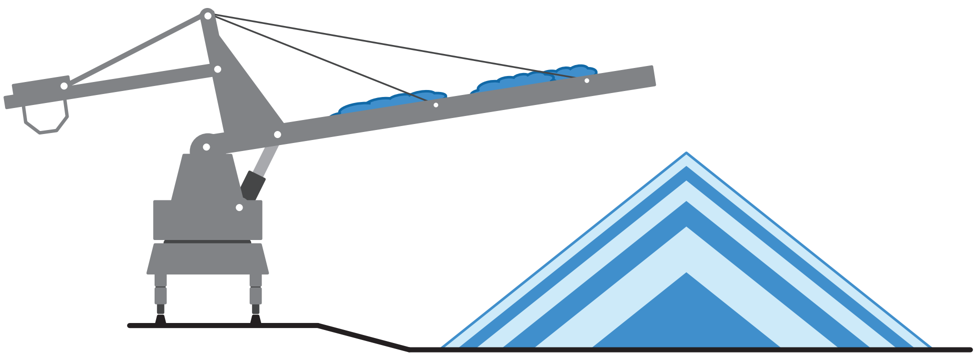


Figure 2.5: Chevron method stockpile

Windrow method

In contrast to the Chevron stacking method, a stacker pours material onto several longitudinal heaps side by side to create a stockpile with the Windrow method. After the first (bottom) level is done, the stockpile is raised by filling the gaps in between the longitudinal heaps at the bottom. The stacker starts at one side of the stockpile. After finishing the first heap over the full longitudinal length of the desired stockpile, the stacker will continue with the second heap by travelling in the other direction on the rails. This procedure is repeated until the top of the stockpile is reached by following the scheme illustrated in Figure 2.6.

With this method, size segregation of the bulk material is decreased, because smaller heaps cause less coarse material to glide down the slopes.

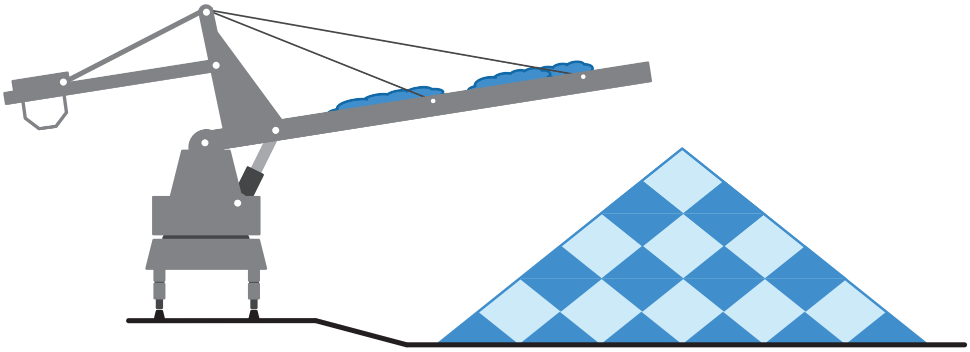


Figure 2.6: Windrow method stockpile

2.2.3.2 Method of reclaiming

To reclaim material from a stockpile, a reclaimer uses its three main movement assembly groups. There is not just one single way of how the software for the reclaiming operation is implemented, as restricting specifications and requirements by clients make custom-fit solutions necessary. The differences in movement sequences while reclaiming can range from minor to fundamental discrepancies: the major differences throughout the international market are provoked by software interlocks between moving assembly groups. These interlocks are often demanded to meet specific safety regulations enforced in different countries. This has to be considered when reclaimers or similar types of heavy-duty machinery are analysed.

Basically, there are two different types of reclaiming operations. Reclaiming can be done via *front-acting* as well as *side-acting* operation [1].

Front-acting operation

Reclaiming via front-acting operation means that the reclaimer's boom is slewed against the stockpile. According to Wöhlbier [6], this operation is also called *slewing*. Slewing of the boom covers the whole width of the stockpile. Following the conventional front-acting operation, the bucket-wheel rotates already when the cut is begun. The bucket-wheel still rotates when it leaves the stockpile at the other side. This is illustrated in Figure 2.7 (*reclaimed area*). After one slewing operation is completed, the reclaimer is moved along the rails to make the next cut by slewing in the opposite direction. The longer the bucket-wheel does not reclaim material while rotating, the more the reclaimer's efficiency is decreased. To fulfill the demand for reclaimed material, the reclaiming process consists of several slewing operations. Due to this fact, the time during which the bucket-wheel is not loading material onto the boom conveyor but is "shoveling air" outside the stockpile, adds up to significant time lost.

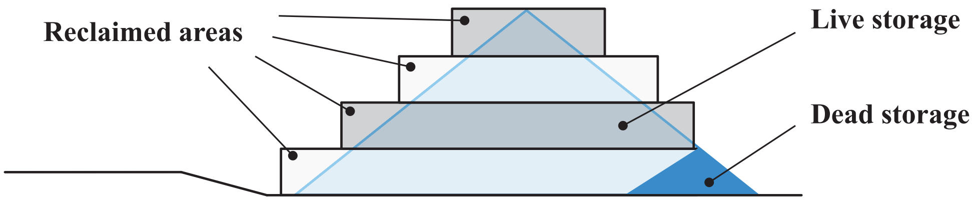


Figure 2.7: Reclaiming areas of stockpile cross section

Side-acting operation

If the slew angle stays the same throughout the reclaiming operation and the reclaimer continuously moves along the rails, the operation is called side-acting.

Figure 2.8: Trench cutting operation (courtesy of Sandvik)

The load of the superstructure onto the undercarriage during the reclaiming operation varies only in amplitude, not in location. It is assumed that heavy usage of this reclaiming mode has a negative impact on the life span of a slew bearing. Nevertheless, the side-acting operation is necessary for special layouts of stockpiles, where the lowest bench of the stockpile is below the rail level of the reclaimer. Side-acting operation is often called *trench cutting*, because a trench is excavated. Wöhlbier [6] also refers to *trenching* when writing about side-acting operation. This trench prevents protruding parts of the boom, e.g., the bucket-wheel drive, from colliding with the bulk material.

2.2.3.3 Operation modes

Reclaimers can be operated in *manual*, *semi-automatic* and *fully automatic* modes. Besides specific modes for maintenance purposes, every reclaimer can be operated in manual mode. Every movement can be controlled by the operator, and by him only. The luffing of the reclaimer is done separately from the slewing; there are two different user controls, e.g., joysticks, for these operations. No movement is done by the reclaimer without the intervention of the operator.

Semi-automatic mode can assist the operator by taking over repetitive and simple actions necessary for the reclaiming operation. For instance, if a reclaimer is at the right long-travel position, the operator can choose a specific bench that has to be reclaimed. The luffing unit then adapts the vertical position of the boom to the height required for the respective bench. An operator can often also define a slew range, within which the reclaimer has to operate to reclaim material. This applies to semi-automatic modes, which are only able to carry out automatic movements within one slewing operation. If safety regulations allow it, complete reclaiming sequences can be carried out by additional automatic controlling of forward or backward long-travel movement.

Fully automatic modes are only safe to be implemented, if the operation is completely manless. While manual and semi-automatic operating modes always require an operator, fully automated reclaimers can be operated without direct human intervention. Usually, reclaimers operated in this way are utilised in fully automated stockyards, where nobody is allowed to enter the hazardous operating area of a reclaimer. The parameters limiting slewing, luffing and long-travelling are provided by an operating centre rather than by an operator located in a cabin on the reclaimer. Other interfering machines and objects have to be considered in a fully automatic operation concept as well. Other machines operating within nearby or same areas have to be interlocked on the software level. If software interlocks are not possible, as this is the case with autonomous equipment (e.g. bulldozers operating on the same stockpiles), sophisticated collision avoidance systems have to be utilised to ensure safe operations without collisions. There are several systems available on the market. For instance, systems based on laser triangulation or radar technology are used as collision avoidance systems.

2.2.3.4 Quadrant operation

The theoretical slewing range of reclaimers of 360 degrees is divided into four slewing quadrants, *quadrant I* to *quadrant IV*. The numbering varies from machine to machine. An example is given in Figure 2.9. The dark segments of the different quadrants indicate the actual operation ranges. A reclaimer is designed to reclaim material within these operation ranges only to ensure structural integrity and safety against machine overturning. Slewing is not allowed outside these operation ranges during the reclaiming operation as per design.

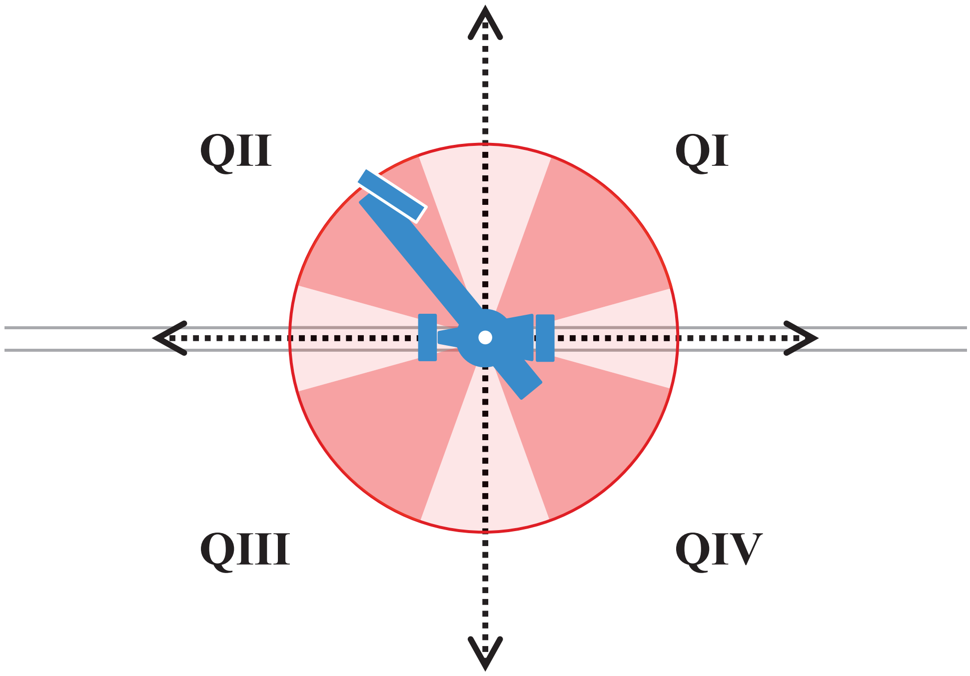
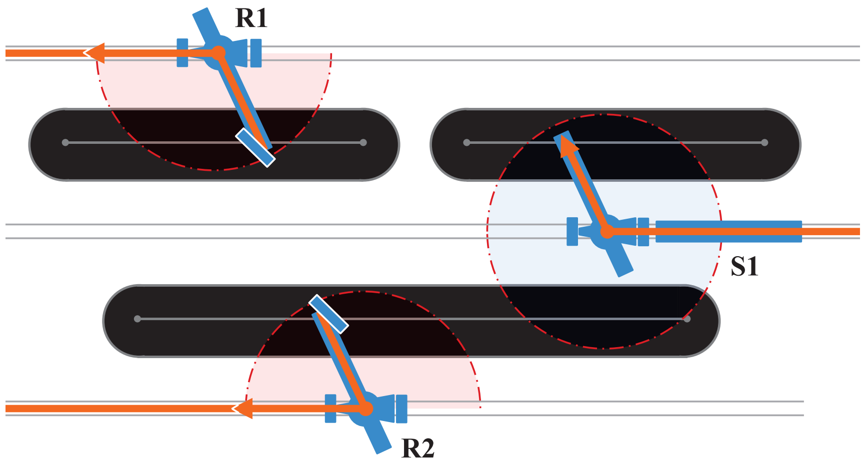
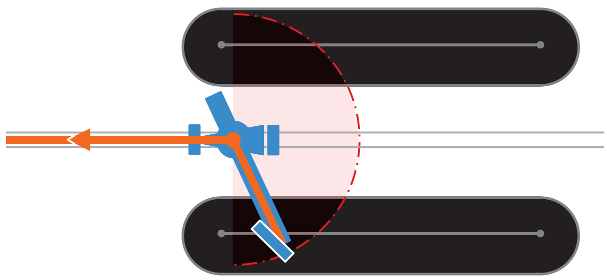


Figure 2.9: Overview of slewing quadrants

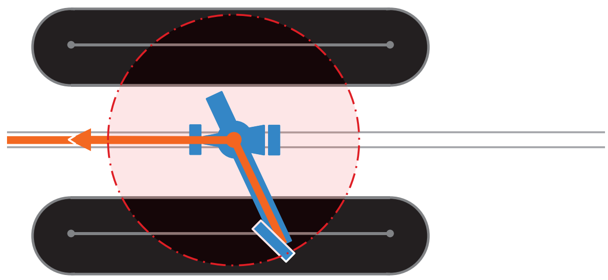
Depending on the stockyard layout, a reclaimer is not always operated in all possible slewing quadrants. The layout in Figure 2.10(a) shows a stacker (*S1*) in four quadrant mode and two reclaimers (*R1*, *R2*), each operable in two quadrants only (*QIII*, *QIV* and *QI*, *QII* respectively). The layout in Figure 2.10(b) represents a reclaimer, which is reclaiming material by going along the long-travel in one direction only. In normal operation, this reclaimer only operates in two slewing quadrants (*QI*, *QIV*).



(a) Two reclaimers (R1, R2) operating in two quadrants respectively, one stacker (S1) operating in all four quadrants



(b) Reclaimer operating in two quadrants only



(c) Reclaimer operating in all four quadrants

Figure 2.10: Reclaimers with different quadrant operations

The most common layout is illustrated in Figure 2.10(c), where a reclaimer operates in all four quadrants. However, not all quadrants might be utilised equally. Utilisation distribution during operation can be part of the outcome of data analyses. The results may reveal unfavourable utilisation of the slew bearing. Operation in all four possible slewing quadrants is called *four quadrant operation*. The details and limits of the slewing operation are considered in the design phase of the reclaimer. Segments of the different quadrants are specified by design as areas available for reclaiming operation to ensure safety against overturning.

2.2.4 Slew control

The reclaiming action of a bucket-wheel boom-type reclaimer can be compared to the terrace cut operation mode of a bucket-wheel excavator, as described in [7]. However, there are two main differences that have to be considered. First, material handled by a reclaimer is already pre-processed. This means that the material is loosened and does not have to be excavated from the dense ground. This provides ideal conditions for a constant reclaiming operation.

Secondly, it has to be mentioned that the operating area of a rail-mounted reclaimer is reduced by the area reserved for the rails, which are needed to move the reclaimer along the long-travel. The principles used for bucket-wheel excavators can be applied to reclaimers serving triangular stockpiles as well.

As indicated in Figure 2.11, there is a geometrical relationship between cutting depth t_α and slewing angle α [7]. The slewing angle is often also referred to as ϕ in other scientific works [8]. The integration of the relation between cutting depth and slewing angle into the machine control systems is often called $cos(\alpha)$ *control* or $cos(\phi)$ *control*. The idealised cut the reclaimer digs out of the stockpile, as seen in Figure 2.11, is sickle-shaped. This sickle-shaped cut is of consistent volume to ensure a continuous and steady material flow while reclaiming.

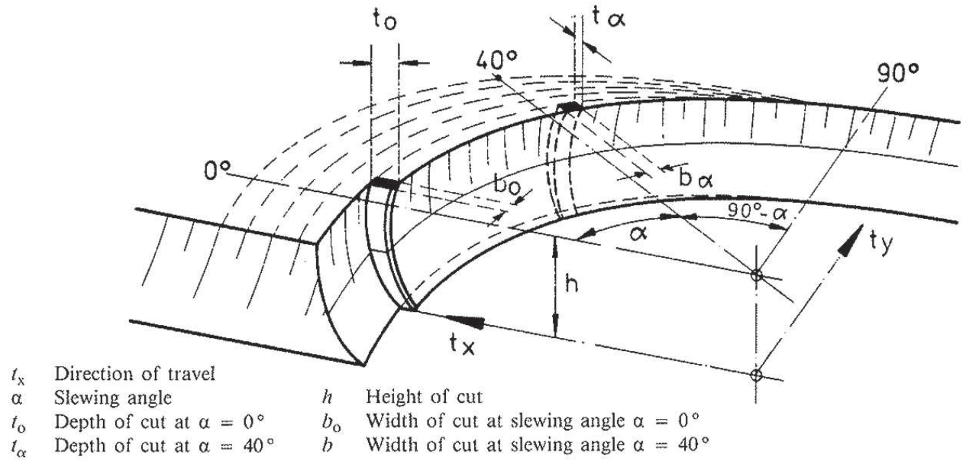


Figure 2.11: Relation between cutting depth and slewing angle [7]

As the reclaimer slews its boom further into the stockpile, the cutting depth t_α decreases, following the relation [7]

$$t_\alpha = t_0 \cdot cos(\alpha) \ . \tag{2.2.1}$$

To maintain constant material flow throughout the reclaiming operation, the slewing speed has to be increased accordingly, so that the decreasing cutting depth can be compensated for. The slewing speed v_α then follows the relation [8]

$$v_\alpha = \frac{v_0}{cos\alpha} \ . \tag{2.2.2}$$

Following the equation 2.2.2, the slewing speed increases as the boom of the reclaimer converges towards $\alpha = 90°$. Especially between 60° and 90°, the slewing speed increases drastically. In real operation environments, the slewing speed is not increased continuously until reaching 90°. Otherwise the slewing speed would reach impractically high numbers [8]. However, the slewing speed is increased to a maximum before it reaches 90°. Usually, stockyard designs allow reclaimers to cover the whole width of stockpiles without reaching a 90° slewing angle.

Chapter 3

Slew bearings of bucket-wheel reclaimers

Slew bearings are one of the main assembly groups of mobile slewable machines. The properties and condition of slew bearings are crucial to every type of slewable machinery, such as stackers, spreaders, bucket-wheel excavators, belt wagons, ship loaders, and reclaimers. Different types of slew bearings are illustrated in Figure 3.1. Slew bearings of types *a)* and *c)* are often used in bucket-wheel boom-type reclaimers and bucket-wheel excavators. The latter are often used in highest load scenarios [9].

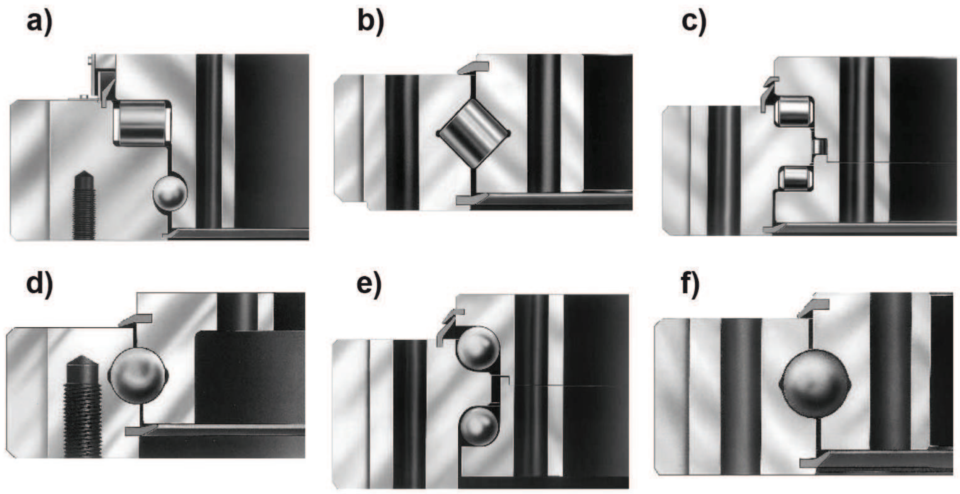


Figure 3.1: Cross sections of different types of slew bearings [10]

3.1 Fundamentals and design criteria

3.1.1 Geometry

The slew bearing illustrated in Figure 3.2 is used for the type of reclaimer described in this thesis. The slew bearing consists of two rings, an inner ring *1* and an outer ring *2* with gear teeth *5* on the outside. Both slew bearing rings are made of *42CrMo4V* with hardened roller surfaces [4]. A row of rollers *3* is utilised for axial load transmission while a row of balls *4* is used for radial load transmission. Seals *6* and *7* on both ring gaps prevent contamination of the bearing by environmental influences. New grease injected via greasing holes (not shown) between the row of rollers and the row of balls presses old grease through the seals out of the bearing.

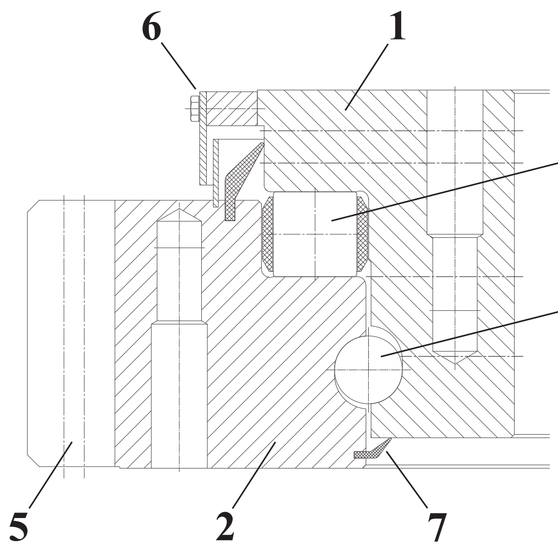


Figure 3.2: Cross section of the slew bearing (courtesy of Sandvik)

Plastic dividers, as seen in Figure 3.3(a), help to maintain constant spacing between the balls of the slew bearing. The shape of the dividers ensures that they remain between the balls. For rollers, spacers or cages are used. The slew bearings of the reclaimers described in this thesis utilise either spacers for single roller elements or cages for multiple roller elements. The latter are shown in Figure 3.3(b). A spacer encases only one roller element whereas a cage holds several roller elements together. Internal reports about failed slew bearings in reclaimers [11] have revealed that slew bearings with cages tend to reach a significantly longer life span than slew bearings with spacers.

(a) Ball divider with ball (b) Five-way roller cage

Figure 3.3: Dividers and cages of roller elements [11]

3.1.2 Nature of loading

A slew bearing connects the undercarriage of a reclaimer with its superstructure. All loads of the superstructure are applied onto the slew bearing. Figure 3.4 illustrates the load transmission of a slew bearing. The different load types are divided into horizontal (radial) loads F_r, vertical (axial) loads F_a and tilting moment M_k.

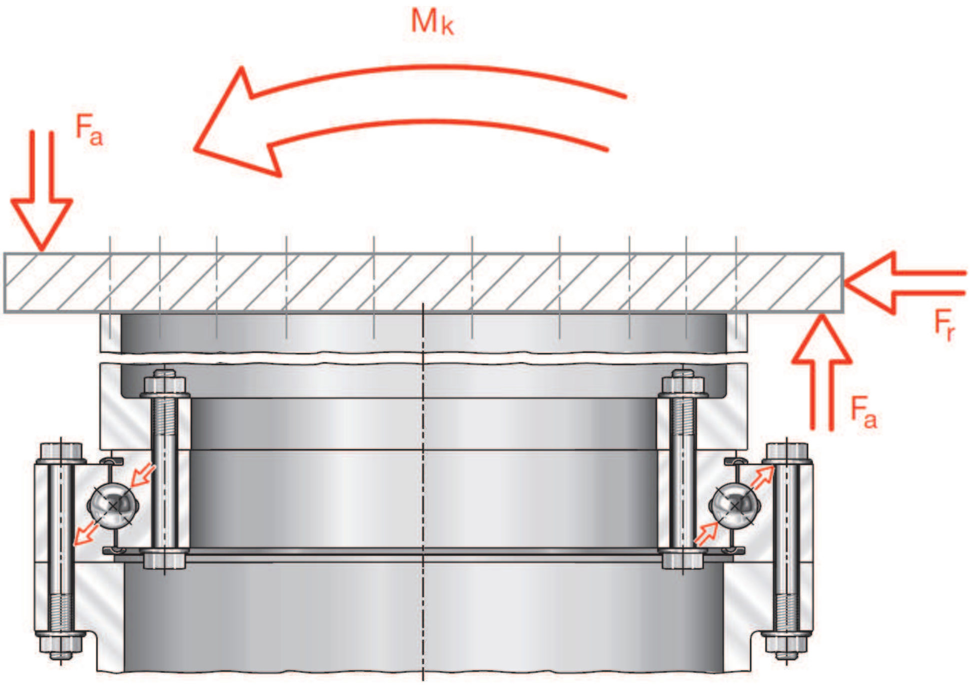


Figure 3.4: Slew bearing load transmission [12]

3.1.2.1 Horizontal loads F_r

The main portion of horizontal loads is induced by the slew drives. Usually, three slew drives are used for reclaimers. These slew drives rotate the superstructure against the undercarriage by driving a pinion that transmits the drive force via the outside gear teeth of the slew bearing. Every single drive causes a horizontal load onto the slew bearing via the pinion-gear assembly. This leads not only to a slewing movement of the superstructure, but also to squeezing of the slew bearing. The horizontal load distribution is not consistent along the circumference of the slew bearing, unless all three slew drives are active for slewing the superstructure. The load distribution is inconsistent, if a slew drive is broken and is not replaced immediately.

Additionally, forces resulting from the interaction between the bucket-wheel and the stockpile during reclaiming are considered as horizontal loads applied onto the slew bearing.

3.1.2.2 Vertical loads F_a

The first type of vertical loads applied onto the slew bearing is the dead load of the superstructure. The dead load consists of the weight of the steel structure, mechanical parts such as cylinders, bracing, boom conveyor components including the belt, and the weight of the counterweight needed for balancing the reclaimer. The second type of vertical loads applied onto a slew bearing are loads that occur during operation. These loads can consist of forces from the reclaimer-stockpile interaction, e.g., digging forces, from the weight of the material on the boom or from the encrustation of the handled material along the boom.

3.1.2.3 Tilting moment M_k

The tilting moment consists of loads applied onto the superstructure, e.g., digging loads. These loads are a direct result of the reclaiming operation (rotating bucket-wheel). Also, distributed loads applied onto part of or onto the whole length of the boom increase the tilting moment. Encrustation along the boom as a result of insufficient cleaning can lead to a significant increase of the tilting moment applied onto the slew bearing. Wind loads also influence the tilting moment.

The location of the reclaimer's centre of gravity (COG) is calculated in the design phase. Placing a proper counterweight on the counterweight boom facilitates a balanced machine state. The tilting moment is directly related to the location of the COG. If an increasing tilting moment shifts the COG to the front, the load situation of the reclaimer is called *front-heavy*. Conversely, if the COG shifts towards the back, the state is called *back-heavy*.

The tilting moment causes an uneven load distribution along the slew bearing's circumference. As a result, it can be stated that the tilting moment applied onto the slew bearing has a major impact on the life span of the slew bearing [9].

3.1.3 Design and calculation

A slew bearing for a reclaimer is pre-selected following geometric specifications. When selecting a bearing, it has to be proven that the slew bearing's properties are appropriate for the loads the slew bearing has to transmit. Proof has to be provided for static load as well as for dynamic load. The highest load onto the slew bearing has to be below a specific static load limit curve. The dynamic load spectrum transmitted during operation is used for the calculation of the theoretical life span in revolutions. The life span in hours can then be calculated with a fixed value for the slewing speed.

For the specific type of slew bearings used in reclaimers, horizontal (radial) loads are permitted as long as they stay below 10% of the corresponding vertical (axial) loads. If they exceed the given threshold, the supplier will have to assess the load spectrum for the slew bearing [10].

A sample calculation is provided in the following section. It follows the guidelines for bearing selection by a major supplier of slew bearings [10]. This guide for calculating the *life span*, also called *service life*, is based on the DIN 281 standard [13].

3.1.3.1 Sample calculation

The load spectrum in Table 3.1 will be used for the calculation of the slew bearing suitability and the theoretical life span. The horizontal loads from the slew drives, from digging forces, and from the wind loads are below 10% of the static load and are, therefore, not listed in the load spectrum. The load case combinations CLC 1, CLC 2 and CLC 3 represent load situations during operation of the reclaimer, whereas CLC 4 characterises an extreme load case only occurring in a static situation.

Load case combination	Vertical loads F_{au} [kN]	Tilting moment M_{ku} [kNm]		
		Boom up (+5°)	Boom horiz. (0°)	Boom down (-12°)
CLC 1	7850	-13250	-12000	-7500
CLC 2	8200	1600	3000	9750
CLC 3	8350	7200	8650	13500
CLC 4	11000			16000

Table 3.1: Unfactored loads

To be able to consider the non-uniform rigidity of the adjacent structures of the slew bearing in the calculation, a specific operational factor has to be determined [14]. This factor is often called *roughness factor*. It is defined as the actual maximum load onto one roller divided by the ideal maximum load onto one roller of the bearing. The roughness factor can be used as a measure for how evenly load is transmitted by the slew bearing. A machine-specific roughness factor depends on the stiffness of the slew deck, the undercarriage and the slew bearing with its components. Several Finite Element Analysis (FEA) models of the reclaimer in different slewing and luffing positions have to be analysed to be able to consider all *soft spots* as well as all *hard spots* of the adjacent structures of the slew bearing. The roughness factor is then defined based on the results of the FEA. The roughness factor strongly influences the theoretical life span of the slew bearing, as this factor is raised to the exponent of $\frac{10}{3}$ during the calculation (see Equation 3.1.2).

An example of a roughness factor analysis for a certain slewing and luffing position is given in Figure 3.5. The blue curve reflects the ideal load distribution along the full circumference of the slew bearing, whereas the red curve indicates the actual load distribution along the circumference.

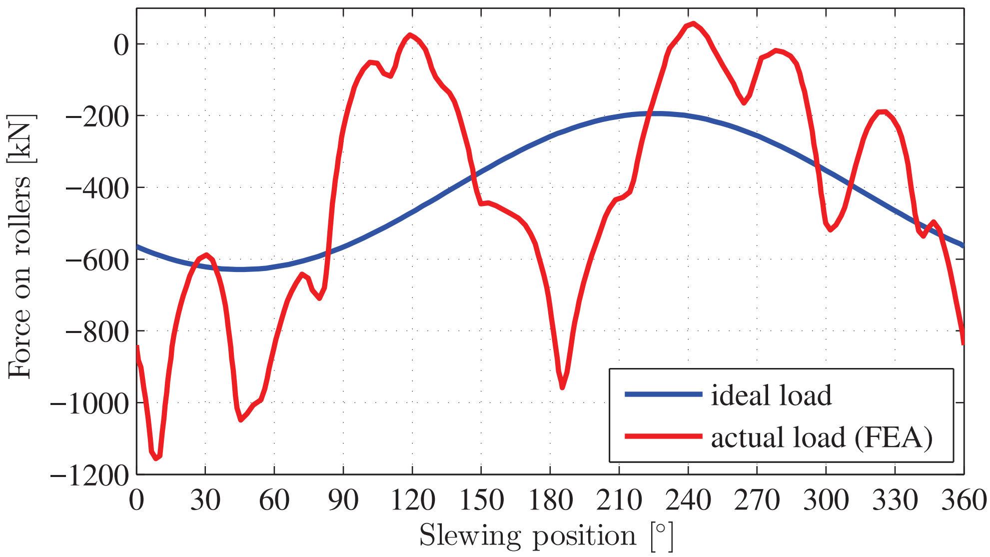


Figure 3.5: Typical slew bearing roughness factor plot

The highest roughness factor for this example is assumed to be 1.6. This factor applied on the load spectrum of Table 3.1 results in the factored loads in Table 3.2. These values are the basis for further calculations of the slew bearing life span.

Load case combination	Vertical loads F_a [kN]	Tilting moment M_k [kNm]		
		Boom up (+5°)	Boom horiz. (0°)	Boom down (-12°)
CLC 1	12560	21200	19200	12000
CLC 2	13120	2560	4800	15600
CLC 3	13360	11520	13840	21600
CLC 4	17600			25600

Table 3.2: Factored loads

The factored static load is within the limits of the static limit load curve (Figure 3.6). This proves that the static calculation is valid.

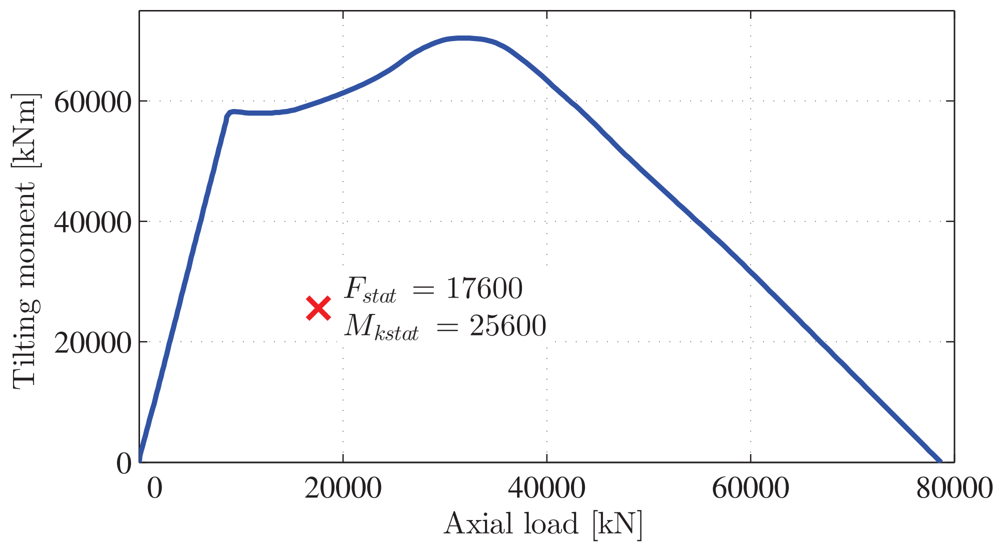


Figure 3.6: Static limit load curve

For the determination of the theoretical life span, the dynamic load spectrum represented by *CLC 1*, *CLC 2* and *CLC 3* in Table 3.2 will be used. The values of the loads F_a and M_k of every load case combination are plotted onto the diagram of Figure 3.7. The extensions of the linear connections between these value pairs and the point of origin of the diagram intersect with the dynamic limit curve. The points of intersection define the values F_{a0} and M_{k0} for each value pair. With

$$f_L = \frac{F_{a0}}{F_a} = \frac{M_{k0}}{M_k} \tag{3.1.1}$$

the load factor f_L can be calculated for every value pair.

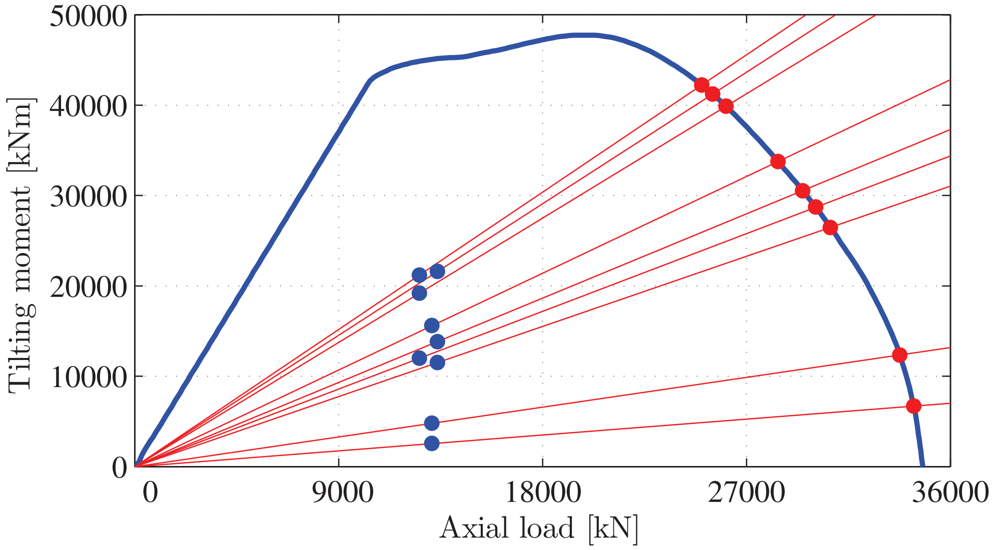


Figure 3.7: Service life curve[1]

The life span G in revolutions is calculated for every value of the load factor f_L, following the relation

$$G = 30000\, f_L^{\frac{10}{3}}\,. \tag{3.1.2}$$

Every load case combination occurs for a certain duration during the life span of a slew bearing, expressed in percentage of the total life span. Table 3.3 reflects the percentages of the different load case combinations, while Table 3.4 reflects the percentages of every luffing position of the reclaimer.

Load case combination	% of life span duty
CLC 1	5
CLC 2	35
CLC 3	60
CLC 4	static

Table 3.3: Duration percentages of different load case combinations

[1]This service life (load limit) curve for the slew bearing type *121.50.6700* is based on 30,000 revolutions under full load [10].

Boom position	% of life span duty
Up position (+5°)	25
Horizontal position (0°)	35
Down position (-12°)	40

Table 3.4: Duration percentages of different luffing positions

The values for F_{a0} and M_{k0} as well as all values for f_L, G, and the combined durations ED in % can be found in Table 3.5.

Combination load case	Luffing position [°]	F_a [kN]	M_k [kNm]	F_{a0} [kN]	M_{k0} [kNm]	f_L	G [revs]	ED [%]
	+5	12560	21200	25027	42243	1.99	298665	1.25
CLC 1	0	12560	19200	26097	39894	2.08	343393	1.75
	-12	12560	12000	30061	28721	2.39	550175	2.00
	+5	13120	2560	34383	6709	2.62	744425	8.75
CLC 2	0	13120	4800	33773	12356	2.57	701306	12.25
	-12	13120	15600	28398	33766	2.16	393521	14.00
	+5	13360	11520	30709	26480	2.30	480823	15.00
CLC 3	0	13360	13840	29484	30544	2.21	419812	21.00
	-12	13360	21600	25507	41238	1.91	258981	24.00

Table 3.5: Result table

The total life span in revolutions can be calculated from the values in Table 3.5 by using the equation

$$G_{ges} = \frac{100}{\frac{ED_1}{G_1} + \frac{ED_2}{G_2} + ... + \frac{ED_i}{G_i}} \tag{3.1.3}$$

which results in

$$G_{ges} = 397449 \; revs. \tag{3.1.4}$$

The life span in hours is then calculated via the relationship

$$G_{ges(h)} = \frac{G_{ges}}{60n} \tag{3.1.5}$$

and with a given slew speed of $n = 0.06 \, \frac{1}{min}$ results in a total theoretical life span of

$$G_{ges(h)} = 110403 \; hours \tag{3.1.6}$$

for the defined load situation.

3.1.3.2 Criticism of assumptions

Slew bearing supplier Rothe Erde preferably uses the expression *service life* rather than *life span* of a slew bearing [10]. One reason for this is that many assumptions made about common bearings, which the ISO 281 standard [13] was introduced for, are not directly applicable to slew bearings. Slew bearings are rotated at relatively slow speeds. The rotation sequences are usually not constant and vary in speed and direction; often only within a limited range of the slew bearing's circumference. Swelling loads caused by the dynamics of the superstructure of a reclaimer are only considered as a static maximum load situation during the design phase of a slew bearing. Excessive rocking of the superstructure, especially during phases of little to no rotation, leads to additional effects on the slew bearing that are currently not considered in the design phase.

The assumption that structures adjacent to the bearing are of uniform rigidity is a major issue. The areas surrounding the slew bearing are of non-uniform rigidity and therefore load distribution cannot be equal along the circumference of the slew bearing. [14], [15], [9]

An often neglected factor is the limited efficacy of the grease inside a slew bearing. Friction properties between two surfaces can be categorised by the *Stribeck curve*. Slew bearings are rotated at slow speeds only: fluid friction is only partially present, the friction level of such a bearing can be described as *boundary lubrication*. This causes metal on metal solid body contact and subsequently increased wear of both, the roller elements and the raceways. Although the lubricant used in slew bearings contains suitable additives that can trigger chemical reactions to reduce friction between the rollers and the raceways, it cannot improve the friction level on the Stribeck curve to *full lubrication*, as is the case for common bearings. [16]

All these assumptions are also concluded by Rothe Erde with the following statement [10]:

> A [slew] bearing has reached its service life when torque resistance progressively increases, or when wear phenomena have progressed so far that the function of the bearing is jeopardized.

Hence, a specific figure for a slew bearing life span in hours is not reliable; it can only give an approximate estimation of theoretical life span based on many different assumptions.

3.2 Modes of failures

Sandvik Mining Systems and its suppliers have investigated several failed slew bearings of reclaimers. The failed slew bearings were dismantled and assessed; there are internal reports[2] [11] available for these assessments. These reports were issued between 2010 and

[2]These reports were made available to the author during the work for this thesis; the information in these reports is confidential and, hence, cannot be accessed by the public.

2015, the majority of which in 2013. Commonalities of several reports are described in the following sections.

3.2.1 Roller element breakdown

The reports [11] revealed details about severe slew bearing breakdowns; numerous roller elements were heavily damaged (Figure 3.8(a)) or even broken into parts (Figure 3.8(b)), while others were still intact. Both roller elements in Figure 3.8(a) were used in the same slew bearing. The balls of the slew bearings were usually only slightly damaged (beginning *pitting*) or did not show any signs of damage at all in many cases. As the rollers were significantly more prone to damage and breakage than the balls in the same slew bearing, it seems probable that the vertical load applied on the slew bearing exceeded the design limits. The varying amount of vertical load applied onto the slew bearing during operation constitutes only a minor percentage of the total vertical load in comparison to the dead load of the whole superstructure. Hence, the reasons for varying vertical loads are rooted in the variations of the tilting moment. An extraordinarily high tilting moment can, therefore, be related to severe damage of the rollers.

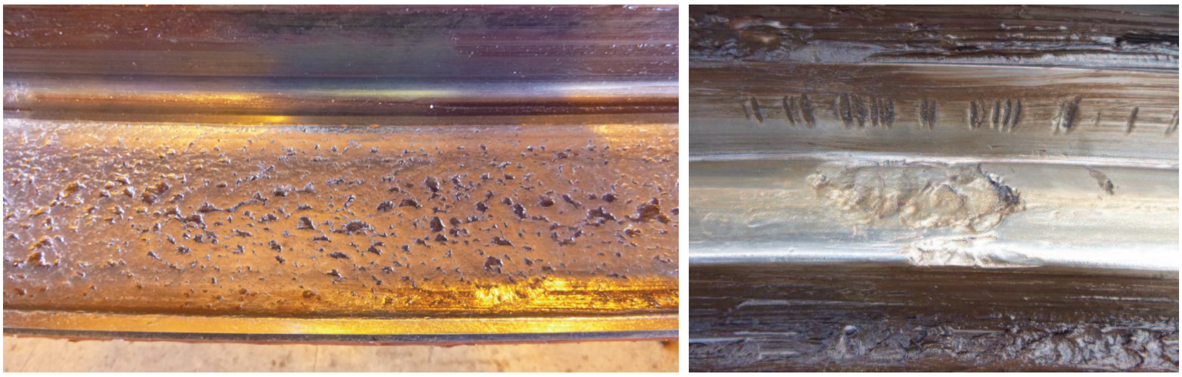
(a) Roller elements of the same slew bearing - Left element with slight wear, right element with excessive damage

(b) Broken roller elements

Figure 3.8: Roller elements of dismantled slew bearings [11]

3.2.2 Roller surface breakdown

Every report [11] revealed that the condition of roller surfaces also varied within a single slew bearing. There were less worn raceway surfaces (Figure 3.9(a)) as well as areas that demonstrated advanced wear or even severe damage (Figure 3.9(b)). The cavities visible on



(a) Raceway with excessive surface damages (b) Raceway with extensive damage

Figure 3.9: Raceways of dismantled slew bearings [11]

the raceway surfaces are a direct result of either advanced wear or particles that damaged the surfaces (also refer to section *3.3.1 Fatigue and wear*). The particles can originate from environmental ingress or from pieces broken off of roller elements that further damage the raceway surfaces. Particle ingress, e.g., caused by insufficient greasing, can lead to severe damaging of the roller elements which can further lead to the destruction of the raceway surfaces by overrunning the particles from broken roller elements.

3.2.3 Roller cage breakdown

The breakdown of roller cages can be the consequence of advanced slew bearing wear. At the same time, a cage breakdown can initiate or accelerate further slew bearing damage. Without an encasing cage, a roller element might get pinched inside the slew bearing and can cause severe damage.

The reports by Sandvik Mining Systems [11] revealed that more than one third of the failed slew bearings did not break down as a direct consequence of wear. These slew bearings did not show signs of raceway wear such as pitting, but showed severe localised damage, as can be seen in Figure 3.9(b). It is possible that either a roller element broke and started severe damage, or that a roller cage failed and benefited further destruction of a slew bearing. A possible theory about roller breakdown is illustrated in Figure 3.10. The normal situation as per design is shown in *I*. A row of roller elements *(3)* is located between the top raceway surface *(1)* connected to the superstructure, and the bottom raceway surface *(2)*, which is mounted on the undercarriage. These rollers are enclosed by roller cages *(4)*. The top raceway traverses against the bottom raceway. If a roller cage is damaged and cannot enclose the roller element anymore or keep it in the track, the roller element can, as a consequence, rotate about its vertical axis as illustrated in *II*. While the top and bottom raceways continue to traverse, the flipped roller element gets dragged over the raceway surfaces. If the friction becomes too high, the roller wedges into the surfaces (*III*). The roller breaks as a direct result of the forced constraint (IV).

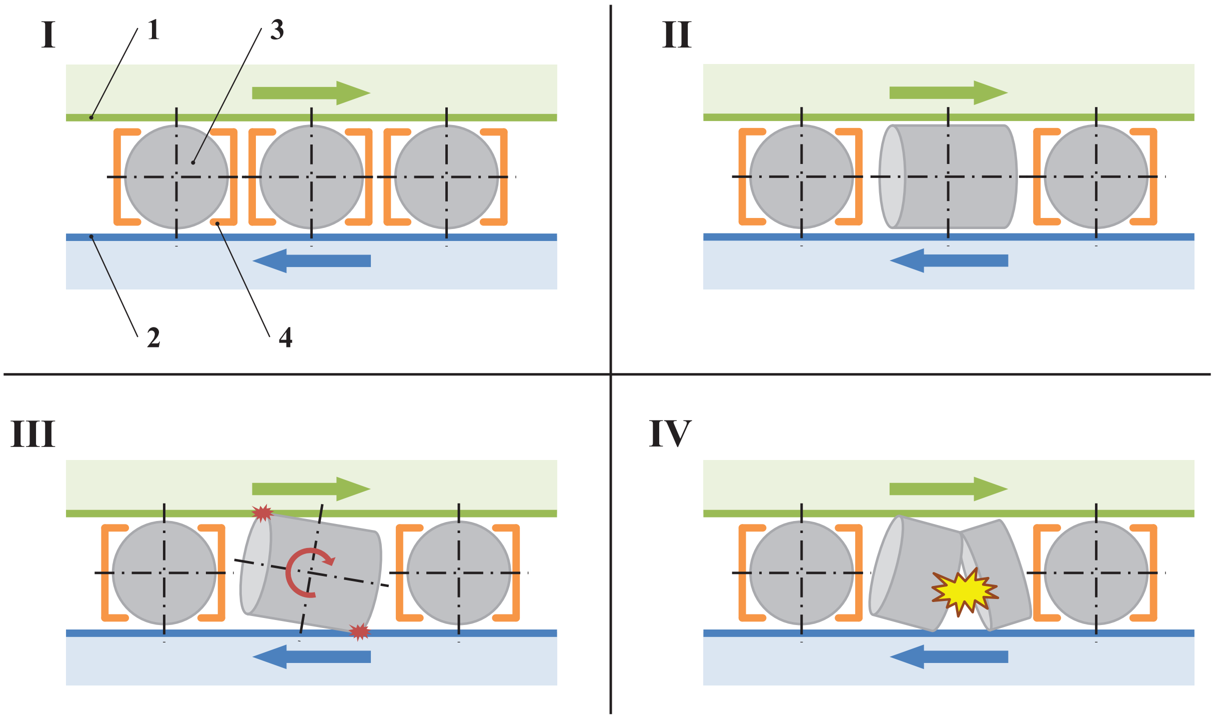


Figure 3.10: Illustration of the breakdown of a roller element as a potential consequence of a roller cage breakdown

A dismantled slew bearing with several flipped roller elements is shown in Figure 3.11(a), whereas Figure 3.11(b) shows a slew bearing area with all roller elements flipped.

(a) Some roller elements are flipped

(b) All roller elements are flipped

Figure 3.11: Flipped rollers in dismantled slew bearings [11]

3.3 Possible causes of slew bearing failure

3.3.1 Fatigue and wear

Cracks on the rolling surfaces can be initiated or exacerbated by rolling contact fatigue. These cracks occur in areas, where stress is concentrated - either on or near the raceway surface. Concentrations of stress can be caused by inherent imperfections of the materials used for the slewing rings. Furthermore, the transformation of the material's microstructure can cause concentrations of stress, due to loads induced by rolling or sliding contact. [17]

Pitting of the rolling surfaces is a consequence of rolling contact fatigue. Roller elements with excessive pitting marks can be seen in Figure 3.8(a) and the effect on raceways can be seen in Figure 3.9(a).

3.3.2 Insufficient lubrication

The injection of fresh grease into the slew bearing hinders particle ingress from the environment. Insufficient greasing can, on the other hand, favour particle ingress and can lead to slew bearing damage or, ultimately, to the breakdown of the slew bearing. Insufficient or no grease supply was traceable in some previous slew bearing breakdowns that were described in internal reports of Sandvik Mining Systems [11]; operational data of the lubrication systems revealed issues with the lubrication system.

By injecting fresh grease into the slew bearing via the provided greasing holes, the old grease is pressed out. The reports on the failed slew bearings [11] also give an insight into the lubrication condition of the slew bearings. Some areas of the slew bearing were covered with a large amount of ferrous particles, while other areas showed fresh or marginally contaminated grease; the latter areas were especially found in the raceways of the ball roller elements. It should be investigated, if grease supply via the provided lubrication holes is sufficient for the greasing of the slew bearings, or if the layout of the lubrication holes has to be redesigned.

3.3.3 Penetrating particles

Particles from the environment, such as iron ore dust, can lead to significant damage if they enter the slew bearing. However, particles originating from the inside of the slew bearing can also lead to a slew bearing breakdown. If a bearing has already been subject to damage, small particles can break off of the roller cages, the roller elements, or the raceway surfaces. These particles can accelerate further destruction of the bearing by preventing the roller elements from transmitting the load from the top ring of the slew bearing through to the bottom ring. This obstruction may lead to local overutilisation of the roller elements and the raceways. The roller elements and the raceway surfaces may become fractured (as described in section *3.3.1 Fatigue and wear*) and particles break off constantly, exacerbating the adverse effects on the slew bearing life span.

3.3.4 Rigidity of adjacent structures

The uniform rigidity and non-deformability of the structures adjacent to the slew bearing are related to two of the assumptions made in the calculation of slew bearing life span [14]. In-situ measurements have been undertaken to prove that the non-uniform rigidity of adjacent structures has an impact on slew bearing life span [15]. After just 1,200 hours of operation, the measurements indicated a load redistribution along the circumference of the slew bearing. The load transferred by the stiff areas of the adjacent structures decreased, whereas the load transferred by the areas with lower stiffness increased significantly. Unequal stiffness of the adjacent structures leads to a load transfer that is limited to parts of the roller elements and the raceways only. The loads onto the roller elements and the raceways exceed the ultimate stress level due to the unfavourable load redistribution and the high tilting moment during a machine's life span [15]. This emphasises the necessity of knowing and monitoring the *actual* tilting moment during the operation of a reclaimer, as this moment is found to be crucial for assumptions about the slew bearing life span.

3.3.4.1 Bolts

Every bolt used for the installation of a slew bearing can be tightened by screwing the nut until reaching a certain tightening torque M_A. Following the formula 3.3.1 [18], the pretensioning force F_V is directly proportional to the tightening torque. The two values are linked by geometric parameters (pitch P, pitch diameter d_2, effective diameter for friction of the contact area of head-face D_{km}) as well as friction coefficients μ_G (thread friction) and μ_K (head-face friction).

$$M_A \approx F_V[0,159P + \mu_G 0,577d_2 + \frac{D_{km}\mu_K}{2}] \tag{3.3.1}$$

These coefficients have to be defined exactly to guarantee accuracy when calculating F_V. In practice, the friction coefficients between the material pairings are either hard to define or vary even within the same charge of bolts and nuts. The coefficients depend on the surface conditions of the bolts and nuts. These surfaces are often covered in grease and lubricant. The properties of the grease and the lubricant vary depending on the environment and, hence, so do the friction coefficients. The friction coefficients also vary once the torque applied on the nut is released. Consequently, this causes a variation in axial tension of the bolt [19]. These deviations accumulate and, hence, the achievable tightening torque can vary to a significant extend [20]. Observations at several manufacturers of Sandvik's machines have revealed that the inaccurate relationship between the tightening torque and the pre-tensioning force can lead to over- as well as undertensioning of the bolts. Both of these cases were observed while installing slew bearings, although bolts and nuts from the same charges were used.

Alternatively, bolts can also be tightened via hydraulic tightening cylinders. These cylinders allow the application of a defined axial tension onto the bolts without applying torque onto the nut. Hence, the tightening process is torsion- and friction-free. Using this method, the bolt is screwed into the hydraulic tightening cylinder. Hydraulic pressure is applied onto the bolt and stretches it. The hydraulic pressure is directly related to the axial force of the bolt. When the necessary axial tension of the bolt is reached, the nut can be tightened without a torque wrench. Once the nut is in place, the hydraulic pressure on the bolt is released and the nut then transmits the axial force between the bolt and the adjacent structure. This allows the reproduction of axial tensioning forces within a tolerance of $\pm 2.0\%$ [21].

The influence of the bolt pre-tensioning is often disregarded in Finite Element Analyses (FEA), which are used for defining the roughness factor of a slew bearing. Nevertheless, the bolts may have a significant impact on the rigidity of the adjacent structures. [9]

3.3.5 Overutilisation

A reclaimer should neither be operated outside the load profile it was originally designed for, nor should it be exposed to load scenarios not considered in the design phase (loads due to excessive winds or earthquakes). Excessive loads can lead to a drastic decrease of the life span of a reclaimer.

3.3.5.1 Excessive tilting moment

The tilting moment applied onto the slew bearing of a reclaimer is crucial to the life span of the slew bearing [9]. Exceeding the tilting moment limits calculated in the design phase can lead to slew bearing overutilisation.

If the load capacity of a reclaimer is exceeded during operation, it results in an overutilisation of the slew bearing. This leads to a reduced slew bearing life span, as the tilting moment exceeds the design limits. The longer the overutilisation lasts, the longer the tilting moment exceeds the design values and, as a consequence, the life span of the slew bearing is further reduced.

Collapses of the stockpile can lead to excessive tilting moment application during the reclaiming operation. This is the case when a reclaimer digs bulk material from a lower bench of the stockpile, while agglomerated bulk material at the top of the stockpile starts collapsing. This collapse causes avalanches of bulk material that could hit the rotating bucket-wheel. If bulk material hits the bucket-wheel, the buckets become overfilled with material and too much load is applied onto the tip of the reclaimer boom. A reclaimer is usually able to detect such a situation solely via a current limit violation of the bucket-wheel drive, as the drive uses electrical current beyond the limit settings. After the violation is detected, the slewing movement stops while the bucket-wheel continues to rotate to unload the overfilled bucket. The boom conveyor stays activated to convey the material away from the tip of the boom. The impact on the tilting moment is the highest for forces applied onto the tip of the boom. If the bucket-wheel drive is overloaded, it cannot be rotated anymore due to the high load and the drive is therefore deactivated. The bucket-wheel can then rotate in the opposite direction to empty the buckets. If the bucket-wheel can not rotate freely because it is dug into the stockpile, the reclaimer will additionally move backwards on the long-travel.

A lack of maintenance can also lead to an increase of the tilting moment. This happens, if encrusted material is not cleaned off of the boom on a regular basis. OEMs (Official Equipment Manufacturers) recommend certain intervals for cleaning off encrustation that accumulates along the boom's steel structure and along the walkways. These intervals are often referred to as *wash-down cycles*. The excessive material has to be removed from the boom to prevent the tilting moment from constantly increasing.

Internal reports by Sandvik Mining Systems about slew bearing failures [11] contain data about the load situation of multiple reclaimers. Although these reclaimers were designed to meet the requirements of Australian Standard AS4324.1 [22] regarding encrustation, operational data revealed that encrustation was present throughout the entire operation time of all reclaimers investigated. Furthermore, the encrustation levels of all reclaimers exceeded the allowed limits by approximately 50%.

Operator errors leading to the collision of the reclaimer with obstacles, such as stockpiles, can also benefit an excessive tilting moment. Moreover, forces of nature, such as heavy wind loads, can increase the tilting moment significantly. Another challenge is posed by modifications and additional installations done by customers after a reclaimer has been commissioned and balanced with an appropriate counterweight by the OEM. Such modifications lead to a significantly higher initial tilting moment.

3.3.5.2 Selective utilisation of slew bearings

Reclaimers can usually slew within a 360° range. However, most reclaimers are not operated using the full range. The slewing movement is often limited to a small range only during reclaiming, which causes some areas of the rolling surfaces of the slew bearing to be utilised more than others. Additionally, this movement is not done in one direction only, but it is bidirectional, causing the roller elements to not change their positions constantly. These facts benefit a higher wear of several raceway areas and rollers, as utilisation of the slew bearing is not distributed evenly.

Operation in predefined slewing quadrants

As described in detail in section *2.2.3.4 Quadrant operation* on page 11, a reclaimer is operated in predefined slewing quadrants. The majority of the reclaimers are used in stockyard layouts, where all four slewing quadrants are utilised during operation. However, the reclaiming operation might not be distributed evenly among all slewing quadrants. That can be a result of the stockyard design or it can be a direct consequence of stockyard logistics. Additionally, a slewing quadrant is not evenly utilised during the reclaiming operation, as described in Figure 2.9. Consequently, the uneven usage of the slewing areas leads to uneven utilisation of the slew bearing, limiting utilisation to certain areas of the raceway surfaces. This effect increases, the less slewing movement there is during operation. Ship loaders, for instance, move little during operation in comparison to reclaimers. Ship loaders load bulk material into compartments, called holes, in a vessel. These holes have hatches, which limit the slewing movements by the ship loader boom. Furthermore, ship loaders normally only operate in one or two slewing quadrants due to the layout of the harbour or jetty.

Trench-cutting

Side-acting reclaiming operation, as described in paragraph *Side-acting operation* on page 10, is responsible for transmitting load in concentrated areas of the slew bearing. Little to no slewing movement during trench-cutting benefits wear of the bearing in concentrated areas.

3.3.5.3 Rocking of the superstructure

Rocking of the superstructure during reclaiming can induce additional loads onto the slew bearing. Rocking can lead to momentary, but periodically occurring high loads onto the slew bearing. Paired with little to no slewing movement, this can benefit local overutilisation of the roller elements and the rolling raceways of the slew bearing.

Such dynamic effects are not considered in the design phase of reclaimer slew bearings. Dynamic load cases are calculated as static load situations, in which the highest load amplitude occurs during operation.

3.3.5.4 Partial operation of slew drives

Three slew drives are used for the reclaimers this thesis is about. They are distributed evenly along the circumference of the slew bearing. All three slew drives are active simultaneously during a slewing movement. Under normal operating conditions (insignificant wind loads, no lateral obstructions, no increased friction of the slew bearing due to advanced wear), it is possible to rotate the superstructure with respect the undercarriage with only two slew drives instead of three. Therefore, if one slew drive is broken, it may still be possible to operate with the two remaining slew drives. In such a case, the slew bearing would not be utilised evenly in its horizontal load direction. This can decrease life span of the slew bearing.

3.4 Consequences of ultimate slew bearing breakdown

3.4.1 Impact on operation

A slew bearing failure can have far-reaching consequences. Not only the costs for replacing the broken bearing have to be considered, but also the downtime of the machine. The downtime of a reclaimer can be crucial to the whole stockyard, as these machines are part of critical processes. For instance, a vessel has to be kept on hold until it can be loaded by a ship loader. The ship loader is supplied with material by a reclaimer. If the reclaimer fails, there is no material for the ship loader to load onto the vessel. In some cases, there is more than one reclaimer providing material for the ship loader. However, unexpected downtime of one reclaimer most probably still causes serious problems with the efficiency of the whole stockyard. This can have a significant impact on the ship loading efficiency as well, and so the vessel has to spend more time at the port than necessary, causing excessive costs.

If the breakdown of a slew bearing is reliably predictable, the impact on the operation of a whole stockyard and on dependant processes, such as ship loading, can be kept at a minimum.

3.4.2 Delivery lead time

The Australian mining industry asks for a certain type of slew bearings to be installed on the reclaimers. As most of the slew bearings used for reclaimers in Australia are the same, customers can keep an economically reasonable number of slew bearings in stock. All slew bearings are custom-made, the lead time for these components can be exceptionally long. However, multiple requirements have to be met to store and preserve slew bearings according to the manufacturer's recommendations. For instance, bearing supplier Schaeffler recommends dry, closed storage rooms with temperatures between 0°C and +40°C, a relative atmospheric humidity below 65%, and protection against influences by chemical agents. If these preconditions are met, a slew bearing can be stored for up to three years. [12]

Chapter 4

Monitoring of slew bearings

To assess the condition of a slew bearing, several different ways of monitoring can be used. This chapter investigates how slew bearings can be monitored using sensors which measure wear and defects of slew bearings.

4.1 Established ways of monitoring

According to the maintenance recommendations by slew bearing suppliers, the condition of a slew bearing has to be determined by constantly monitoring variations in the axial movement, also called tilting clearance or drop-height, as well as by monitoring the condition of the lubricant used for the slew bearing. The lubricant is examined in detail to determine the amount of ferrous (Fe) particles it is contaminated with. An increase of the axial movement as well as of the amount of ferrous particles in the grease correlates with the condition of a slew bearing. The higher the increase of axial movement is, the more the slew bearing is affected by signs of wear. The same relation applies to the amount of ferrous particles in a lubricant and the slew bearing condition. The correlation between these two factors over the life span of a slew bearing is illustrated in Figure 4.1.

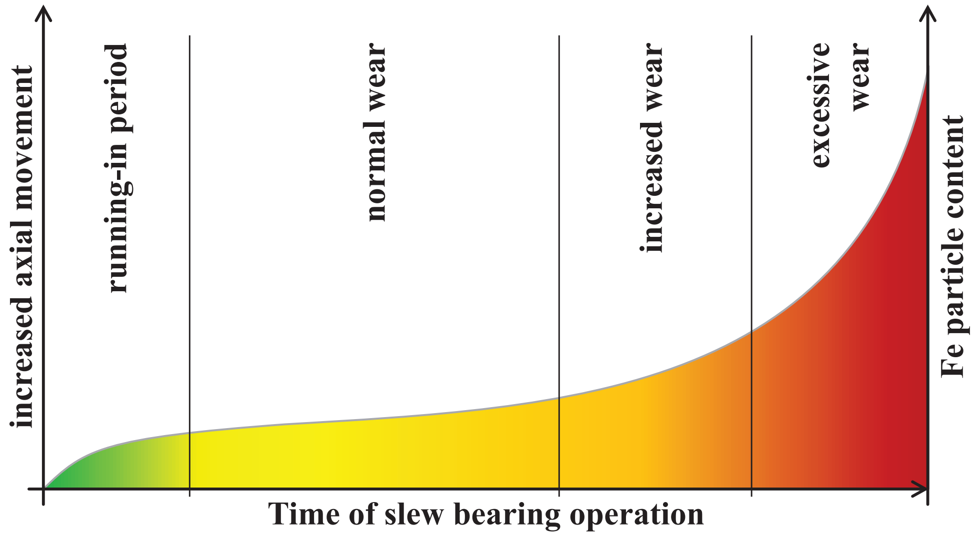


Figure 4.1: Typical wear curve for axial movement and Fe particle content [23, cf.], [24, cf.]

Both established ways of monitoring slew bearings are explained in more detail in the following sections.

4.1.1 Tilting clearance monitoring

Axial movement of the slew bearing increases with advanced operating time, as wear of the slew bearing raceways and roller elements benefits the reduction of axial clearance. Axial movement can be determined by measuring the tilting clearance of a reclaimer slew bearing.

The tilting clearance is measured at several points along the circumference of the slew bearing. These points have to be marked on the top and the bottom slew bearing ring (marked with ① in Figure 4.2), so that the same points are measured over time. The relative positions of the top slew bearing ring and the bottom slew bearing ring have to be the same during all measurements. The number of measurement points should be higher in areas where high loads are applied onto the slew bearing. A reference measurement has to be performed before the reclaimer goes into operation. This should preferably be done during the commissioning phase of the reclaimer. Repeated tests have to be performed using a test gauge with an accuracy of 0.01 mm to determine the tilting clearance at the designated measurement points, as illustrated in Figure 4.2. These measurements should be carried out while the reclaimer is not being loaded and, if possible, another measurement should be carried out while the reclaimer is being loaded. The measurements have to be carried out as close to the raceway system as possible to avoid elastic deformations of the adjacent structures that can influence the measurement results. The tilting clearance measurements have to be carried out at fixed intervals. The measurements have to be performed more often, if the tilting clearance values show an upward trend. If a limit value defined by the supplier is reached, the slew bearing has to be replaced. [23], [12], [25]

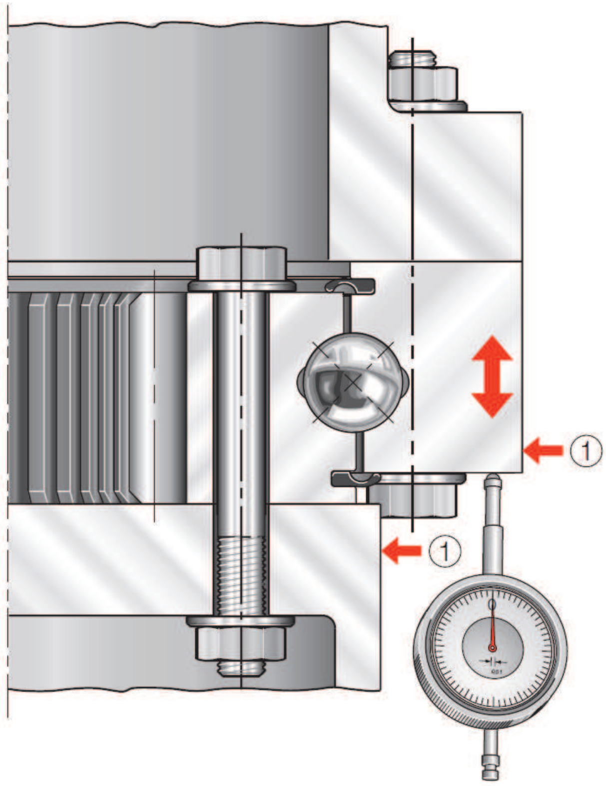


Figure 4.2: Tilting clearance measurement installation [12]

These tilting clearance measurements have to be carried out manually during maintenance downtime, when the reclaimer is not operating. The usage of limit switches is a simple method of detecting if a tilting clearance is exceeding its designated limit values. As illustrated in Figure 4.3, an electrical conductor pin is installed in the bottom slew bearing ring. This pin is electrically isolated against the bottom slew bearing ring and protrudes into a groove milled into the top slew bearing ring. If a critical tilting clearance limit is reached, the pin comes into contact with the top slew bearing ring, closing an electric circuit and triggering a signal. [26], [23]

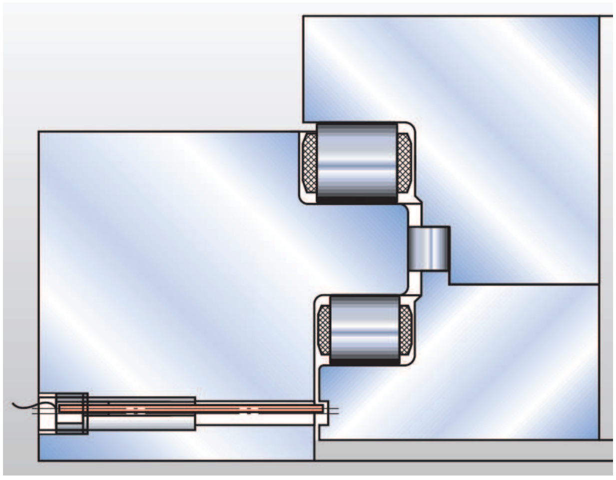


Figure 4.3: Tilting clearance limit switch [23]

More advanced methods can not only measure if a limit is reached, but can also measure the tilting clearance values. It is possible to measure the relative axial and radial distances between the top and the bottom slew bearing rings with different types of distance sensors. [27], [28]

4.1.2 Lubrication monitoring

The *Reliability Centered Maintenance (RCM) curve*, as seen in Figure 4.4, is a more detailed version of the specifications of the *Naval Sea Systems Command* [29] and the *National Aeronautics and Space Administration (NASA)* [30]. RCM is focused on an application on common bearings. Methods for vibration and acoustic emission evaluation of slew bearings are still in their early stages and significant temperature variations might not be traceable due to the slow and limited slewing operation of a reclaimer. Nevertheless, the curve illustrates that evidence of discrepancies in the properties of the used lubricant can benefit the early detection of a beginning slew bearing failure. This emphasises the necessity of lubricant monitoring.

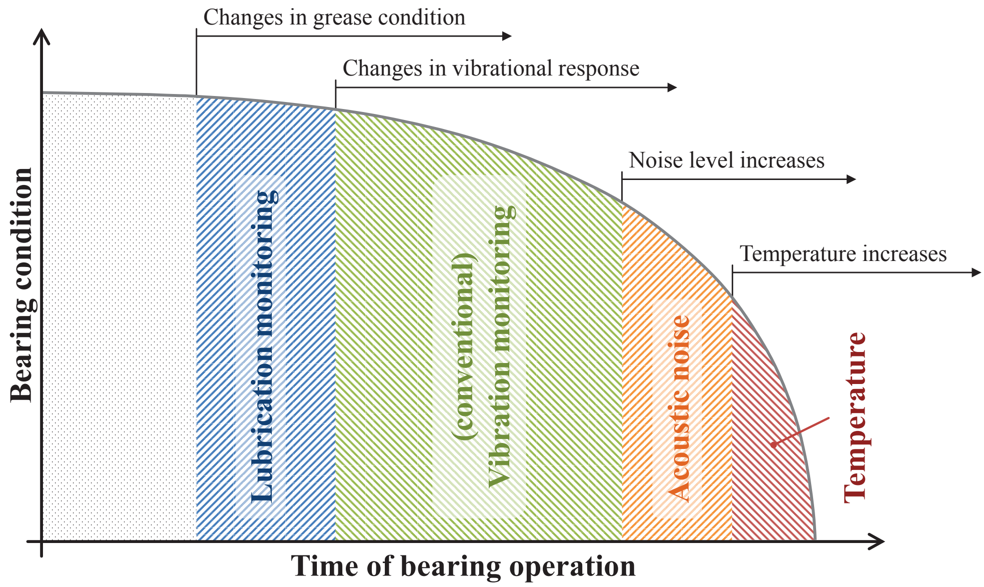


Figure 4.4: Typical Reliability Centered Maintenance (RCM) curve [31, cf.]

Lubrication can be monitored via manual grease sampling. It should be carried out at the same intervals as the tilting clearance measurements. The samples are taken from existing sampling holes in those areas of the slew bearing, where the highest load is applied. A suction device (syringe) is used to extract the grease sample from the inside of the bearing, as shown in Figure 4.5. It is especially important that the grease is not contaminated with dust or debris while the sample is being taken. The samples are then forwarded to the slew bearing supplier, who examines the samples together with additional information about the operation environment and re-lubrication intervals. Based on the meta-data, the limit values for the amount of ferrous particles can be defined. If the amount of ferrous particles in the sample exceeds the limit, the slew bearing is suffering from extensive wear and a timely replacement should be considered.

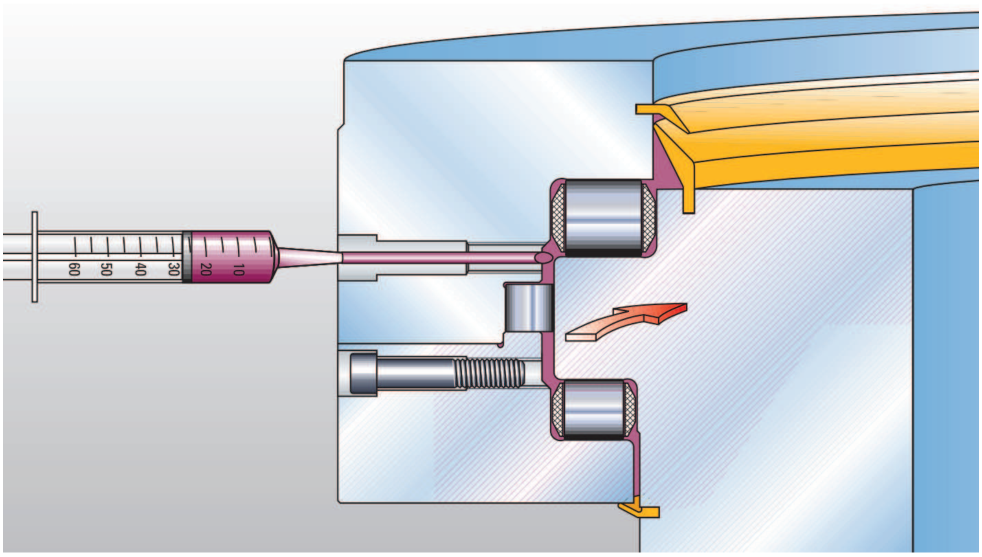


Figure 4.5: Procedure of taking a grease sample [23]

Grease sensors for measuring the turbidity, the ageing, the temperature and the water content of the lubricant are already available [32], [31]. As soon as a sensor for detecting the amount of ferrous particles in the grease has been approved for the utilisation in a reclaimer slew bearing, grease monitoring can be accomplished entirely via sensors.

4.1.2.1 Monitoring of re-greasing procedures

Re-greasing of a slew bearing is done via an automatic re-greasing system. A grease pump distributes fresh grease from a central reservoir to the different greasing points of a slew bearing. The old grease is pressed out of the slew bearing during the re-greasing cycle. Monitoring of the basic functionality of the automatic re-greasing system can be accomplished by observing the cycle times as well as the grease flow.

4.1.3 Eddy current monitoring

Using the eddy current technology, a complex system of sensors is deployed for monitoring a slew bearing's condition. Several sensors mounted inside the cages of the roller elements are distributed along the circumference of the slew bearing. The sensors produce high-frequency electromagnetic alternating fields. These fields induce eddy current in the steel raceways and in their transition surfaces. The receiving component of the sensor detects variations in the amplitude of the eddy currents caused by alterations of the transition air gaps. The signal is made available to a processing unit outside the slew bearing via wireless data transmission. The sensors inside the slew bearing are powered by a transformer. The primary coil of the transformer is mounted electrically isolated on the inside of the bottom ring of the slew bearing. The secondary coil is part of the sensor and, therefore, mounted in a cage inside the slew bearing. Whenever the sensors inside the slew bearing are rotated past a primary coil, the accumulator of the sensor is charged. As long as the battery power lasts, the sensor can measure changes in the induced eddy current and transmits the data to a separate processing unit. [33], [34]

4.2 Additional potential ways of monitoring

Monitoring technologies, such as monitoring vibrations or acoustic emissions, are well established for common bearings. Standards, such as *ISO 10816: Mechanical Vibration - Evaluation of Machine Vibration by Measurements on Non-Rotating Parts* and *ISO 7919: Mechanical Vibration of Non-Reciprocating Machines - Measurements on Rotating Shafts and Evaluation Criteria*, regulate analyses for these monitoring technologies. Characteristic behaviour of common bearings differs in many respects from that of slew bearings. However, the basic principles of monitoring technologies for common bearings can be the subject for further research work as they could potentially also be used for monitoring slew bearings.

Due to increased efforts in green energy, wind turbines draw a lot of attention in engineering, especially in condition monitoring. Bearings of wind turbines and slew bearings of reclaimers are not used under the same conditions. Usually, wind turbines rotate in full cycles and at constant, low speeds. In contrast, a reclaimer slews only within specific ranges most of the time and the slewing movement is non-continuous, which results in varying slewing speeds that are even slower than the rotation speeds of wind turbines. However, wind turbine bearings and reclaimer slew bearings are similar in size and they face similar problems in condition monitoring. The development of monitoring methods for reclaimer slew bearings benefits from advances in wind turbine bearing monitoring. Some of the techniques used for wind turbines, such as *vibration* and *acoustic emission monitoring*, qualify for further research work as they could also be used for condition monitoring of reclaimer slew bearings. [35]

Moodie evaluated in his doctoral thesis *vibration analyses* and *acoustic emission* with regard to possibly applying these methods on slow rotating slew bearings. Although his work is focused on acoustic emission, the thesis shed light onto the matter of condition monitoring of slew bearings in a fundamental mathematical manner, introducing *symmetry* as a central concept which can be applied to all measuring systems. [36]

4.2.1 Vibration monitoring

Piezoelectric accelerometer sensors are used for vibration monitoring. These sensors consist of a piezoelectric crystal to which a seismic mass is attached. The crystal induces voltage when put under stress. The seismic mass is a measure for the sensor's sensitivity: the heavier the mass, the higher the sensitivity. Generally, the results of vibration monitoring are only significant, if a defect already exists. Slew bearings rotating at low speeds create vibrations

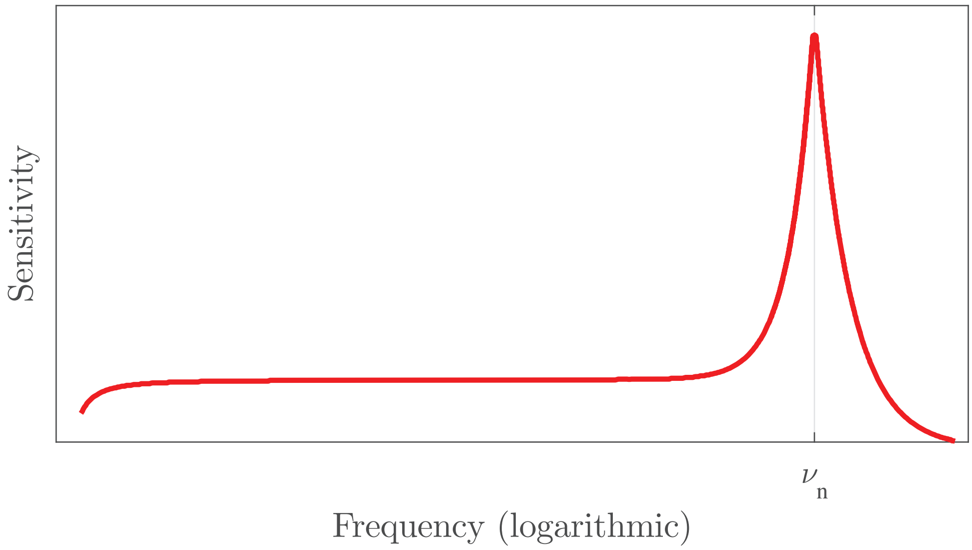


Figure 4.6: Typical frequency response of a piezoelectric accelerometer [37, cf.]

with only a small energy content which leads to low amplitudes that are being buried in signal noise. Two different ways of signal processing enable the extraction of information from the signal despite the low energy content of the signal.

One way of obtaining information from a vibration signal is to utilise the behaviour of a sensor at its natural resonance frequency. This technique is also known as *shock pulse measurement* or *high frequency detection*. Every accelerometer has a specific resonance frequency ν_n, as illustrated in Figure 4.6. A signal in the frequency range around ν_n leads to a high relative sensitivity of the sensor. If a roller element of the slew bearing rolls over a defect in the slew bearings raceway surface, a tiny peak can be seen in the acceleration signal. To prevent this tiny amplitude from being buried in signal noise, the natural resonance of the accelerometer is used to amplify it. Slew bearing supplier SKF claims that the frequency induced by rolling over defects in slew bearings lies around 10 kHz [38]. Hence, the natural resonance frequency of a sensor should lie in this range as well in order to benefit from the amplification effect. As a defect grows, its edges are smoothed by continuous metal on metal contact between the roller elements and the raceway, causing the amplitude in the acceleration signal to decrease significantly. The amplification effect is lost as soon as the frequency produced by rolling over the defect decreases below the natural frequency range of the sensor. [38]

The second way of analysing vibration signals of slew bearings is *demodulation*, also called *enveloping*. A series of signal processing methods, such as a *bandpass filter (BPF)*, a *rectifier*, and a *lowpass filter* are used to process the raw acceleration signal. The part of the signal, which identifies the event of rolling over a defect, can be extracted from the noisy signal using a combination of the aforementioned methods. The selection of the right *BPF* is crucial to the quality of the achieved results. The slow slewing speed of the slew bearing does not affect the identification of these amplitude peaks negatively, as the frequencies generated by roller elements rolling over defects still lie in the same (high) frequency range. [38]

The selection of sensors and their mounting methods is also crucial to the results of a vibration monitoring system, regardless of which aforementioned method is used. It is mandatory that the full frequency range of the sensor encompasses the frequencies from rolling over defects. A low frequency 500 mV/g piezoelectric accelerometer is reasonable for accurately measuring the raw acceleration of a slew bearing. However, frequency generated by roller elements rolling over raceway defects might not be detectable by this type of sensor, as the highest frequency detectable by a 500 mV/g sensor is 2.3 kHz. An ordinary 100 mV/g sensor is better suited, as it can measure frequencies up to 14 kHz. [38]

4.2.2 Acoustic emission

Vibration in the slew bearing is excited while roller elements roll over an existing defect. *Acoustic emission (AE)* can be used to identify the formation of such defects. Miettinen and Pataniitty give a concise definition of AE [39]:

> Acoustic emission can be described as a shock wave inside a material, which is under stress.

AE covers the frequency range in which shock waves occur in a material. These shock waves can originate from fractures of crystallites, phase transformations in materials, crack nucleation, or crack growth. All these mechanisms are based on a rapid collective motion of a group of atoms. [39]

The metal on metal contact between a roller element and the bearing raceway leads to a temporary adhesion of the two contact partners. As the roller element keeps rolling, the point of adhesion is immediately ruptured. This event can be a source of stress waves in the material, which are observable using AE. In the early stages of a defect, the energy of the emitted waves is low. As a consequence, the defect is difficult to detect in the frequency spectrum; however, it might still be observable in the time domain. [40]

The time-based signal can be characterised by calculating statistical values. Another way of signal characterisation is counting pulses per time unit, expressed as pulses/second. The usage of pulse counting also implies a simple compression, as only the pulse counts per time unit have to be stored. Analysing the signal in the time domain as well as counting pulses per time unit can be used successfully for the interpretation of acoustic emission of slew bearings with slow rotation speeds. [39]

Acoustic emission appears to act as a point source and has an isotropic propagation. The damping of wave propagation depends on the condition of the boundary surfaces between the AE source and the AE transducer (sensor). AE sensors are piezoelectric accelerometers which do not have any seismic mass attached to the piezoelectric crystal. [39]

A few side effects have to be taken into account when using AE:

1. The low energy level of acoustic emission by the slew bearing comprises a high sensitivity for disturbances occurring during operation. If the noise level gets too high, the signal can become ambiguous and might lead to misinterpretation. [39]

2. A material under load only generates acoustic emission, if the applied load exceeds the prior load level. The material behaves elastically until the prior maximum load level is reached. This is known as the *Kaiser effect*. [41]

3. Even though a bearing is at an advanced stage of destruction, high frequency amplitude levels tend to decrease due to *self-peening*. This effect is particularly common when bearings are used in low-speed settings. [42]

4.2.3 Conoscopic holography

The technology of conoscopic holography can be used for detecting surface roughness. The basic principle can be seen in Figure 4.7. A laser beam is projected through a beam splitter onto a point of the surface, e.g., the surface of a slew bearing raceway. The immediate reflection of the laser beam returns along the original path of the laser beam and is routed through circular polarisers and a birefringent (conoscopic) crystal. The laser beam forms an interference pattern, which is projected onto a charge-coupled device (CCD) image sensor. The frequency of the fringes of the interference pattern is directly related to the distance between the holographic device and the point on the surface. Thus, the system can identify variations in surface roughness, such as early signs of pitting. [43]

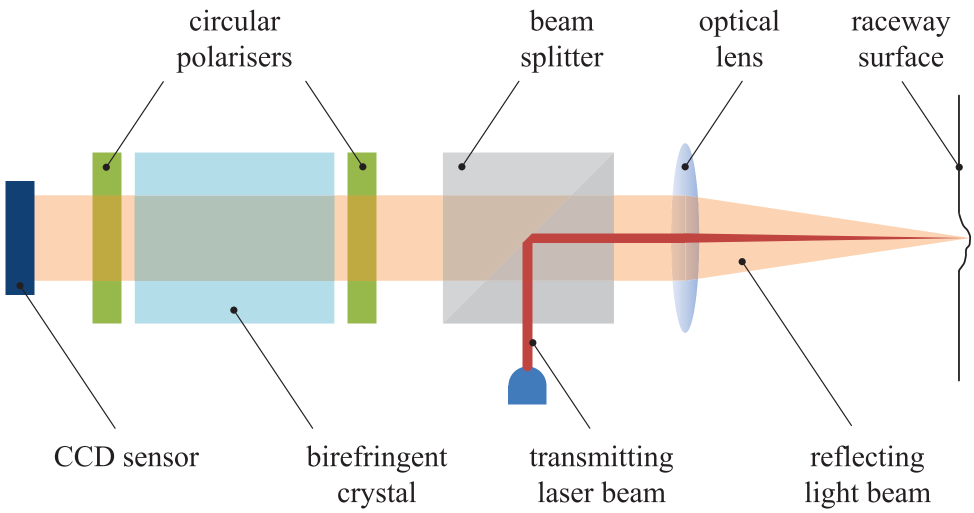


Figure 4.7: Linear conoscopic holography system

The main advantage of such a system, in comparison to other optical roughness detection systems, such as laser triangulation, is that the light projected back from the measured point is routed along the exact same beam path as the initially transmitted laser beam. This makes it possible to use a compact design for the system. Furthermore, conoscopic holography is also used in medical engineering, e.g., for dental applications [44]. This also comprises a small-sized design, which is suitable for an application inside a slew bearing.

A conoscopic holography sensor system could be mounted inside the bottom part of the slew bearing. The sensor should fit in one of the already existing inspection holes. If advanced optical lens systems are used, both raceways can be measured at the same time. If an optical lens system is not able to cover the full width of both raceways, it might be possible to mount parts of the sensor device inside the cages of the roller elements.

One of the biggest challenges of using an optical system, such as conoscopic holography, is the opaqueness of the grease used for the slew bearing. If this problem is not properly dealt with, the grease might interfere significantly with the results of the measurement. Transparent greases are used in cold steel rolling mills and may qualify for further investigations.

Even though the utilisation of conoscopic holography for detecting raceway roughness shows promising potential, it will take further research and prototyping for such a system to become reliable under rough application conditions.

Chapter 5

Data collection for system analytics

Maintenance is the instrument that is necessary to ensure the functioning of a machine or process over time. More traditional approaches distinguish between *corrective* and *preventive* maintenance. Corrective maintenance includes the repair or replacement of machine components after major defects have been detected or when components have broken down. Corrective repair has to be carried out immediately to avoid long unplanned downtime. The costs for downtime can rise rapidly, depending on the process the machine is part of. In contrast, preventive maintenance is characterised by the repair or replacement of components before they show defects and before they break down. Preventive maintenance is carried out at fixed intervals, which are often recommended by the component suppliers. This implies that components do not exhaust the full life span they were initially designed for. Unplanned downtime can be reduced by preventive maintenance, however, planned downtime necessary to carry out preventive maintenance tasks will increase. A more recent approach to maintenance is *condition based* maintenance, also called *predictive maintenance*. Condition monitoring technologies are used to plan maintenance tasks regarding the condition of a component. A *reliability centred maintenance (RCM)* process helps to determine which maintenance tasks need to be carried out and when they should be carried out. This process is supported by monitoring systems. [35]

The previous chapter, *Monitoring of slew bearings*, described monitoring technologies currently in use, as well as potential approaches for future monitoring. Internal failure reports[1] by Sandvik Mining Systems [11] have revealed that methods of measuring the tilting clearance or analysing grease samples failed to reliably predict fatal failures of slew bearings in multiple cases. Prior to the breakdowns, there was no traceable evidence as to why the slew bearings had failed. It can be concluded that there is currently no ultimately reliable solution available for monitoring slew bearings of reclaimers.

A major problem of slew bearing monitoring lies in the fundamental assumptions about monitoring techniques: All available condition monitoring systems focus on the detection of wear or defects of slew bearing components. However, excessive wear and defects in the

[1] The content of these internal reports is described in detail in section *3.2 Modes of failures*.

early stages of life span of a slew bearing are symptoms of utilisation above the design limits. Diagnosing the cause rather than drawing conclusions from the symptoms warrants the determination of the machine's real load situation. **The collection and analysis of sensor data facilitate the determination of the real load situation of a machine during operation.**

Cyber-physical systems (CPS) can be used to link data from sensors on a machine with physical models that represent a machine's behaviour. The concept of CPS enables this on a global scale. A sufficient and concise definition for cyber-physical systems is given by the Institute of Electrical and Electronics Engineers (IEEE) and the Association for Computing Machinery (ACM)[2]:

> Cyber-physical systems are systems with a tight coupling of the cyber aspects of computing and communications with the physical aspects of dynamics and engineering **that must abide by the laws of physics**.

Following this definition, conclusions based on sensor data must obey the physical models of the systems being observed. Hence, the problems can be considered to be inverse problems. Figure 5.1 illustrates how an inverse problem allows determining the *cause* of an *observed effect*. An *inverse model* is commonly described by differential equations that follow the laws of physics. A general definition of such a problem is $\hat{y} = f^{-1}(x)$. *A priori knowledge (metadata)* supports the inverse model in linking the observed effect with its cause. In general, the solutions to inverse problems are non-unique. The integration of a priori knowledge is essential to yield the desired result. [45], [46]

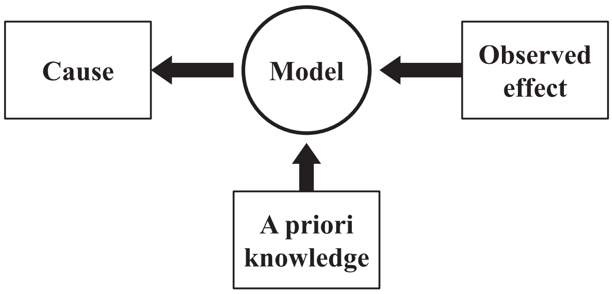


Figure 5.1: Representation of an inverse problem [46, cf.]

Inverse problems are not addressed in literature on *sensor data mining*. Present data mining approaches define correlation as a reliable measure for significance; they do not take into account that sensor data follow physical models. In contrast, inverse problems facilitate semantic links between sensor observations and their causes. Without this semantic relationship, no *knowledge discovery* based on physical models can be performed. [47]

It is mandatory to follow a certain structure when mining data to ensure clear terminology and that results from the analyses can be interpreted properly. The proposed *data mining*

[2]ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS): `iccps.acm.org`

wisdom pyramid, as shown in Figure 5.2, provides a hierarchical system that can form the base for further research. [48]

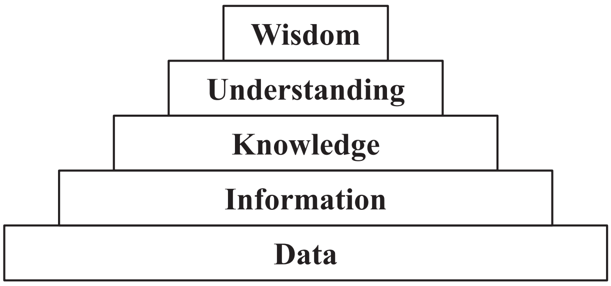


Figure 5.2: Data mining wisdom pyramid [48, cf.]

Data from a reclaimer's sensors acts as the fundamental base for further analyses. The *information content* can be computed from this data [49]; an example for the computation of the first temporal derivative of a reclaimer's slewing position signal is illustrated in Figure 5.3.

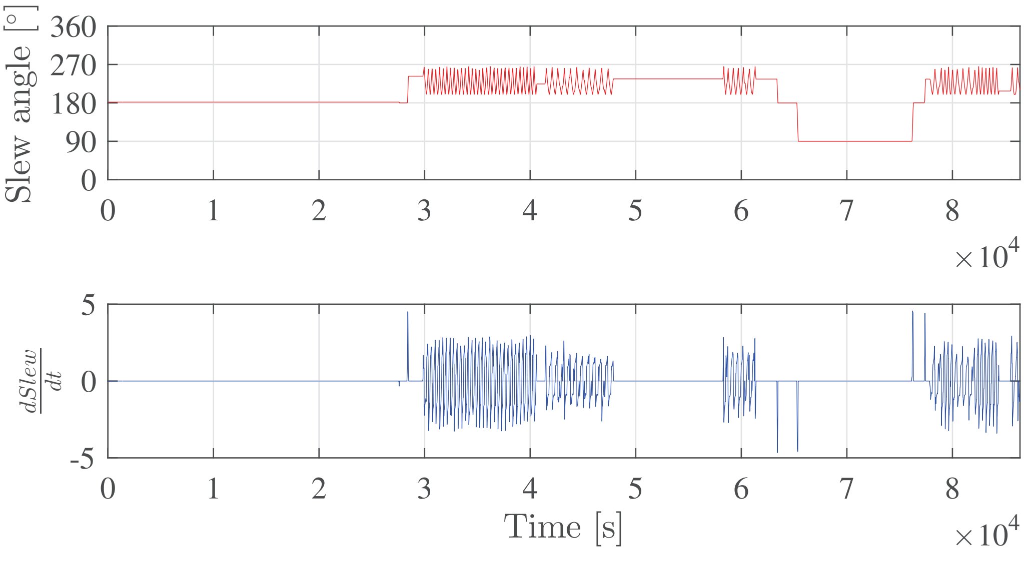


Figure 5.3: Rate of change of slewing signal

Although this measure of information is neither a valid measure for significance nor for meaningfulness, it can, however, provide support in identifying points in time when the information content of data changes [47]. This is especially helpful when segmenting data based on information content, rather than based on fixed time intervals or based on any other inflexible method of segmentation.

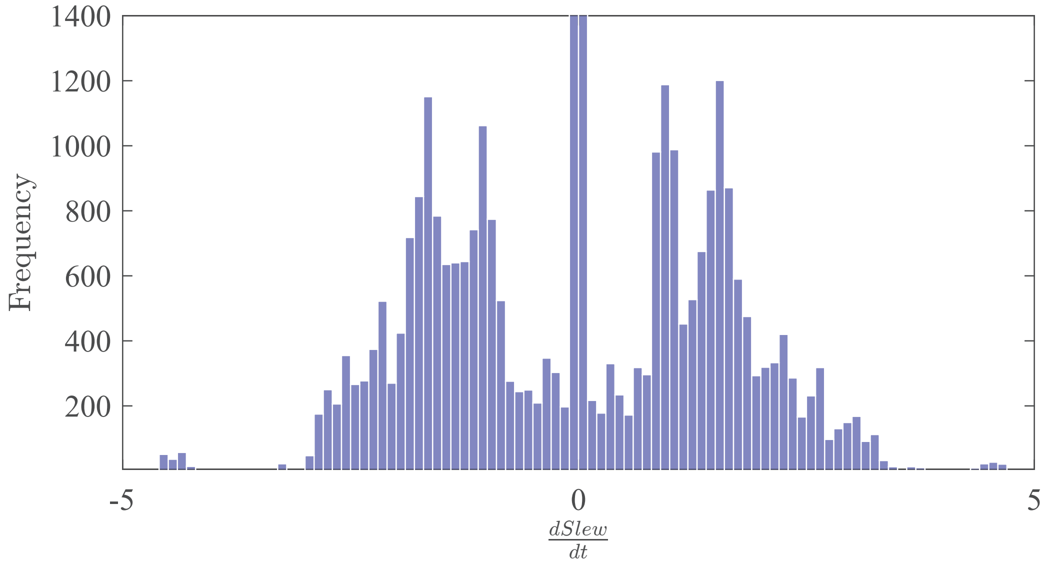


Figure 5.4: Histogram of first temporal derivative of the slewing signal

The histogram in Figure 5.4 of the first temporal derivative of the slewing position signal of a reclaimer reveals that there are two significant slewing speeds in both directions.

Metadata is necessary to link data streams with meaning; a data stream from a position sensor only describes a sequence of values before applying metadata to give the stream the meaning of position. A low level of *knowledge* can be a timestamp (or datum), because it reflects a statement about a fact. [47]

The fundamental aspect of extracting *system understanding* from data is the ability to predict the behaviour of the system in the future under similar circumstances and conditions.

Although a precise definition of *wisdom* is currently difficult to give, a possible approach for a definition can be to consider wisdom as contextual, situative actions supported by knowledge gained from past experiences.

These fundamental definitions of the different stages of a structured data mining process form a reasonable approach to processing sensor data.

5.1 A structured approach to data mining

The *Cross Industry Standard Process for Data Mining (CRISP-DM)* [50] can be used as a guideline for investigating and documenting data mining processes properly[3]. A predefined structure for objectives and tasks supports the stakeholders in managing such data mining projects. CRISP-DM divides the overall process into six major phases: *business understanding*, *data understanding*, *data preparation*, *modelling*, *evaluation*, and *deployment*. Following the nature of data mining, the outcome of the CRISP-DM model process is iterative and cyclic; the documentation of the process is dynamic and has to be maintained throughout the whole duration of such a project.

CRISP-DM was originally designed for data mining in the financial sector. Within this sector, all data available can be used for data mining. This is not necessarily true for data obtained from technical systems. The question of feasibility needs to be addressed before starting such a project. Feasibility studies for bulk material handling machines were performed by the Chair of Automation. Approaches to mining historical operational data of reclaimers were successful and their validity for data mining was proven. Hence, CRISP-DM is also strongly recommended for applications such as data mining of reclaimer sensor data.

[3] CRISP-DM was published in 2000. IBM Corporation published a methodology called *Analytics Solutions Unified Method for Data Mining/Predictive Anayltics (ASUM-DM)* in 2015. In ASUM-DM, the methods of CRISP-DM are refined and extended, so that the original publication from 2000 retains its validity.

Chapter 6

System analytics

In general, the dynamics of physical problems are modelled using differential equations. These equations permit us to determine the system's response to phenomena affecting it; the response of the system can be observed using sensors. An inverse model has to be solved to relate the system's response to its cause; this can be done using *Linear Differential Operators (LDO)* and their inverses. [47]

6.1 Linear Differential Operators

The application of an LDO to the data computes the corresponding dynamic model. The measurement model is considered to be an Ordinary Differential Equation (ODE) [51]:

$$a_n(x)\,y^{(n)} + a_{n-1}(x)\,y^{(n-1)} + ... + a_1(x)\,y^{(1)} + a_0(x)\,y = g(x), \tag{6.1.1}$$

where y is a function of x. All derivatives of y ($y^{(n)}$) are in respect to x. The sensor data is represented by $g(x)$. Constraints of the value of the function y or its derivatives y^n at specific locations x give indications as to whether the system is an inner-, initial- or boundary-value problem; or a mixture of these problems.

The general notion of a Linear Differential Operator, D [52], is used. $D^{(n)}\,y(x) = y^{(n)}$ used in equation 6.1.1 yields

$$a_n(x)\,D^{(n)}\,y + a_{n-1}(x)\,D^{(n-1)}\,y + ... + a_1(x)\,D\,y + a_0(x)\,y = g(x). \tag{6.1.2}$$

Lifting y out of the equation and defining the Linear Differential Operator L as

$$L \triangleq a_n(x)\,D^{(n)} + a_{n-1}(x)\,D^{(n-1)} + ... + a_1(x)\,D + a_0(x) \tag{6.1.3}$$

results in the following notation of equation 6.1.1:

$$L\,y = g(x). \tag{6.1.4}$$

6.2 Lexical analysis and knowledge discovery

The implementation of LDOs in data mining processes facilitates the recognition of events within the data streams. This is done with a form of symbolic aggregate approximation (SAX), where the value of a variable is segmented into ranges using measures for entropy [53]. Identified events can be labelled with symbolic identifiers, such as R for *slewing right*. Examples for simple events of a reclaimer are shown in Table 6.1, in which every event group represents a single channel. A separate LDO is used for every single channel.

Group	**Events**	
	Symbol	**Description**
Slewing	L	Slewing left
	N	Neutral; no slewing
	R	Slewing right
Luffing	U	Luffing up
	N	Neutral; no luffing
	D	Luffing down
Long-travel	F	Travel forward
	N	Neutral; no travel
	B	Travel backwards
Bucket-wheel	P	Powered rotation
	R	Non-powered rotation
	N	Neutral; no rotation
Tonnage	H	High tonnage
	L	Low tonnage
	N	Neutral; no tonnage
	E	Invalid (negative) tonnage

Table 6.1: Examples for events within data obtained from a reclaimer

The events identified in a stream of sensor data form a time sequence of symbols. Lexical definitions (textual symbols and human readable text) of every event are defined a priori. Hence, there are lexical definitions available for every identified event. This process is called *Single Channel Lexical Analysis (SCLA)* [53]. The scheme for a Single Channel Lexical Analyser is shown in Figure 6.1.

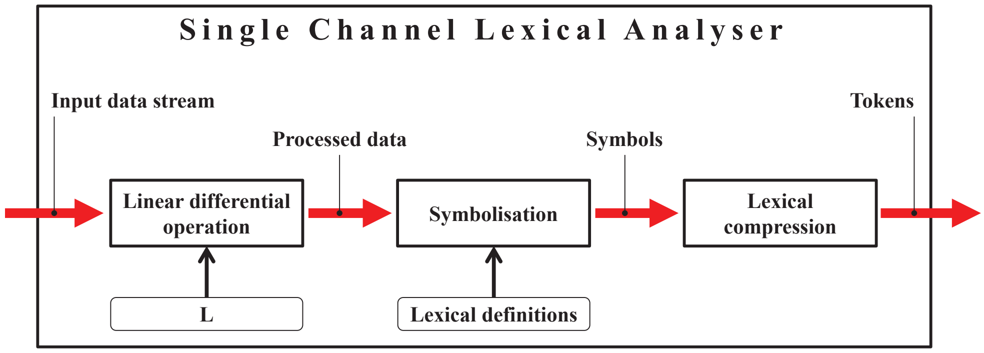


Figure 6.1: SCLA scheme [53, cf.]

The output of the SCLA are tokens, which carry more information than simple symbols: information about the length of the event (predicate) and about the starting and ending points (pointers) of the event within the sensor data stream. A distinct relation between the identified events and the respective sections in the data stream is given via the information content of the tokens; this enables backtracking at all times. Furthermore, the amount of data for subsequent analyses is compressed significantly, since the tokens can be used instead of the time series data. The compressed size of a lexical analysis' output was found to be less than 0.5% of the size of the original time series data [54].

An example for the application of an SCLA on a sensor data stream is given in Figure 6.2. The different segments (events) within the data stream are illustrated using colour patches.

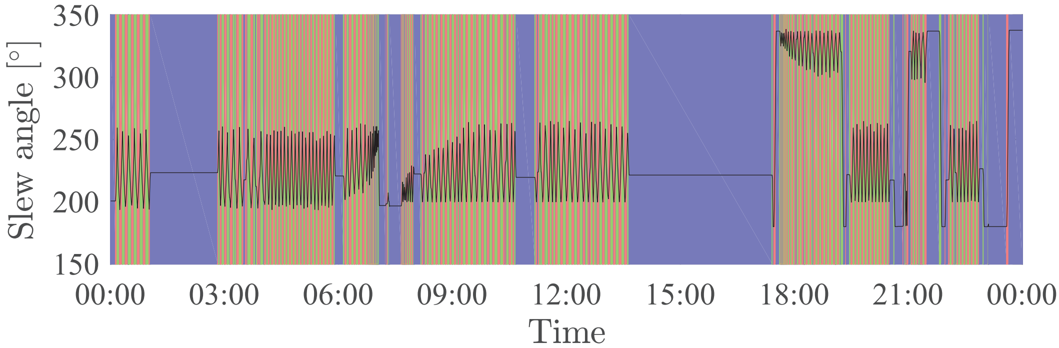


Figure 6.2: SCLA applied on slewing position sensor data

A detail of Figure 6.2 is shown in Figure 6.3. *Slewing left* is highlighted in red colour, *slewing right* in green colour, and *no slewing* is highlighted in blue.

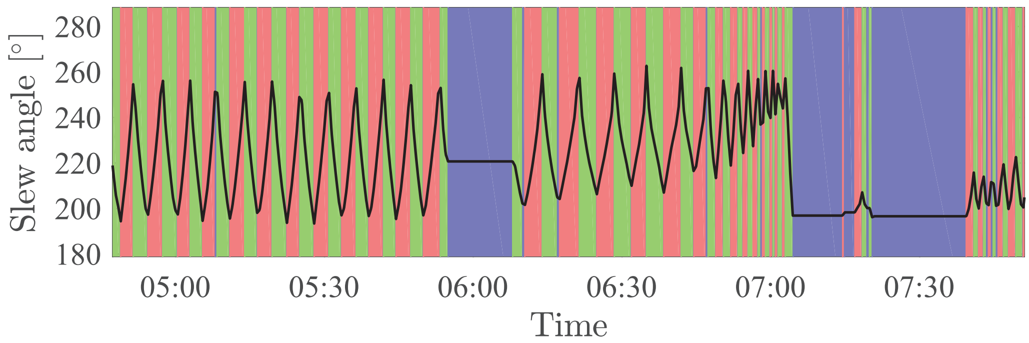


Figure 6.3: Detail of an SCLA applied on slewing position sensor data

Symbolic searches can now be performed to find specific events or sequences within the segmented data.

The outputs of multiple SCLAs can be aggregated using *Multiple Channel Lexical Analysis (MCLA)* as illustrated in Figure 6.4.

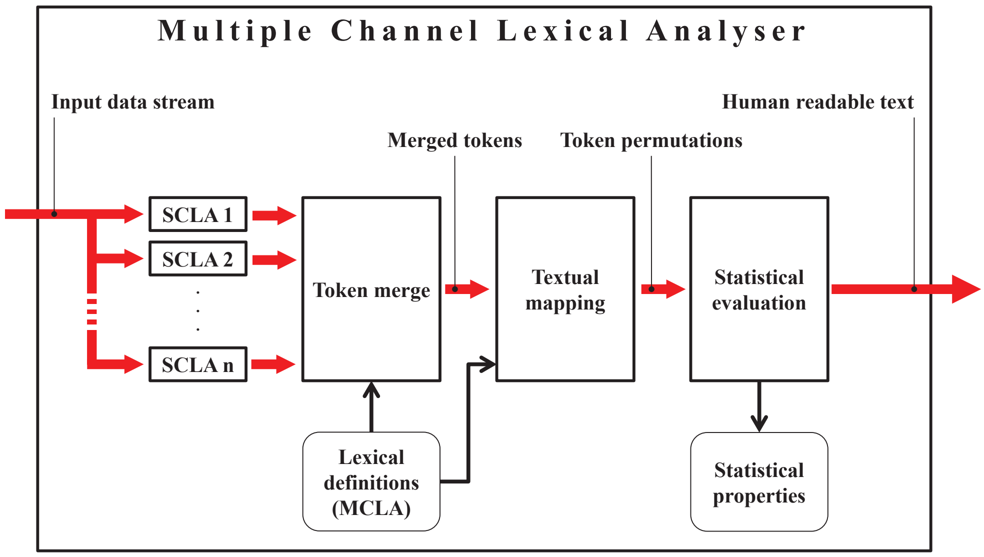


Figure 6.4: MCLA scheme [53, cf.]

The individual token tables are merged automatically; the occurrences of each combination are statistically analysed. This identifies repetitive sequences, seldom sequences, and sequences that do not occur at all. Automatic operation recognition can be performed using MCLAs [53], [55]. Furthermore, symbolic queries can be performed to find events or sequences within the token tables.

An advanced output of an MCLA can be the generation of a sequence frequency dictionary. Since the tokens are linked to human readable text, the discovered sequences are directly available for interpretation by domain experts, which are not required to have detailed knowledge about the data analysis methods. For instance, an MCLA can be performed on the channels *Slewing movement*, *Long-travel movement*, and *Tonnage*. A typical generated frequency dictionary by an MCLA merge algorithm is listed in Table 6.2.

No.	**Count**	**MCLA input channels**			**Operating state**
		Slewing	**Long-travel**	**Tonnage**	
1	32101	neutral	neutral	no	idle
2	18812	right	neutral	high	front-acting reclaiming
3	17904	left	neutral	high	front-acting reclaiming
⋮	⋮	⋮	⋮	⋮	⋮
10	2101	neutral	forward	no	positioning
11	1508	right	backward	no	positioning
12	1006	neutral	forward	low	trenching
⋮	⋮	⋮	⋮	⋮	⋮
26	59	left	neutral	negative	error (invalid tonnage)
27	37	neutral	backward	high	unknown
⋮	⋮	⋮	⋮	⋮	⋮

Table 6.2: Typical sequence frequency dictionary of an MCLA of slew, long-travel, and tonnage channels of a reclaimer

This process represents the concept of *knowledge discovery* during the exploratory phase of machine operation [53]. The table gives an overview of what kind of operations are common, uncommon, or do not exist at all within the data. The count of the event occurrences is a measure of occurrence probability during the considered time period.

6.3 Analyses of historical data

6.3.1 Input data properties

The evaluation of operational data provides support in identifying the real load situation of a reclaimer during operation. A client of Sandvik Mining Systems provided historical data of multiple machines. Multiple boundary conditions had to be considered regarding this data:

File format Data was available in CSV format. For some machines, one file per day was available; for others several days were concatenated to a single file.

Data acquisition It was not possible to clarify how the data had been acquired; on-change data acquisition or storage of one sample per fixed time interval.

File organisation The first column represents the timestamps, whereas the other columns contain the values of the different channels per timestamp; the order of the value channel columns varies within the files.

Sampling rate For every data channel, there is one value per second (1 Hz) available in the exported data sets.

The majority of the files contained channels as listed in Table 6.3. Further analyses were performed based on these channels.

Channel description	**Unit**
Timestamp	Date and time
Luffing position	°
Slewing position	°
Long-travel position	m
Luffing speed	%
Slewing speed	%
Long-travel speed	%
Cylinder 1 piston pressure	bar
Cylinder 1 rod pressure	bar
Cylinder 2 piston pressure	bar
Cylinder 2 rod pressure	bar
Tonnage	t/h

Table 6.3: Available data channels

The numerous findings in the historical data from the reclaimers are described in the following sections.

6.3.2 Findings regarding slew bearing utilisation

6.3.2.1 Problems with luffing hydraulics

It was found that major changes in pressure levels of the hydraulic luffing cylinders occurred in relatively short time periods. These frequent short-time pressure losses correlate with the oscillation of the luffing position signal; the superstructure of the machine is rocking during reclaiming. This observation is illustrated in Figure 6.5.

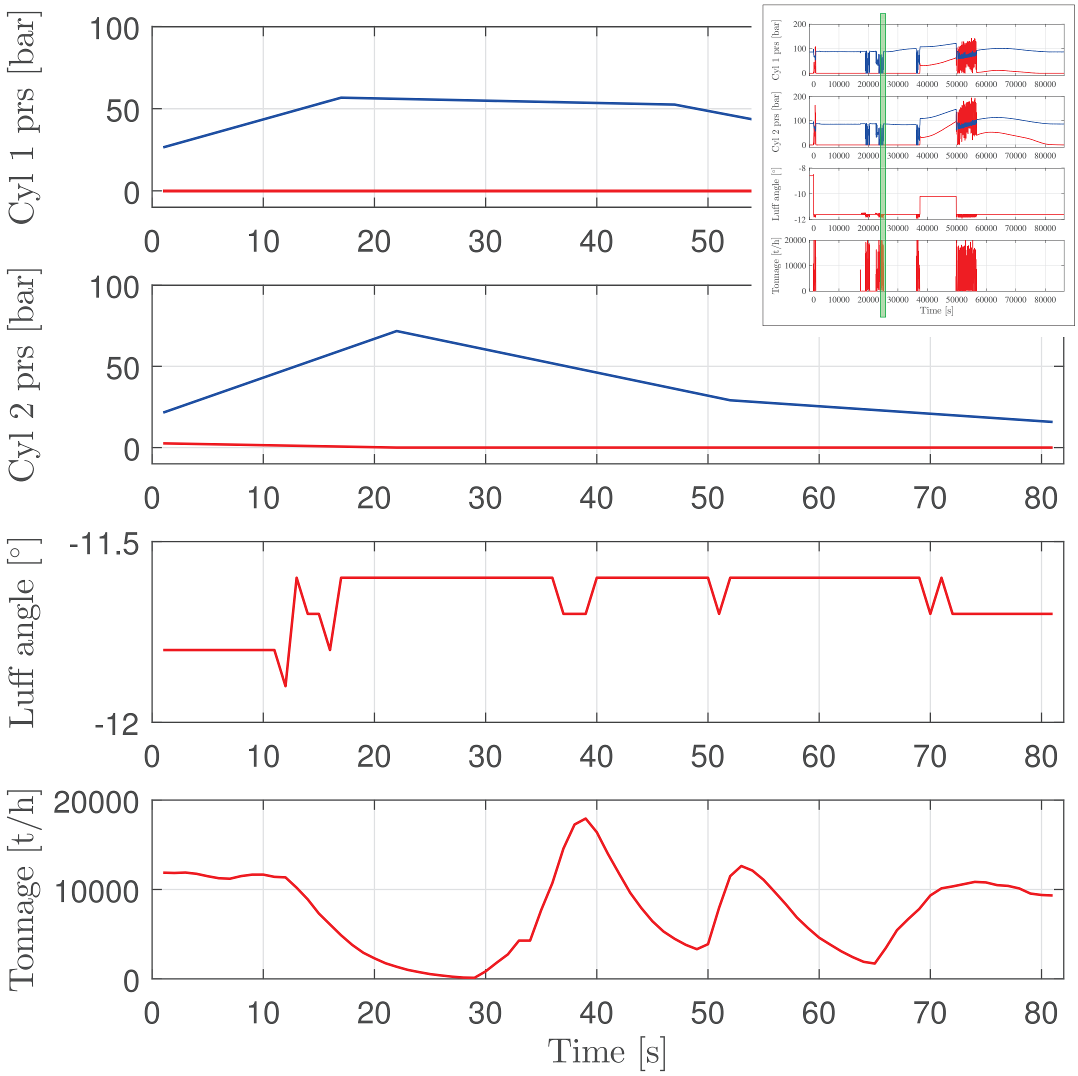


Figure 6.5: Rocking of superstructure

It is likely that the hydraulic system is overloaded as the bucket-wheel enters the stockpile and starts to reclaim material. As a consequence, the pressure in the hydraulic cylinders drops off, forcing the system to reapply pressure to the cylinders in order to maintain the current position. This provokes an oscillation of the system until it is finally stabilised. The superstructure keeps rocking during the settling time as a direct consequence of the poor hydraulic control system. As described in chapters 2 and 3, the slew bearing transmits all loads from the superstructure to the undercarriage. The forces of the luffing cylinders are proportional to the tilting moment applied onto the slew bearing through geometric relations. Every change in cylinder pressure has an influence on the slew bearing. Excessive rocking of the superstructure results in hydraulic hammering, decreasing the life span of hydraulic components and leading to local overutilisation of the slew bearing. Hence, rocking of the superstructure is presumed to have a major influence on slew bearing life span. This behaviour may be an interesting field for further investigations.

It was further found that there were significant differences in pressure between the left and right cylinders while the machine was not reclaiming and also while it was in operation. The pressure difference is shown in Figure 6.6. These asymmetric pressures may be related to the application of torque onto the superstructure, even when the machine is not reclaiming.

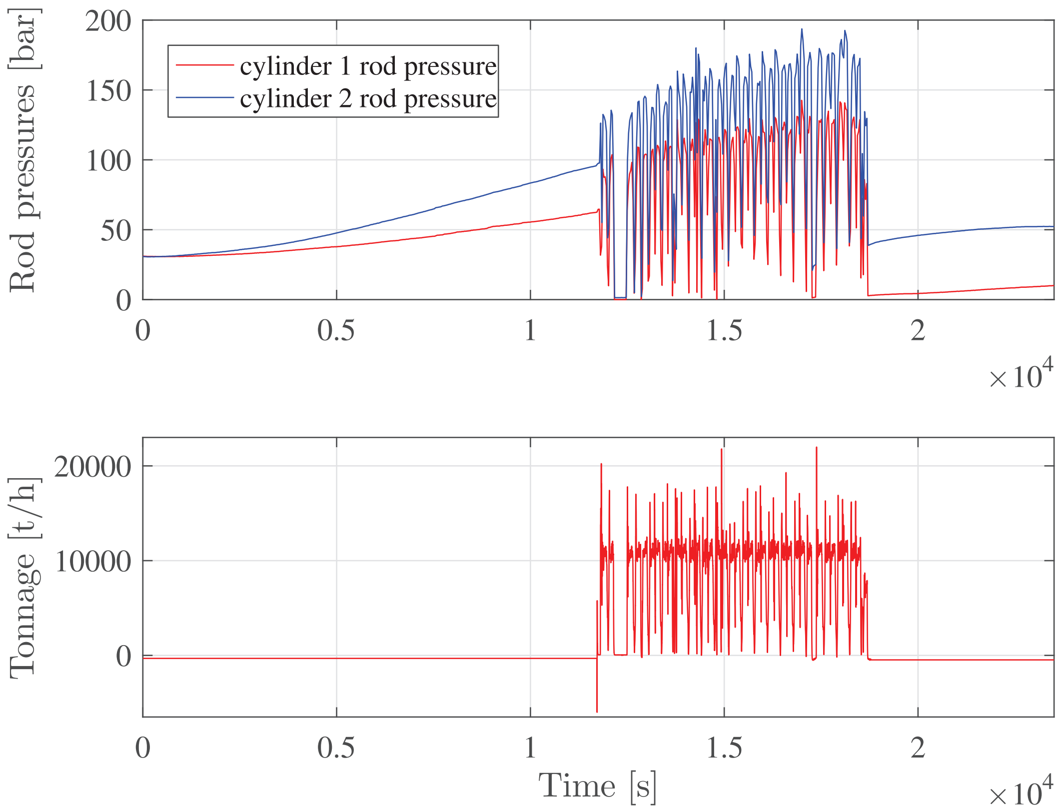


Figure 6.6: Asymmetric cylinder pressures

The pressure levels of the luffing cylinders were found to be around or even below 0 bar at certain points in time. This significant loss of hydraulic pressure is directly related to the loss of stiffness of the superstructure during reclaiming. A non-existent stiffness of the luffing cylinders induces additional rocking of the superstructure when the bucket-wheel is reclaiming material from the stockpile. Hydraulic system pressures at or below 0 bar benefit dirt ingress and excessive wear of valves and seals, as there is no relative overpressure of the system in respect to the ambient pressure. This is especially critical in environments of iron ore dust. Also, cavitation can occur as a consequence of negative pressure levels.

6.3.2.2 Non-uniform utilisation of the slew bearing

Polar plots are found to be a reasonable option for illustrating slew bearing utilisation. These plots show the distribution of reclaimed material in respect to the slewing positions of a reclaimer; this load distribution is found to be non-uniform.

One day of operation is summarised in Figure 6.7. Material was reclaimed mainly in quadrant IV on this particular day.

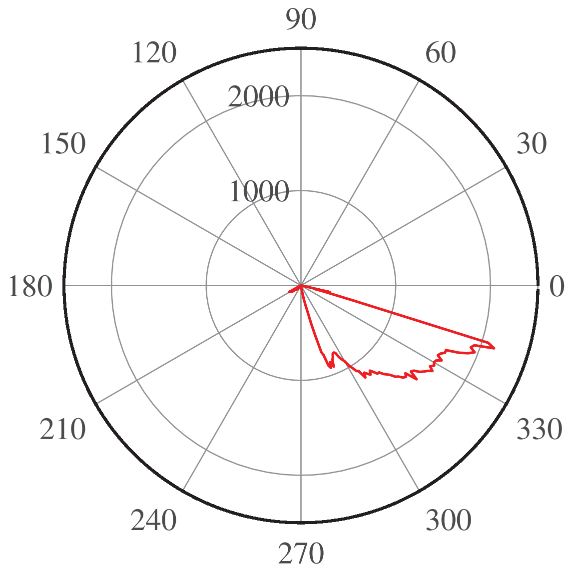


Figure 6.7: Reclaimed material over full slewing range for one day of operation

If a longer time period is observed, the plot might look different. An example is given in Figure 6.8: 202 days of operation[1] yield a completely different illustration, showing where material was reclaimed in quadrant III as well as IV, with the former dominating slightly. Hence, these two quadrants were more utilised than others during this particular time frame.

[1]Data was available for a total of 202 days.

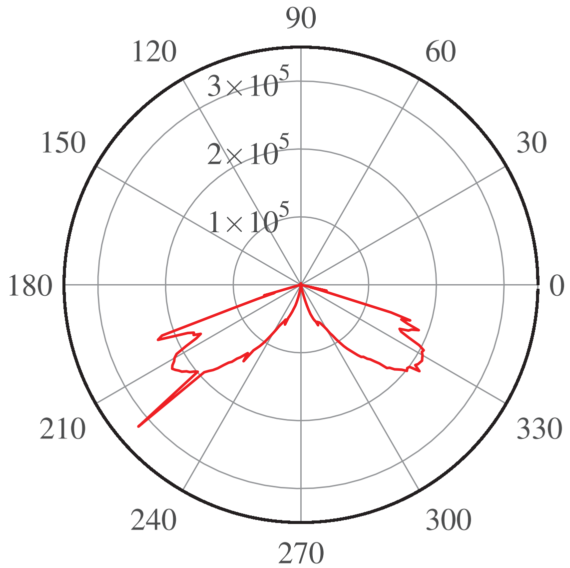


Figure 6.8: Total reclaimed material over full slewing range for 202 days

The plot for a different day exhibits trenching operation in quadrant III (Figure 6.9). Utilisation of the reclaimer is concentrated at a narrow slewing range. Such a form of utilisation is suspected to have a significant influence on slew bearing life span, as the load is not evenly distributed along the circumference of the bearing and the roller elements and the raceway areas stay the same over a long period of time. Without the roller elements moving and changing position, there is little load redistribution within the slew bearing.

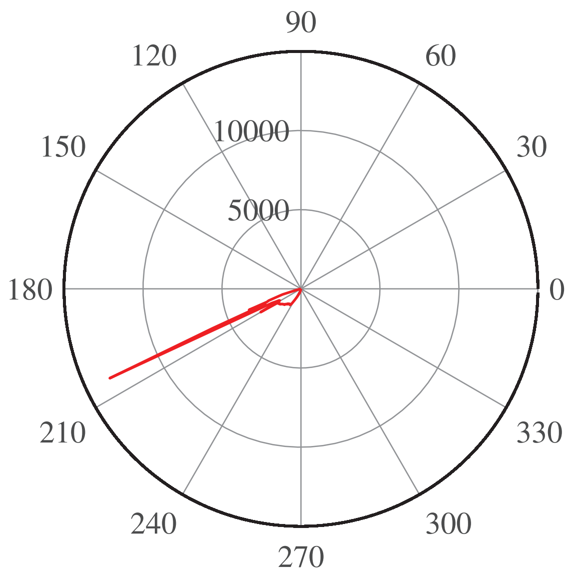


Figure 6.9: Tonnage over full slewing range for one day indicating trenching operation

6.3.2.3 Inefficient reclaiming operation

Lexical analyses of *slewing position* and *tonnage* indicated efficiency issues during the reclaiming operation. The bucket-wheel is slewed across the full width of the stockpile. The bucket-wheel leaves the stockpile's outer edges; the bucket-wheel "shovels air" during reclaiming. This effect was observed to be more dominant on one side. Figure 6.10 illustrates this behaviour.

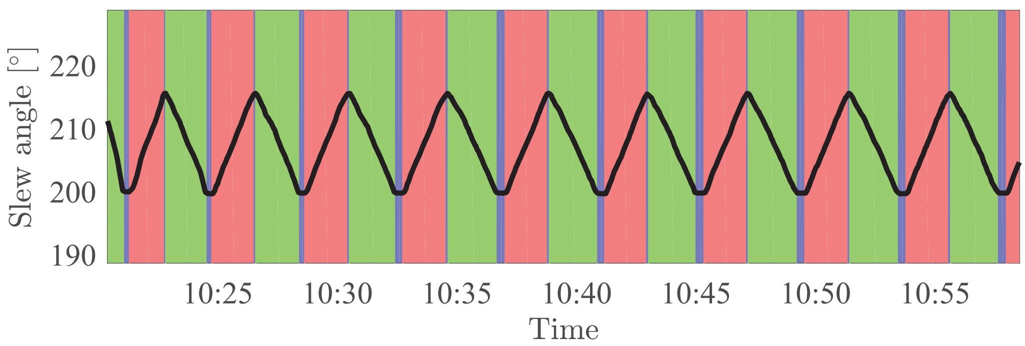


Figure 6.10: Loss of productive time during reclaiming

Such problems cause loss of operational time; the reclaiming operation is considered to be inefficient. These issues can be resolved by revising the control logic of the machine.

Furthermore, the hydraulic luffing unit seems to have an unstable system response to load changes, as indicated in section *6.3.2.1 Problems with luffing hydraulics*. This behaviour can occur when the bucket-wheel enters (or leaves) the stockpile. Hence, frequent load changes due to entering and leaving the stockpile are considered to have an impact on slew bearing life span.

A lexical query of *slewing right* - *stop* - *slewing right* and *slewing left* - *stop* - *slewing left* revealed short, but frequent, interruptions during slewing as shown in Figure 6.11.

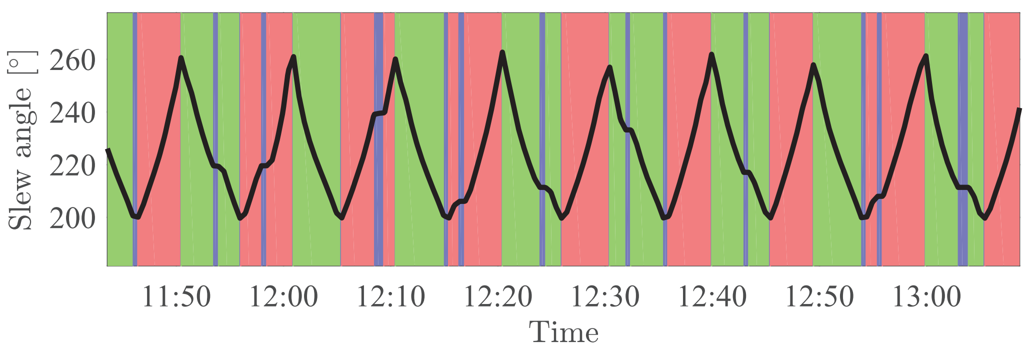


Figure 6.11: Interrupted reclaiming

These interruptions may indicate stoppages of slewing as a consequence of a collapsing stockpile face. Such mechanisms are mandatory to protect the machine against excessive overload. There are several reasons for a collapsing stockpile face; for instance, an insufficiently stacked stockpile can significantly increase the probability of a stockpile collapse. Collecting and analysing operational data of stackers can be interesting for further investigations: linking the logistics data for incoming material with the parameters for reclaiming material can provide support in reducing or even avoiding collapses of the stockpile face.

6.3.3 Additional findings

6.3.3.1 Different sampling rates of pressure data

The CSV files had been exported from a central database. The sampling interval was adjustable for the file export; this justifies that data was resampled whilst being exported. The plot in Figure 6.12 illustrates the different real sampling rates, although the general sampling rate was given at 1 Hz. The original sampling rate of the raw data and the method of resampling are not known.

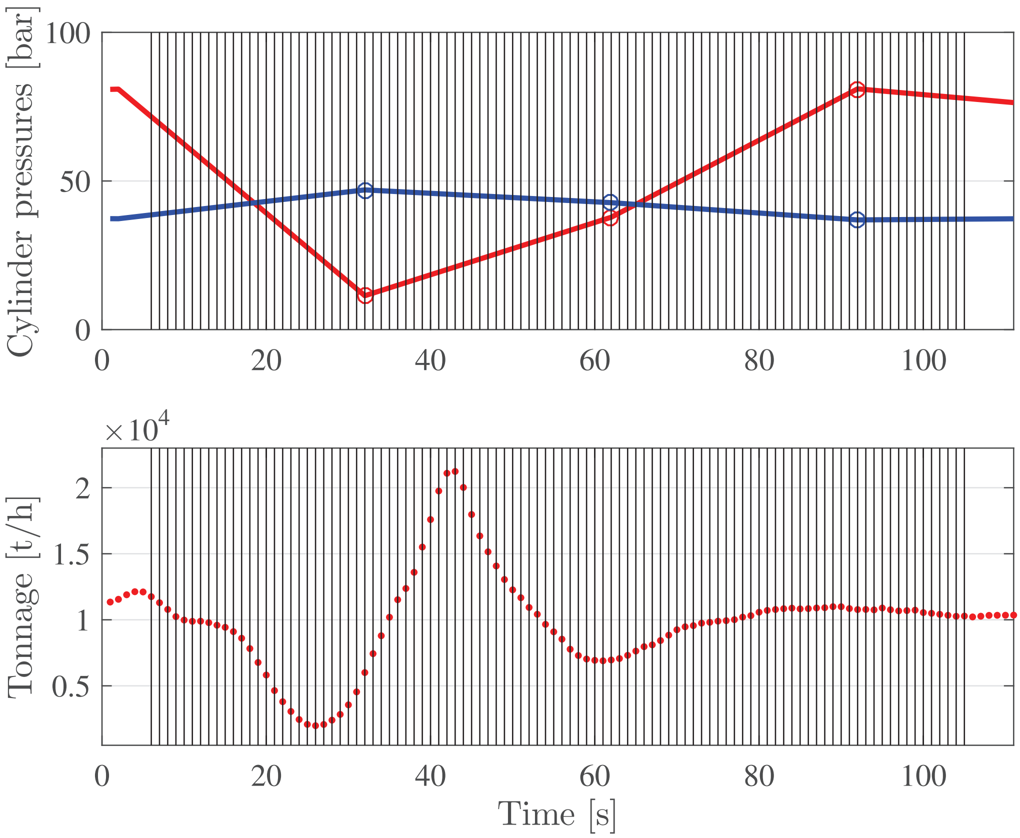


Figure 6.12: Plot of interpolated cylinder pressure data

6.3.3.2 Incorrect and misleading speed values

Speed values for the position signals *luffing*, *slewing*, and *long-travel* were contained in some CSV files. However, the data was found to be inconsistent; the speed values did not change for longer periods of time, although the respective positions did change. Furthermore, calculated speed values based on the position changes over the course of time did not correlate with the speed values in the files.

6.3.3.3 Abnormalities in data of belt scale

The tonnage signal is obtained from a belt scale, which is installed on the boom of the reclaimer. A typical belt scale measures two separate parameters: the current weight m_m of the material on the belt at the belt scale location, as well as the speed $v_{m,B}$ of the belt. The combination of both yields the mass flow ("tonnage") $\dot{m} = m_m\, v_{m,B}$, which cannot have values below zero as only positive speed values are measured by the belt scale. Hence, a properly installed belt scale can only produce positive values for mass flow, with 0 as the minimum. However, a lexical search for *negative tonnage* revealed tonnage values below zero existed among the data; a detail of one particular finding is shown in Figure 6.13.

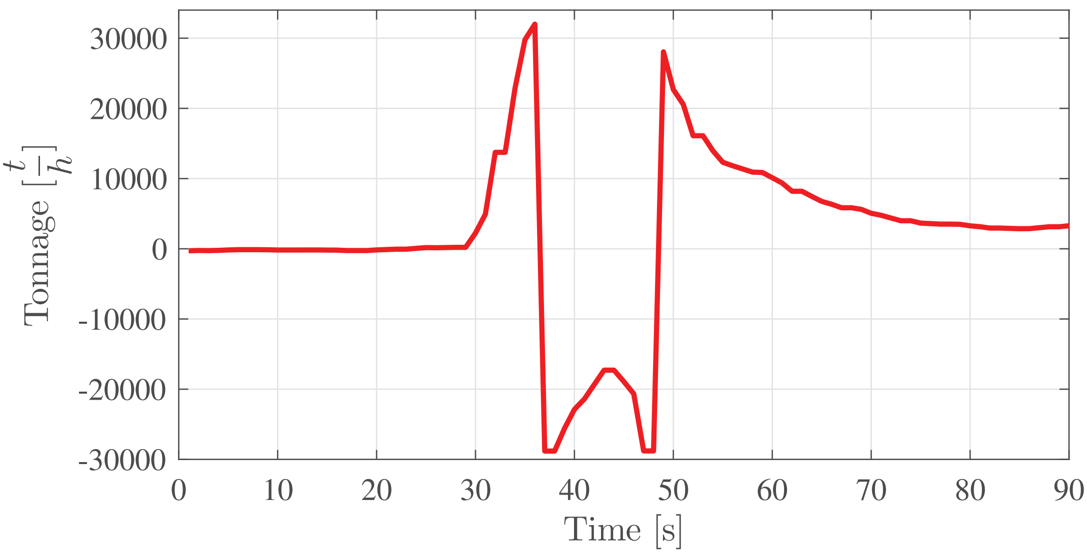


Figure 6.13: Abnormalities in belt scale signal

The client was not aware of this problem and was not able to give a sufficient explanation for the negative values. The visual nature of the negative tonnage signal within the time series data allows for the conclusion that the negative values are the consequence of poor overload behaviour of the sensor: the raw signal from the belt scale is most probably mapped to a signed integer data type. The highest bit of this data type contains information about the sign of the value, whereas the other bits contain information about the absolute value.

When the maximum (positive) value of the signed integer data type is exceeded, the first bit is overwritten and results in a change of sign. The typical arithmetic overflow behaviour of an 8-bit integer data type is shown in Table 6.4. An overflow will be provoked, if the value is increased above the data type's positive limit - which is 127 for an 8-bit integer. Following the rules for the *two's complement* of a binary number, the next value will be represented as the lowermost negative value of the 8-bit signed integer value range, which is -128.

Binary								**Decimal**	
2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0	**unsigned**	**signed**
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	1	0	2	2
0	0	0	0	0	0	1	1	3	3
			⋮					⋮	⋮
0	1	1	1	1	1	1	0	126	126
0	1	1	1	1	1	1	1	**127**	**127**
1	0	0	0	0	0	0	0	**128**	**-128**
1	0	0	0	0	0	0	1	129	-127
			⋮					⋮	⋮
1	1	1	1	1	1	0	0	252	-4
1	1	1	1	1	1	0	1	253	-3
1	1	1	1	1	1	1	0	254	-2
1	1	1	1	1	1	1	1	255	-1

Table 6.4: Arithmetic overflow of an 8-bit signed integer

Chapter 7

Framework for data mining

As more data is collected and is available for analysing, more output can be produced. The efforts for data transmission, storage, and processing increase with every additional data channel and with every new machine monitored. To satisfy the requirements for a stable and consistent data flow on a long-term perspective, a resilient infrastructure is necessary. Such a data mining framework can support the process of knowledge discovery as well as the implementation of processes, which produce results from data automatically.

Furthermore, it is possible to compare machine characteristics to find ergodicity or patterns of similar behaviour by having multiple machines of the same or a similar type in the same data flow structure. Machine type characterisation can facilitate fleet management.

7.1 Machine system definition

All monitored sensors of a machine are defined in a Microsoft® Excel workbook (XLS-file). This simplifies and accelerates the metadata definition and integration of new machines into the data mining framework. Apart from channel name (tag), value type and range definitions, lexical definitions are contained in this file. In this manner a data expert is not required to integrate a new machine into the framework.

The definition for the reclaimer investigated in chapter 6, *System analytics*, is listed in Table 7.1.

Channel	Unit	Range		Short desc.		Long description
Tonnage	t/h	0	12400	BC	tonnage	tonnage on boom conveyor
LFEncPos	°	-12.8	16.5	LF	angle	luffing angle
LF.Prs01	bar	0	155	LF	cyl1 prs1	luffing cylinder 1 piston pressure
LF.Prs02	bar	0	220	LF	cyl1 prs2	luffing cylinder 1 rod pressure
LF.Prs03	bar	0	155	LF	cyl2 prs1	luffing cylinder 2 piston pressure
LF.Prs04	bar	0	220	LF	cyl2 prs2	luffing cylinder 2 rod pressure
LTEncPos	m	0	1000	LT	position	long-travel position
SLEncPos	°	0	360	SL	angle	slewing angle

Table 7.1: Sensor definition for data mining framework

7.2 Modes of data collection

There are multiple ways of collecting and collating data for further processing; an illustration is given in Figure 7.1.

The analyses in this thesis were carried out based on historical data of a reclaimer. The data was collected and stored on a central database server (data archive) and was exported as one file per day. Theoretically, it would also have been possible to obtain the archived data via direct database access.

Encouraged by the potential of the initial findings in the historical data, Sandvik Mining Systems installed three prototypes of local data acquisition units on different machine types. Data is transferred from the collection units to the incoming server on a daily basis as exports of the local databases. Furthermore, tests to transfer the data instantly (live data) are being undertaken. This enables the detection and immediate notification of stakeholders about suddenly occurring severe incidents. For safety reasons, it is at a later stage possible to implement parts of the logic directly on the locally installed data collection unit, which can be an industrial computer or a field programmable gate array (FPGA).

The input data is processed by using sensor definitions (metadata) as well as a set of rules for data quality. The latter are mandatory for performing quality checks on the input data to separate valid from invalid data. The valid data is then stored as full table data in a contiguous data model.

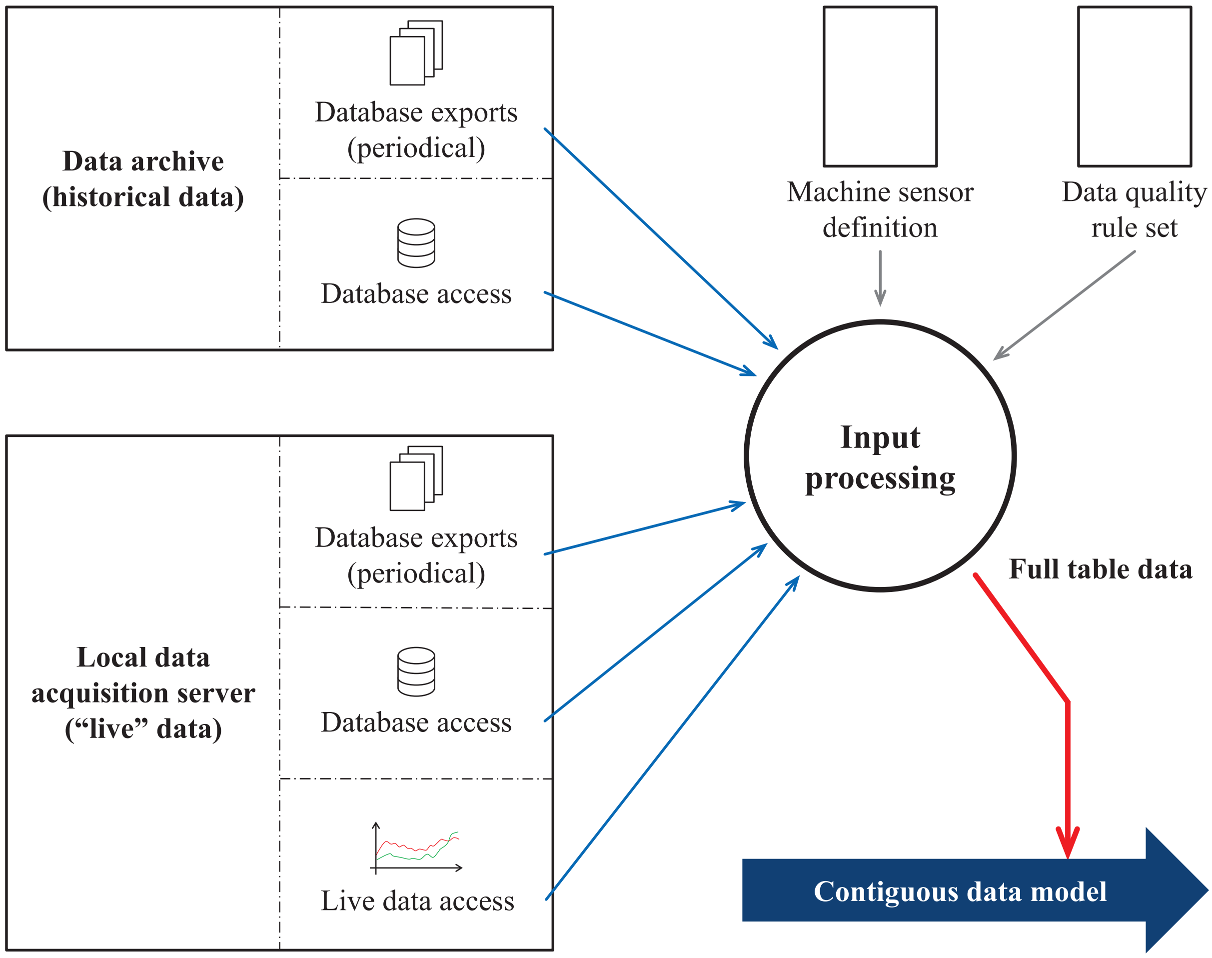


Figure 7.1: Data input processing which is independent from the data source

The data mining framework is independent of the type of input data. Historical data from data archives, daily exported files, or live data are valid inputs for processing within the framework. This is an important feature, as some machines are located in remote areas with unstable or no internet access, resulting in irregular data transmission. As described in the following section, a contiguous data model enables the framework to be adaptable to different formats of data input.

7.3 Data organisation and storage

7.3.1 Contiguous data model

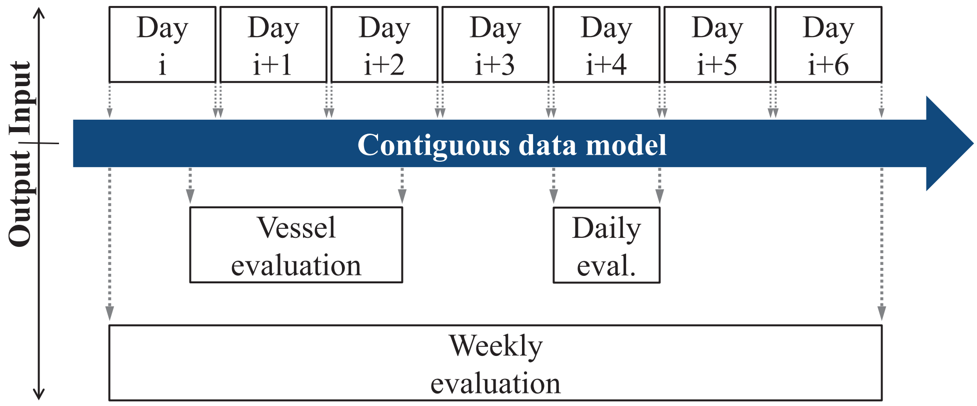


Figure 7.2: Contiguous data model with full separation of input and output formats

A contiguous data model, as illustrated in Figure 7.2, benefits the separation of the input and output data format of the time-series sensor data. The input, e.g., full table data of daily database exports, is merged with the already existing data to form a contiguous data stream. The data stream is advanced every time a new input is fed into the system. Data can be retrieved from the contiguous model by using a function such as:

```
getData(channel, fromTimestamp, toTimestamp)
```

The start and end time of the requested data can be chosen as needed. This enables the retrieval of daily, weekly, monthly, or annual data. If the data is recorded in coordinated universal time (UTC), data can be retrieved in local time zones as well. Furthermore, detailed data for specific events or time ranges can be requested from the continuous data stream. This is particularly relevant for loading bulk carrier vessels: a reclaimer supplies material from a stockpile to a ship loader, which then loads the vessels. Data can be retrieved for the full duration of this task. Specific results for this specific time frame can be produced. The start and end points are defined using metadata.

7.3.2 Reconstruction of on-change data

The data acquisition prototypes of Sandvik Mining Systems collect data on-change: values are only stored in the local database, if they exceed a specific hysteresis threshold. Values from some data channels are updated and stored more frequently, while others rarely change in value. This behaviour also depends on whether a machine is currently being operated or not. Storing data on-change enables the data sets to be automatically compressed, as non-changing value states are omitted.

To use the data mining framework to its full extent, data has to be available in a full table format: a contiguous data model with the same sampling rates for all data channels. Such a format can be generated from on-change data with different sampling rates. This process is illustrated in Figure 7.3. One row of on-change data contains the timestamp, the channel identifier, and the definite value at storage time. A master sampling rate has to be defined, to which the values of the different channels are resampled to. In the next step, the gaps between the values in the resampled table are reconstructed by using zero-order hold (ZOH) and first-order hold (FOH) models [55]. Calibration data (highlighted in blue in the figure) is used as a reference for the reconstruction models. All these steps result in a full table of sensor data, which can be used for further processing.

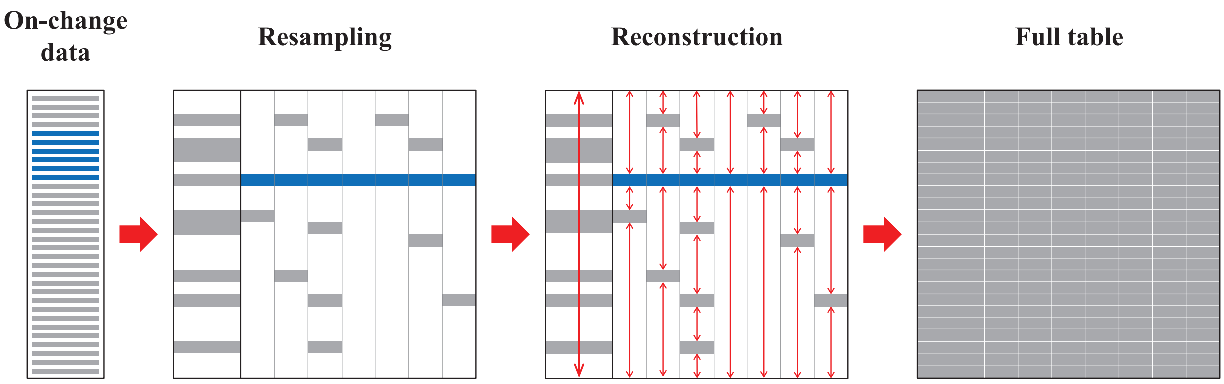


Figure 7.3: Resampling and reconstruction of on-change data to full table data

7.3.3 Storage organisation

Raw sensor data is reconstructed as a full table from an on-change format. A well-defined and structured storage organisation is mandatory to achieve adequate access times for large amounts of data. Such a setup is illustrated in Figure 7.4. The data is stored with each row referring to a definite timestamp. Derived measurements can be calculated from raw sensor data by considering physical models, relationships, and sensor metadata. These computations are carried out as soon as the full table data is available and the results per data row are stored per time step as well. Symbols representing certain machine or sensor states are also stored by linking sensor data with lexical definitions contained in the machine system definition (sensor definition file). Human readable text can be produced based on the data available as well. Furthermore, summary tables for a certain number of data sets can be generated during the data storage phase. These *data chunks* provide support in reducing access times for frequent queries significantly [56].

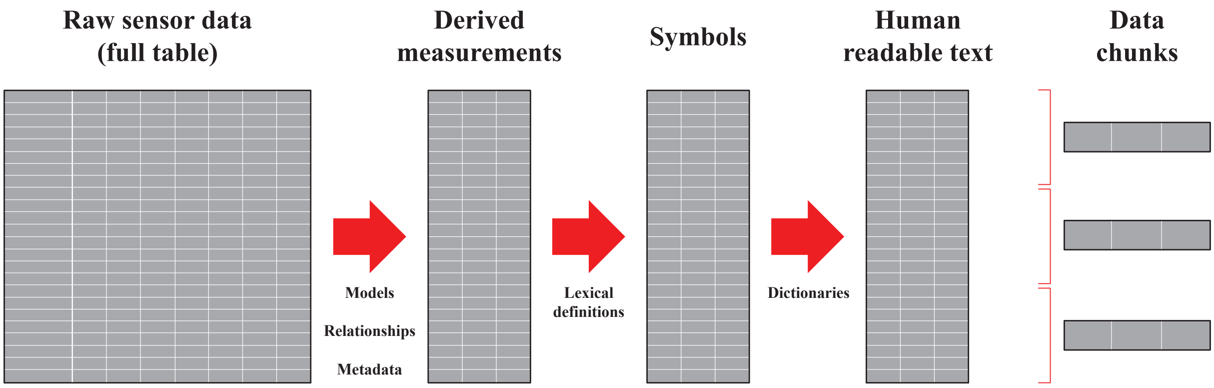


Figure 7.4: Data structure for storage of derived measurements, symbols, human readable text, and data chunks along raw sensor data [54, cf.]

7.3.4 Data access methodology

Storing data from numerous reclaimers leads to a comprehensive data archive. The more data is queried from the main data archive for performing an analysis, the slower the access to the data.

A data access methodology with a three level cache contributes to fast retrieval times of stored data. The idea is to hold the most frequently queried data available in a memory location that is quickly accessible, while less-frequently queried data is stored in locations with longer access times. A version of a three level cache implementation is given in Figure 7.5.

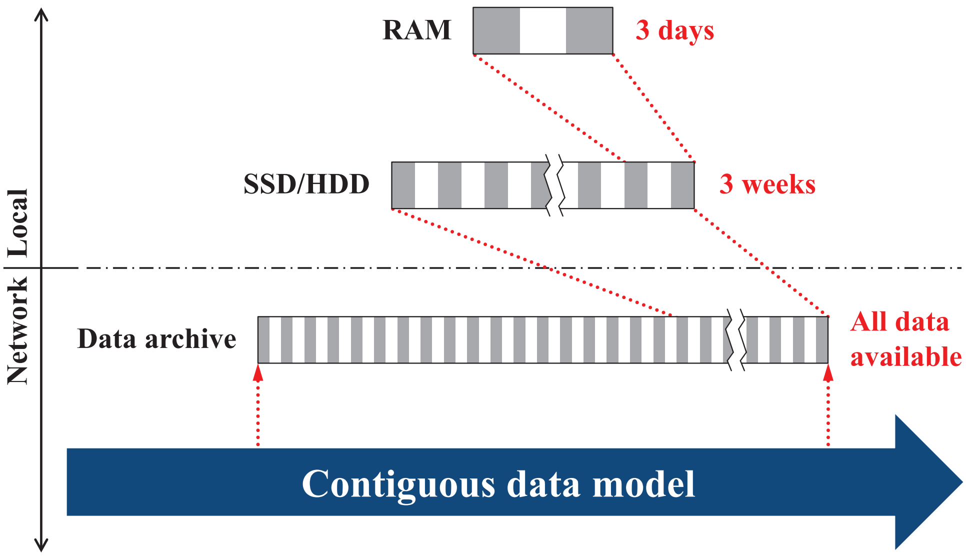


Figure 7.5: Data access structure with three level caching

This implementation holds the most recent data, e.g., the last three days, in the random access memory (RAM) of the analyst's local computer. Data from the last few weeks is kept on the local computer's solid state drive (SSD) or hard disc drive (HDD). All other data needs to be retrieved from the data archive, where all data is stored in a contiguous data model. In contrast to the analyst's local computer, the data archive is a network server. Querying data from the data archive takes the longest as benchmark tests have shown [47].

All data queries are re-routed internally, in such a way that users of the system do not notice where the data is retrieved from. If data of the last two days is requested, it can be retrieved quickly from the RAM of the local computer. Data from the previous week will also be retrieved quite fast, as this data is available on the local SSD or HDD. If data from the previous six months is requested, the data access methodology will source the data from the data archive automatically. It takes longer to produce results for such queries, but they are also requested less frequently.

7.4 Data flow structure

A reasonable data flow structure for mining a machine's operational data can be established by combining the steps *data collection*, *storage*, *analytics*, and *evaluation*. A structured overview is illustrated in Figure 7.6.

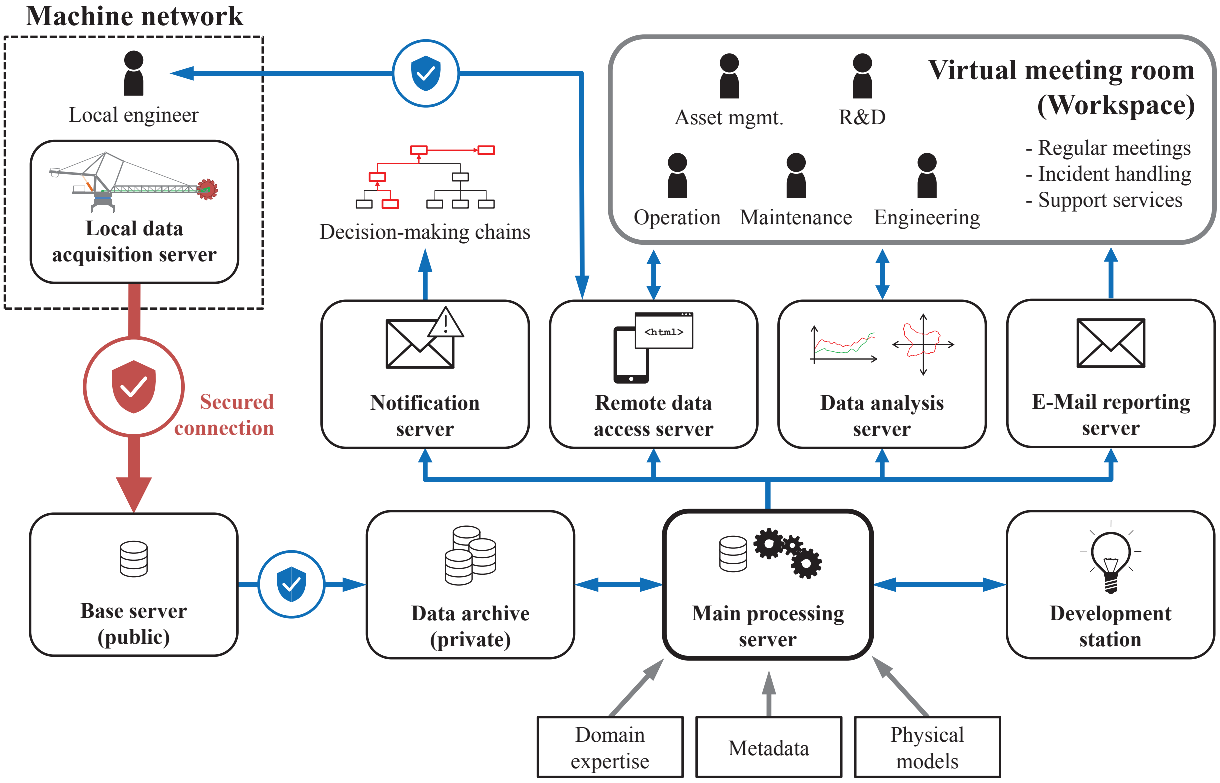


Figure 7.6: Data flow model

Data is collected by a *local data acquisition server*, which is connected to the main logic controller of a reclaimer.

Data is buffered in a database before being extracted as CSV files on a daily basis. After these files are compressed, they are sent to a *public base server*. Alternatively, a live data connection can be established, e.g, by using a database replication service within a virtual private network (VPN) tunnel. The connection for all of these transfer methods is secured to reduce the risk of security breaches. There is one public base server for every machine. Multiple such servers can be run in parallel in a virtual environment.

Next, the incoming data is pre-processed on the public base server to integrate the data into the contiguous data model of the data mining framework on the *private data archive server*. All incoming data is stored simultaneously as full table comma-separated values files (CSV), as MATLAB® binary data files (MAT), in a hierarchical data format (HDF5), and in Apache HBase[1]. For security reasons, the data archive server only accepts data coming from the public base server.

A central *processing server* has access to the complete data archive, to machine knowledge from *domain expertise*, to machine (sensor) *metadata*, and to definitions of *physical models*. Subsequent data services source their input from this mainframe. Data experts using *development stations* have access to the processing server to develop, advance, and verify concepts, methods, and models for data mining. A *notification server* can identify abnormalities that need human interaction. It is designed to support decision-making chains within the project organisation with implemented fallback routines to enforce timely approvals. Engineers at the machine's location can access information on mobile devices via RESTful[2] web services; data queries by engineers are sent to a *remote data access server*, which performs the necessary calculations and provides the results, e.g., as a HTML5 website. This remote data access service is also available to other authorised users, e.g., those within a proposed virtual workspace.

The establishment of a *virtual meeting room* offers such a virtual workspace for the different stakeholders within a data mining project. Reports are sent to the members of the virtual workspace periodically by an *e-mail reporting server*; these reports can be the basis for discussions during regular meetings held in such virtual environments. Meetings prior to or after an incident are facilitated by this workspace as well. Immediate results are retrievable from a *data analysis server*. All data is also available in HBase as soon as the data is stored in the data archive. A search engine, such as *Elasticsearch*, can be connected to the operational data of a machine via HBase. *Kibana*, a visualisation plug-in for generating charts and dashboards, can be used with Elasticsearch. The use of such tools assists in making decisions based on facts retrieved from operational data.

[1] *Apache HBase* is a non-relational, distributed database and is part of the *Apache Hadoop* framework. HBase is modeled after *Google Bigtable*.

[2] *Representational State Transfer*

Chapter 8

Conclusion and outlook

8.1 Conclusion

A main result is the insight that sufficient definitions for a data flow model, for a data model, and for a data storage model are needed for mining operational data. These models are generic and independent from the type of machine being monitored.

A new concept for data analytics has been implemented and tested for an exemplary case. The results achieved with lexical analyses – high data compression, enabling of lexical searching, automatic sequence exploration – warrant further research.

In the exemplary case of the bucket-wheel boom-type reclaimers considered in this thesis, it was possible to automatically identify issues related to the control of the luffing unit, to the non-uniform utilisation of slew bearings, to interrupted reclaiming, and to the validity of input data. For example, engineering feedback corresponding to improvements in the hydraulic system was identified. Issues with the belt scale measuring the mass flow during reclaiming ("tonnage") were found as well as random and systematic interruptions of the reclaiming process. Furthermore, polar plots showed in a simple and straightforward manner that the load on the slew bearing was not equally distributed; the "trenching" reclaiming operation may cause a significant reduction of slew bearing life span.

8.2 Outlook and recommendations

The presented data mining framework is convenient for collecting, collating, storing, analysing, and evaluating operational data of reclaimers and other bulk materials handling machines. The initial results of the work for this thesis motivated Sandvik Mining Systems to install and maintain data acquisition units on two bulk materials handling machines and one mining machine. It is also intended to acquire data from additional machines for further detailed research.

Abnormalities, such as the rocking of a reclaimer's superstructure, can be investigated in more detail, if the set values of the machine's control system are logged as well. The collection of these additional channels supports a comparison between the desired action and the respective system response; control systems can be characterised. Problems with components can be identified in time and new concepts can be verified. Findings support the design and development of new machine generations. The integration of *deep learning* concepts can benefit the recognition of specific machine and process states.

The commissioning phase of a machine can be improved significantly by data mining; the machine's response to different movements can be discovered and stored during commissioning. Once the machine is put into service, this set of discovered sequences can be compared to the actual sequences during operation. Differences between these sets of sequences can indicate potential problems during operation.

Appendix

For accomplishing the work for this thesis, the author developed his own code and used code and data mining tools available at the Chair of Automation. The computations were performed using Mathworks MATLAB® R2013b and R2016a.

Sandvik Mining Systems provided access to media files, standards, design documents, drawings, specifications, and internal failure reports for the duration of this thesis. The author has worked for Sandvik Mining Systems since 2011. It has to be noted that the author worked on this thesis exclusively outside his daily work at Sandvik Mining Systems and was therefore not subject to directives from the company at any time.

All illustrations were designed and created by the author unless otherwise cited. If templates were used for illustrations, the respective figures are cited using the following format [*source of template*, cf.].

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