WWW.JAMK.FI

A RELIABILITY ANALYSIS FOR THE GRINDING PROCESS

Pekka Tolvanen

Bachelor's Thesis
June 2011

Degree Programme in Paper Machine Technology
School of Technology

JYVÄSKYLÄN AMMATTIKORKEAKOULU
JAMK UNIVERSITY OF APPLIED SCIENCES

JYVÄSKYLÄN AMMATTIKORKEAKOULU
JAMK UNIVERSITY OF APPLIED SCIENCES

Author(s) TOLVANEN, Pekka	Type of publication Bachelor´s Thesis	Date 27.06.2011
	Pages 65	Language English
	Confidential ( ) Until	Permission for web publication (X)
Title A RELIABILITY ANALYSIS FOR THE GRINDING PROCESS		
Degree Programme Paper Machine Technology		
Tutor(s) TUUKKANEN, Harri Jyväskylä University of Applied Sciences		
Assigned by Outotec (Finland) Oy		

Abstract
This Bachelor's thesis was made in collaboration with the Service Product Center Espoo of Outotec (Finland) Oy during the spring semester 2011. The main objectives of this thesis were to create a reliability analysis of the mineral enrichment process grinding circuit and to examine the possibilities for the analysis as a company's new service product. The scope for this thesis was limited by the mandator.

As the machinery of the process industry is getting older, the role of maintenance is increasing. Demand for different supporting solutions for maintenance is growing in various industry fields. The past few years have shown that the downward trend of new technology deliveries hasten the service business growth of many companies.

Mineral Engineering means the processing of raw materials from the soil without changing their composition. The purpose is to liberate valuable minerals from valueless. It can be divided into two separate subareas; mineral comminution and mineral concentration. The research of this thesis is made of the grinding process which belongs to mineral comminution.

The reliability analysis is based on RAM methodology and the analyzed process was modeled by ELMAS 4 RAMoptim Dynamic –software. The software is a tool for reliability management. RAM is an acronym for Reliability, Availability and Maintainability. RAM is a method to examine equipment total dependability. The analysis is a quantitative research and its purpose is to solve system failure behavior, cause-consequence relations and occurrences through numbers and statistical data. Information for the analysis was collected by interviews with Outotec specialists and by inquiries via email.

A reliability analysis as a company's service product is very versatile entity and it serves many business areas. It requires a large amount of work to perform the analysis but when experience and information base increases the time usage will decrease substantially.

Keywords
Maintenance, RAM, RCM, Reliability, Mineral engineering, Grinding

Miscellaneous

JYVÄSKYLÄN AMMATTIKORKEAKOULU
JAMK UNIVERSITY OF APPLIED SCIENCES

<table>
<tr><td rowspan="3">Tekijä(t)
TOLVANEN, Pekka</td><td>Julkaisun laji
Opinnäytetyö</td><td>Päivämäärä
27.06.2011</td></tr>
<tr><td>Sivumäärä
65</td><td>Julkaisun kieli
Englanti</td></tr>
<tr><td>Luottamuksellisuus

( )</td><td>Verkkojulkaisulupa myönnetty
(X)</td></tr>
<tr><td colspan="3">Työn nimi
A RELIABILITY ANALYSIS FOR THE GRINDING PROCESS</td></tr>
<tr><td colspan="3">Koulutusohjelma
Paperikonetekniikka</td></tr>
<tr><td colspan="3">Työn ohjaaja(t)
TUUKKANEN, Harri
Jyväskylän ammattikorkeakoulu</td></tr>
<tr><td colspan="3">Toimeksiantaja(t)
Outotec (Finland) Oy</td></tr>
</table>

Tiivistelmä

Opinnäytetyö tehtiin yhteistyössä Outotec (Finland) Oy:n Service Product Centerin kanssa kevätlukukauden 2011 aikana. Opinnäytetyön päätavoitteina oli luoda käyttövarmuusanalyysi rikastamon jauhatuspiirille, sekä kartoittaa analyysin mahdollisuuksia yrityksen uudeksi palvelutuotteeksi.

Teollisuuden laitekannan ikääntyessä, kunnossapidon rooli osana yrityksen liiketoimintaa kasvaa. Kunnossapidon tueksi kehitetään jatkuvasti uusia ratkaisuja eri teollisuuden aloilla. Palveluliiketoiminnan merkitys on viime vuosina kasvanut uusien teknologiatoimitusten vähentyessä.

Mineraalitekniikalla tarkoitetaan maaperästä saatavien raaka-aineiden jalostamista muuttamatta niiden koostumusta. Tarkoitus on erotella arvomineraalit arvottomista. Mineraalitekniikka voidaan jakaa kahteen osa-alueeseen; mineraalien hienonnukseen ja mineraalien rikastukseen. Opinnäytetyö tehtiin jauhatusprosessista, joka on mineraalien hienontamista.

Käyttövarmuusanalyysi pohjautuu RAM metodologiaan ja analysoitava kokonaisuus mallinnettiin ELMAS 4 RAMoptim Dynamic – ohjelmistolla. Edellä mainittu ohjelmisto on työkalu luotettavuuden hallintaan. RAM on lyhenne sanoista Reliability, Availability ja Maintainability ja se on metodi valitun kohteen käyttövarmuuden tarkasteluun. Analyysin tarkoitus on selvittää järjestelmän vikakäyttäytymistä, sekä syy-seuraus-suhteita ja tapahtumia tilastollisen datan avulla, joten analyysi on kvantitatiivinen tutkimus. Tiedonkeruu suoritettiin haastattelemalla Outotecin asiantuntijoita, sekä tekemällä kyselyjä sähköpostin välityksellä.

Käyttövarmuusanalyysi yrityksen uutena palvelutuotteena on monikäyttöinen ja se palvelee useita eri liiketoiminta-alueita. Alkuvaiheessa analyysin suorittaminen vaatii melko paljon työtä, mutta kokemuksen ja tietoperustan karttuessa ajankäyttö tulee pienenemään ja analyysin hyödyt yrityksen kannalta korostuvat.

Avainsanat (asiasanat)

Jauhatus, Kunnossapito, Käyttövarmuus, Luotettavuus, Mineraalitekniikka, RAM, RCM

Muut tiedot

CONTENTS

FIGURES

TABLES

ABBREVIATIONS

FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
LCC	Life Cycle Cost
MTBF	Mean Time between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MWT	Mean Wait Time
OEE	Overall Equipment Effectiveness
RAM	Reliability, Availability, Maintainability
RBD	Reliability Block Diagram
RCM	Reliability Centered Maintenance

1 INTRODUCTION

As the machinery of process industry is getting older, the role of maintenance is usually increasing. Also maintenance as part of the company’s business, suffers from cuts and savings. Therefore new tools are constantly developed to improve maintenance and for its growth needs.

This thesis was made in collaboration with the Service Product Center Espoo of Outotec (Finland) Oy in the spring and summer of 2011. The service business area of the company is increasing and suggestion for the investigation came from the company. Technical support team started the investigation in autumn 2010, but the lack of resources stopped the research. So the subject of this thesis was already defined to be about the process line of the mining industry. The scope for this thesis was defined to concern a grinding process because it is one of Outotec’s key technologies. This thesis was a pilot project for testing a new service product for the company.

The analysis was performed by using RAM –methodology. RAM is an acronym for *Reliability, Availability and Maintainability*. This methodology is not so well known in maintenance literature, but the definitions are familiar. The purpose was to examine the grinding process failure behavior for process line total dependability. RAM –methodology can briefly be determined as a critical assessment. The analysis observes system failure and cost information. The analysis yields valuable information about the system availability values and financial risks.

The analysis can be considered as a preface, when planning improvements for maintenance. This thesis also discusses RCM (Reliability-Centered Maintenance) as a possibility to improve the production plant maintenance. The purpose of RCM –methodology is to create a cost-effective maintenance plan and it can be very toilsome to implement in a large production plant. It is not always necessary to observe all the equipment in a preventive maintenance plan. The reliability inspection of this thesis creates good background information and allocates the targets to focus on when creating a new maintenance plan.

1.1 Objectives of the Thesis

Objectives for this thesis are to adopt the operation of the grinding process, maintenance in the grinding process and also to understand the requirements, methods and restrictions of a reliability analysis process. One of the most important objectives of this thesis is to determine the options, suitability and requirements for a new service product for the company.

As mentioned, grinding is part of the “ore to metal” production chain and the thematic entity for this thesis is chosen carefully. The scope of research is not too extensive neither too abridged in the perspective of a successful analysis.

An objective of this work is to model the process line elaborately in order to achieve the most realistic and reliable results of the system availability performance. Availability performance is illustrated with the dynamic computer simulation which includes reliability calculations, information of the system costs and the system’s operational behavior. A specific model guarantees that the conclusions are scientifically justified and the simulation is repeatable.

A reliability analysis as a title of the thesis was a familiar theme theoretically based on school courses, so the basic information and requirements to do the analysis were available. The biggest challenge of the thesis was the lack of knowledge about the grinding process. As a process the preparation of ore was new to the author and the complexity of the system surprised. Outotec training material of grinding and the literature of the subject were studied to find out the basic information of mineral engineering. The most important things to succeed with the analysis were the interviews, which were performed in the data acquisition phase of the thesis.

The process was modeled with ELMAS 4 RAMoptim Dynamic –software. The software is made by Ramentor Oy and it is a tool for reliability management. It is possible to model the reliability of the equipment and complete processes by this software. The simulation of the software gives all necessary data to complete the analysis. The biggest challenge is the data gathering for the software. The old proverb of engineering “Garbage in, garbage out” holds up also in this case.

2 OUTOTEC OYJ

Outotec is one of the world’s leading companies as a technology and service provider in the mining and metal industry. Products of the company include all technology applications in mineral and metallurgical processes and their parallel industries. (Outotec 2011.)

As a company, Outotec is former Outokumpu Technology. Outokumpu Technology was a part of Outokumpu concern. Outokumpu was founded in 1910 to commence the mining and metallurgical industry in Eastern Finland. The company expanded uniformly first in Finland and later in Europe. Overseas sales the company established in 1970’s in the North and South America and ever since the global growth has been huge. In 2006, Outokumpu Technology was listed on to Helsinki Stock Exchange. In 2007, the company resigned from the parent company and changed its name to the present one, Outotec. (Marketline 2011.)

Outotec has about 3130 employees in attendance in 24 different countries and the turnover of the company in 2010 was 970 million Euros. The distribution of the sales and operating profit is specified in Figure 1. The service business area represents about 29% of sales and it is included in the technology sales. (Annual Report 2011.)

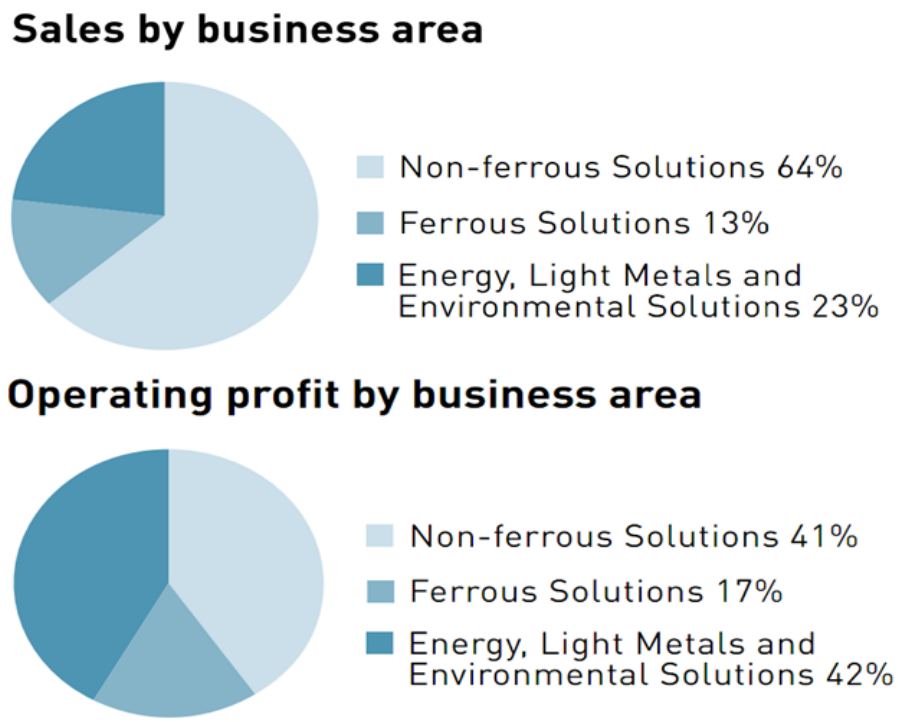

FIGURE 1. Financial distribution (Annual Report 2010.)

The company has four main operating divisions;

- Non-ferrous solutions
  - Processing of copper, nickel, zinc, lead, gold, silver, platinum and industrial minerals
- Ferrous solutions
  - Processing of iron, steel and other ferrous materials.
- Energy, Light metals & Environmental solutions
  - Energy and light metals processing
  - Developing environmental solutions
- Service solutions
  - Developing the service business globally
  - Providing life cycle services

(Annual Report 2010.)

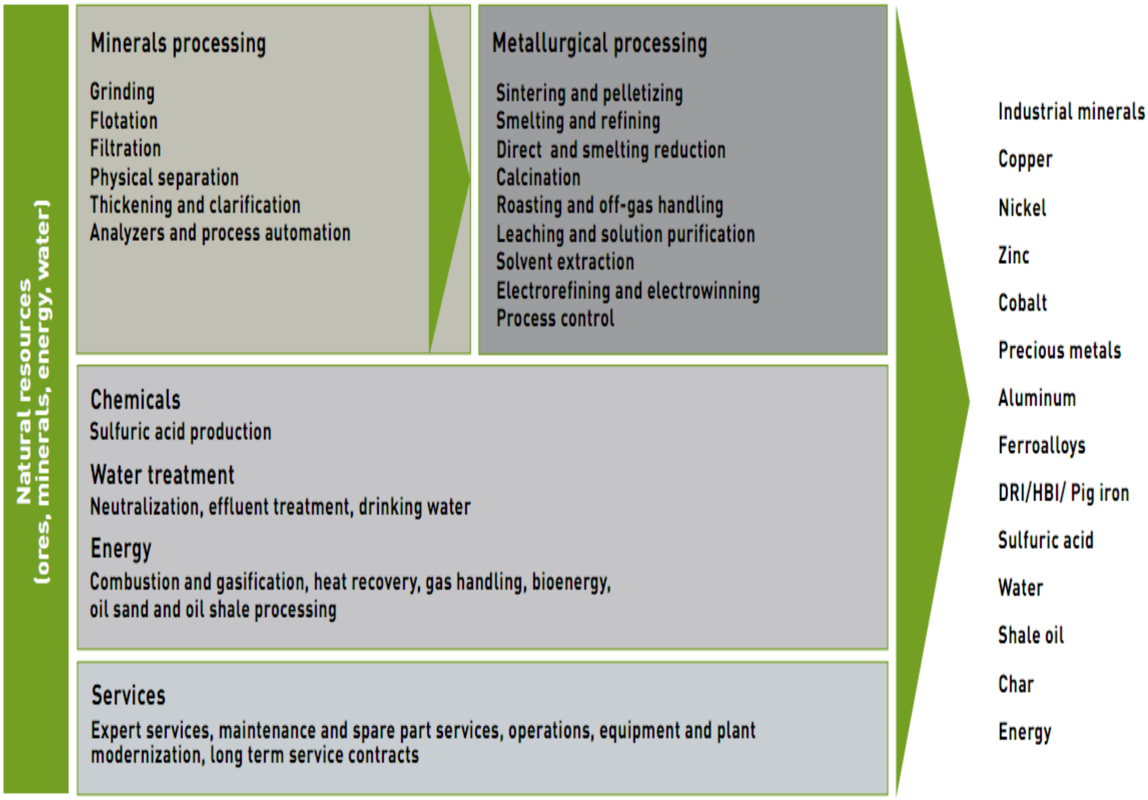

FIGURE 2. Main business areas (Annual Report 2010.)

3 MINERAL ENGINEERING

3.1 Basic information

Mineral Engineering means the processing of raw materials from the soil without changing their composition. The purpose of mineral engineering is to liberate valuable minerals from the valueless gangue. Ores consists of heavy metal deposits or other valuable raw materials, which are profitable to exploit financially. Exploitable materials are metal deposits, industrial minerals, fossil fuels and regolith types. (Lukkarinen 1984, 1)

- Metal deposits consist of copper, iron, nickel, aluminum, zinc, ferroalloys, precious metals and other metals
- Industrial minerals consist of alkali metals, limestone, feldspar, quartz, phosphate, salt and sulfur compounds

- Fossil fuels consist of natural gas, mineral oil, coal, lignite, peat and pyroshale
- Regolith types consist of clay, sand, gravel and phosphate deposits

Mineral Engineering can be divided into two separate subareas; mineral comminution and mineral concentration. The purpose of mineral comminution is to crush the stone so fine that valuable minerals can be separated from the valueless ones in mineral concentration. Mineral comminution is comprised of blasting, crushing and grinding. Simply, the raw material must be comminuted to proper grain size before it can be concentrated. (Lukkarinen 1984, 1-2)

Ore concentrates and industrial minerals are refined in separate plants. Ore is refined in metallurgic plants and the process consists of three phases, rough concentration, re-concentration and scavenging. Concentration is measured by the recovery ratio. (Lukkarinen 1987, 1-2.)

$$Recovery\ ratio = \frac{Total\ metal\ in\ concentrate}{Total\ metal\ in\ feed\ ore} * 100\%$$

3.2 Grinding

Grinding is the final phase of mineral comminution. In grinding, the ore is comminuted to preferred grain size for its purpose of the end use. Grinding is one of the most important phases in mineral engineering. The grinding process handles enormous amounts of material and energy. If ore is ground badly, the whole process can go awry. Exclusively good grinding does not mean that mineral processing is successful but it creates a good base to success. (Lukkarinen 1984, 175-177.)

The capacity of grinding is typically defined by the mass of material it handles in a certain time. In real life the capacity and power consumption of the mill are the most observed quantities of grinding. (Lukkarinen 1984, 177-178.)

The most important factors which interact in the grinding mill operation and capacity are the mill speed, volumetric efficiency, material grindability, grinding bodies and mill structure. (Lukkarinen 1984, 177-178.)

Grinding can be separated to coarse and fine grinding. There is no specific definition for these methods. It can be assumed that the end product of coarse grinding is over 25 mm in diameter. Thus it is spoken about primary grinding. In fine grinding the end product is less than 1-2 mm in diameter. Thus it is spoken about secondary grinding. (Lukkarinen 1984, 190-191.)

3.2.1 Comminution techniques

In mining industry the ore is typically ground in a flat rotary drum. Grinding is based on abrasion, compression and impact.

In grinding based on abrasion and compression the grinding media is sliding over each other comminuting the ore. In proportion grinding based on impact, the comminuting occurs by low or high energy impacts. The comminution techniques are specified in Figure 3. (Training seminar 2009.)

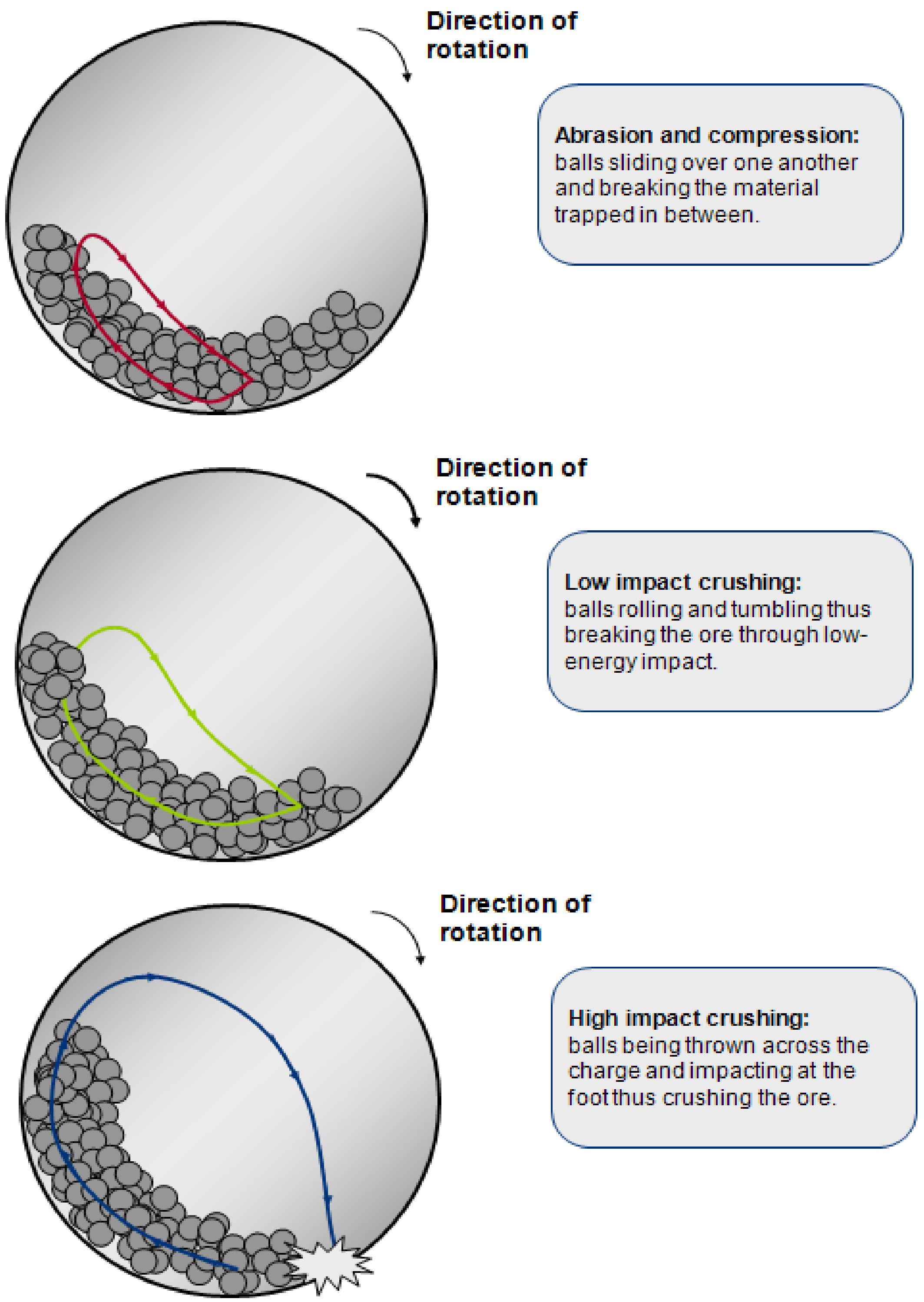

FIGURE 3. Comminution in the grinding mill (Training seminar 2009.)

The mill speed and shape of the mill lining contributes to the type of the grinding method. The mill rotating speed is typically about 50-80-% of its critical speed. When the mill reaches its critical speed the grinding media starts to rotate in the mill centrifugally, and comminution does not occur. The mill critical speed can be determined by the following formula:

$$n_{cr} = \frac{42.3}{\sqrt{D}}$$

$$D = Inside\ diameter\ of\ the\ mill\ [m]$$

Depending on the application, the grinding process can be wet or dry. In case that the water may change the properties of the material, dry grinding is the preferred option. The dry grinding process can produce a finer end product. In the wet grinding process it is easier to transport and classify the material. Wet grinding is generally used as an option in minerals processing. (Training seminar 2009.)

The choice of grinding method is based on the hardness of the material and the grain size of the end product.

3.2.2 Mill designs

Basically the constructions of grinding mills are nearly similar. There are differences in the mill support and discharge methods. A grinding mill is either trunnion supported or shell supported. Mostly used discharge methods in mills are overflow, grate or peripheral discharge. In addition to these the most important difference is the grinding bodies of the mill. (Training seminar 2009.)

Typically used grinding bodies are steel rods, steel or cast iron balls and big ore particles (pebbles). Steel rods or a small amount of heavy balls are used as grinding media in primary grinding. In secondary grinding there are typically used balls or pebbles as the grinding media. (Lukkarinen 1984, 176.)

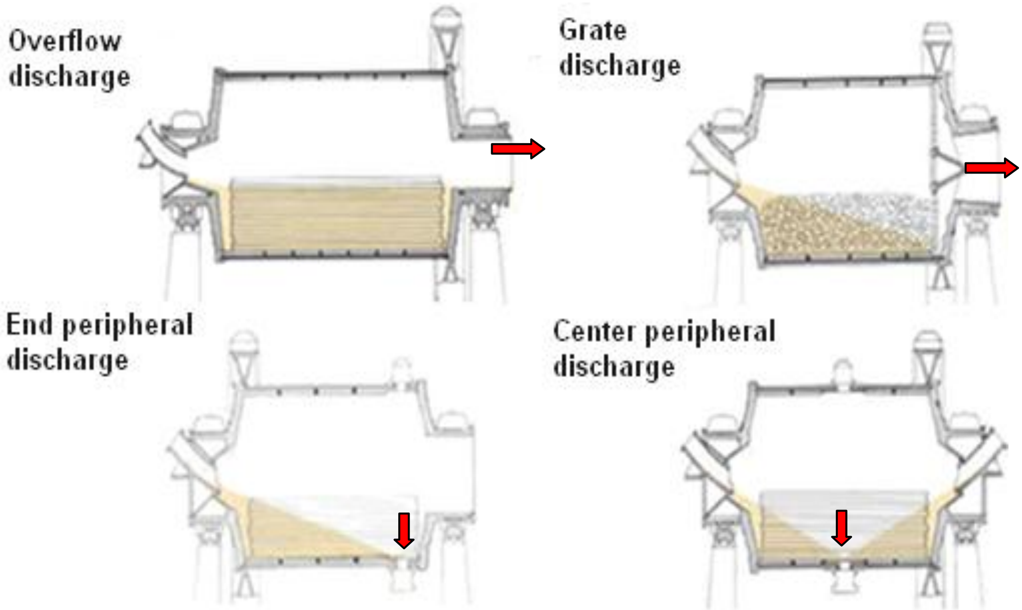

FIGURE 4. Discharge methods (Lukkarinen 1984, 198.)

3.2.2.1 Autogenous (AG) and Semi-autogenous (SAG) mills

Autogenous and semi-autogenous mills are designed for primary grinding. Any distinct grinding media is not used in an autogenous mill, whereas it uses ore itself as the grinding media. A semi-autogenous mill is similar to an autogenous mill but it contains a small amount of discrete grinding media, typically 5-10-% of grinding balls or rocks. Usually comminution is performed by impact. (Training seminar 2009.)

3.2.2.2 Ball mills

Ball mills are designed for secondary or final grinding. The end product of ball mills is finer than from the AG or SAG mills. In ball mills the grinding media is steel or steel alloy balls. Comminution is performed mostly by attrition and abrasion. (Training seminar 2009.)

3.2.2.3 Rod mills

Rod mills are generally designed for primary grinding. The end product is usually quite coarse. Steel rods are as the grinding media in these types of mills. Rods are typically of about 50-100 mm diameter and the length is almost equal to the mill length. (Training seminar 2009.)

3.2.2.4 Pebble mills

Pebble mills are used less than the aforementioned mill types because they are suitable only for certain ore types and applications. These mills are designed for secondary or final grinding. The grinding media of these kinds of mills consist of pebbles. Pebbles are coarse particles of ground ore. (Training seminar 2009.)

3.2.3 Mineral classification

Mineral classification means the method where the ore is divided into two or more fractions by the velocity. Fraction velocity is determined by the movement in a certain medium which is mostly air or water, thus talking about pneumatic or hydraulic classification. Typically the material is separated into fine and coarse grades. Fine grades are directed forward in the process and coarse grades are usually returned to the previous stage. In mineral technology the fine grades are called overflow and coarse grades underflow. (Lukkarinen 1984, 249.)

3.2.3.1 Trommel screen

Trommel screen is a rotating round sieve mesh in the discharge end of a grinding mill and the purpose of the screen is to separate the material from the mill by its size. Typically the material is quite coarse, about 6-50 mm of a diameter. The construction of a trommel screen is quite simple; there is a rotating drum where there is a sieve mesh on the inner surface. Fine material passes the sieve mesh and coarse material erupts from the end of the trommel. In some cases there are controllers installed inside of the trommel screen. The purpose of these controllers is to guide the coarse material back to the mill (See Figure 5.).

A trommel screen is installed in the discharge end of a grinding mill by the pivot shaft or on the bearing wheels. The capacity of a trommel screen is quite small comparing to the other screening methods. (Lukkarinen 1984, 131.)

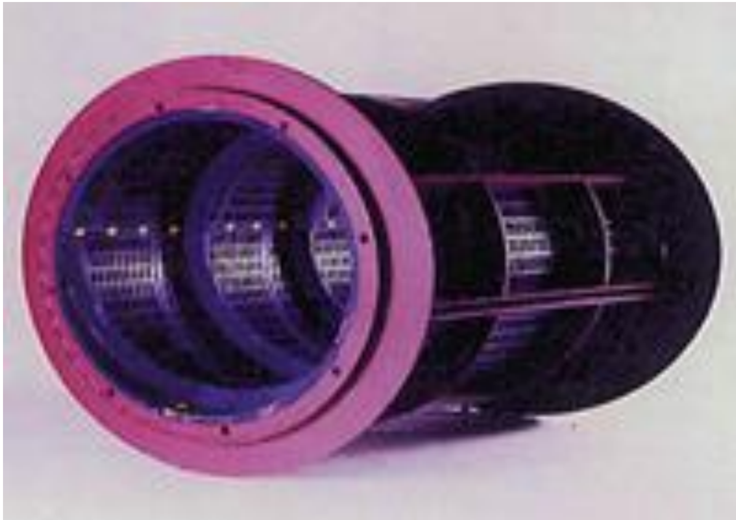

FIGURE 5. Trommel screen (Lehto 2011.)

3.2.3.2 Screw classifier

A screw aka spiral classifier consists of a half-round tub and one or two spirals. Spirals are installed to the classifier approximately in the 14° to 18° angle. Slurry is fed to the middle part of the classifier. The rotating screw separates the material by its weight. Lighter, fine material overflows out from the bottom end of the classifier. The screw transports the heavier material to the upper end where it falls to a sand channel. (Lukkarinen 1984, 258.)

The scale of classifiers size is quite variable. The widths vary between 0.75 to 6.5 meters and the lengths 3 to 12.5 meters. The capacity of the screw classifier is relatively high. The screw is rotating 0.25 to 0.7 m/s and it transports large quantities of sand. (Lukkarinen 1984, 258.)

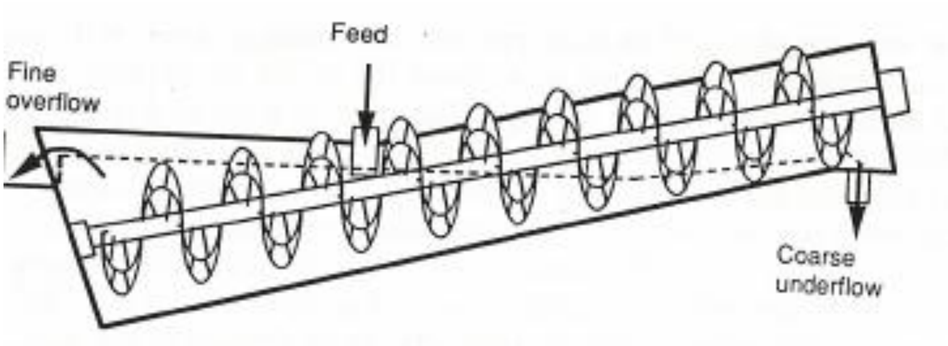

FIGURE 6. Screw classifier (Lehto 2011.)

3.2.3.3 Vibrating screen

The purpose of a vibrating screen is to separate particles by size. Separation is obtained by bouncing the particles on a screen net. The particles that pass the net are directed forward in the process and the coarse material is either returned to the previous section or directed to the mill reject. Separating capacity of the screen depends on the time that the material stays on the screen and the proportion of the grain size on the permeability of the screen. (Lynch 1977, 99-100.)

There are two ways to operate the screens, the batch and continuous way. In batch screening the material is fed on the screen and vibration is on a certain period of time. In continuous screening the vibration is on all the time and the material is fed constantly onto the screen. (Lynch 1977, 99-100.)

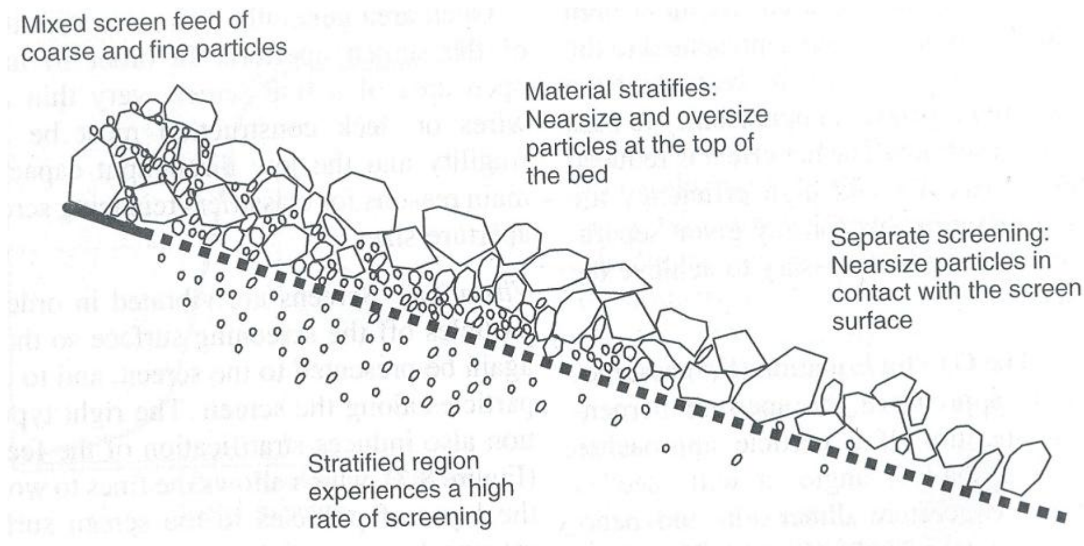

FIGURE 7. Screen principle (Wills 2006, 190.)

3.2.3.4 Cyclone

A cyclone is a very simple device by its construction and operational principle. But controlling and analyzing the operation is extremely difficult because the separation method of a cyclone is based on centrifugal forces. The main components of a cyclone are cylinder, cone, overflow pipe, feed pipe and underflow aperture. The cone part of a cyclone adjusts the discrimination of the device. The cone part angle varies between 15° and 30°. In some cases the inner surface of a cyclone is lined with rubber to decrease the wear of the device. (Lukkarinen 1984, 260-261.)

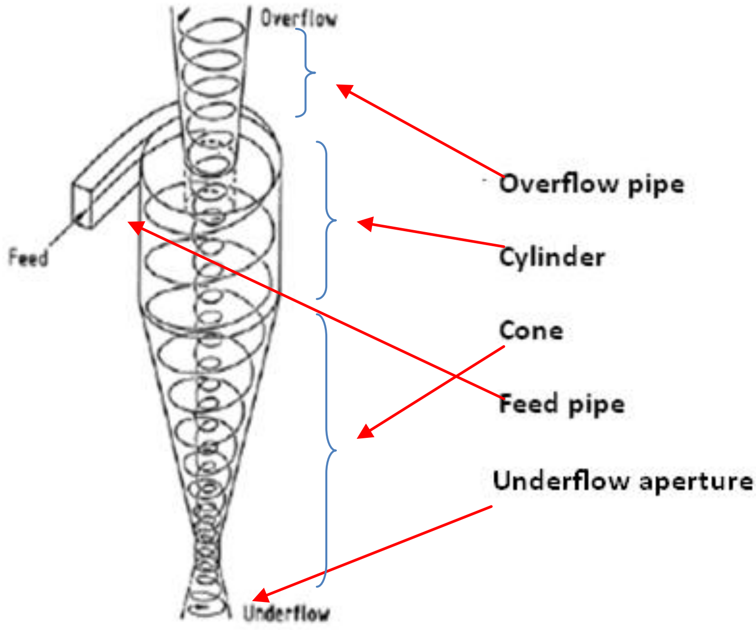

FIGURE 8. Cyclone classifier (Lukkarinen 1984, 262.)

The slurry is fed to the cyclone tangentially. The velocity of the slurry is about 3-4 m/s and the pressure is 0.4-1 bar. By these feed parameters the material gets into a fast circular motion against the inner surface of the cylinder. The motion creates centrifugal forces which are essential for the cyclone's operational performance. The cyclone operation consists of two opposite flows. The heavier particles are rotating in the flow against the outer shell of the cyclone and the centrifugal forces are pushing the material down towards the underflow aperture. The lighter material gets into inner flow which directs the material to the overflow pipe. The discrimination capacity of a cyclone can be controlled by pressure adjustment. (Lukkarinen 1984 260-267.)

In its entity the cyclone is a very reliable device in mineral classification. The biggest consequences of cyclone failures are the wear of the cyclone wall structure and underflow aperture blockage. These issues can be controlled by the pressure monitoring. The pressure fluctuation of a cyclone always indicates about an incipient failure. The pressure variation can also be a consequence of a leakage, unequal material flow, pump operational failure, etc. (Lukkarinen 1984, 260-267.)

3.2.3.5 Magnetic separation

Magnetic separation is used for concentration of magnetic minerals and for removal of unwanted magnetic particles from the material. The separation occurs when material is routed through a non-homogenous magnetic field. Successful separation depends on the fact that the magnetic force in the separator is stronger than the sum of all competing forces. (Svoboda 1987, 1-2.)

Lots of different kinds of technologies are available for magnetic separation. Magnetic separators can roughly be divided into two main groups. (Wills 2006, 356.)

- Low-intensity magnetic separators
- High-intensity magnetic separators

These two groups can be divided in accordance with the process, either wet or dry. Low-intensity separators are suited to treat ferromagnetic materials and highly paramagnetic minerals. (Wills 2006, 356.)

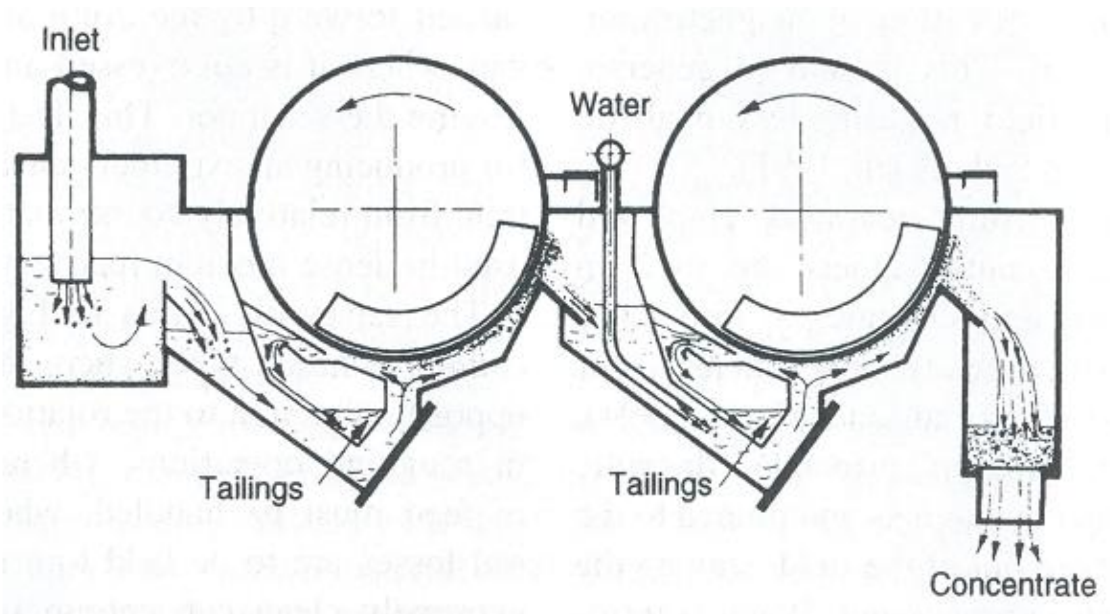

FIGURE 9. Magnetic separator principle (Wills 2006, 358.)

4 RELIABILITY ENGINEERING

4.1 RAM

RAM-analysis is a method to examine equipment total dependability. RAM is an acronym for Reliability, Availability and Maintainability. It is a very useful tool when inspecting equipment proportion for the process total availability performance. The analysis is also used as a tool in maintenance and application planning. This method observes equipment criticality and costs partly considering the system availability performance. (Lyytikäinen 2010, 40-42.)

Reliability can be defined as the probability that a system will perform its assigned mission in a satisfactory manner for a given period of time under specified operating conditions. (Blanchard 2004, 33.)

Reliability of the equipment that fails randomly can be calculated by the following formula:

$$R(t) = e^{-\lambda t}$$

$$\lambda = Item\ failure\ rate$$
$$t = Intended\ mission\ time$$

Availability can be easily confused with reliability. However, availability can be defined as the probability that an item or a system is available to perform its function when required. (Dhillon 2006, 3.)

Availability can be calculated by the formula:

$$A = \frac{Planned\ production\ time - Shutdowns}{Planned\ production\ time} * 100\%$$

Maintainability can be defined as the probability to restore an item or a system to its operational state and it can be measured by mean time to repair (MTTR). (Blanchard 2004, 34.)

To put it simply the RAM-analysis consists of the phases below

1. Establish a reliability block diagram of the system and make a reliability model based on the diagram
2. Collect the failure data of the system
3. Identify different methods to improve the system reliability by the model
4. Calculate the effects of proposed improvements in the production and maintenance costs.
5. Prepare a proposal for improvement of the system reliability

RAM –methodology consists of various maintenance development tools. The reliability block diagram (see Chapter 5.3.2.) and the fault tree analysis (see Chapter 5.3.3.) was exploited in this thesis.

The analysis observes only the coincidental failures that cause unplanned shutdowns. In the proposal for improvement of the system reliability it is desirable to focus on the most critical equipment and subsystems which do not fulfill the requirements. In the proposal it is also recommended to consider the system redundancy. (Lyytikäinen 2010, 40-42.)

4.2 RCM

RCM is an acronym for Reliability-Centered Maintenance. RCM methodology was invented for the aircraft industry in the end of the 1960's. Nowadays this method is widely applied in the technology industry. RCM is a method to establish cost-effective preventive maintenance plan which observes equipment and device safety and availability requirements. The basic idea is to improve plant safety, availability and economy. (Järviö 2000, 20.)

The methodology contains a decision tree diagram which helps to choose valid preventive maintenance tasks. The results of this tree are based on recognized failure modes and effects. The last level of this tree reveals the requirements to do individual maintenance task. (Järviö 2000, 20-21.)

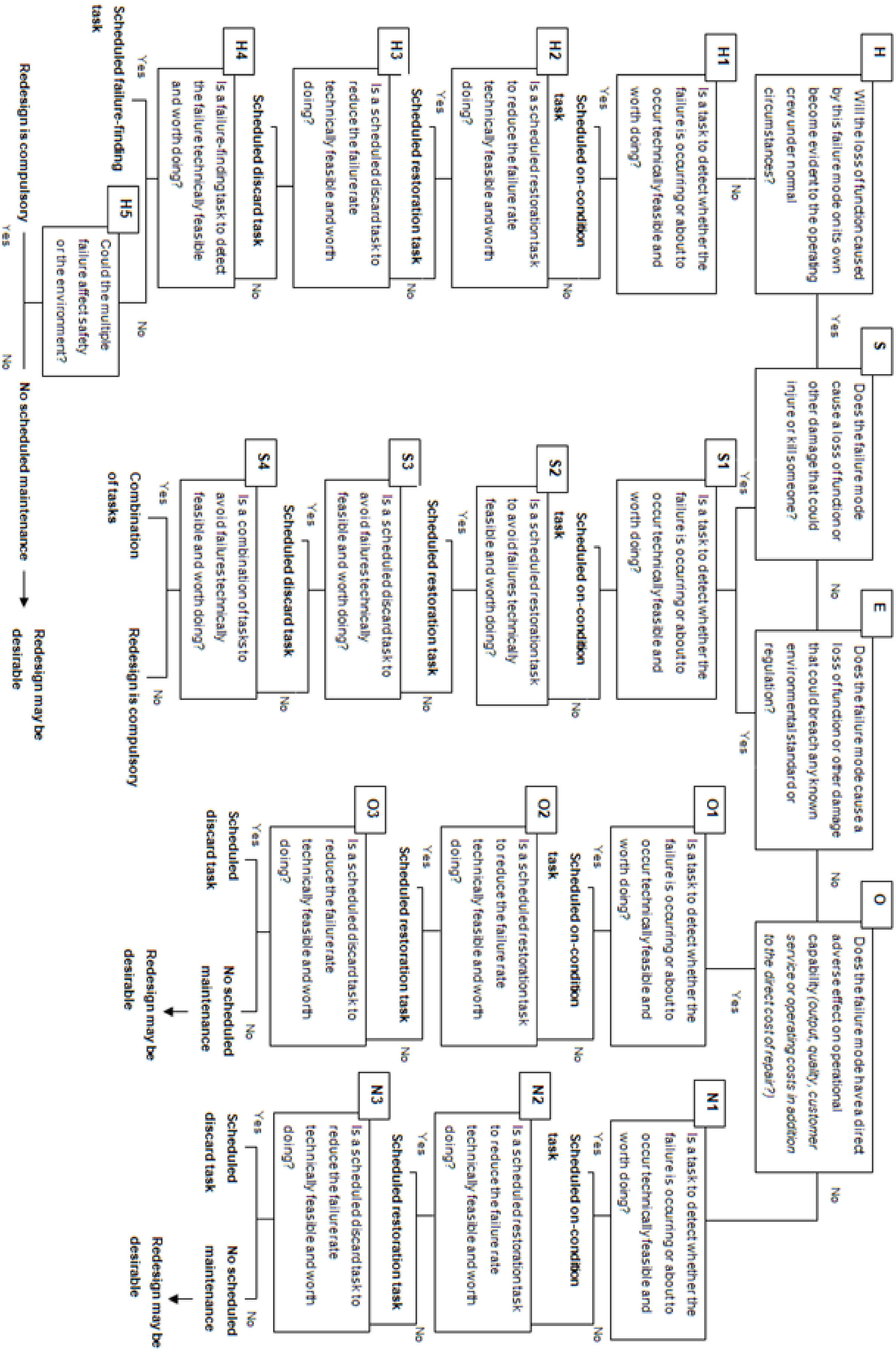

FIGURE 10. RCM decision diagram (Moubray 1997, 200-201.)

4.2.1 RCM method utilization

The most important reasons to do RCM are the lack of preventive maintenance or the corrective maintenance is dominating. Also the lack of condition monitoring and poor documentation of failure history may be reasons to do RCM. A problem of conventional maintenance is often the preventive maintenance planning. On occasion the preventive maintenance is misallocated or ignored completely. In some cases the maintenance plan is copied to other devices or equipment although the process or the environment is different. (Järviö etc. 2007, 125-126.)

The maintenance plan of the manufacturer is not always the best option from the economical point of view. Usually the manufacturer specifies a safety factor for all failure modes and the maintenance plan is established based on that. This kind of maintenance plan is not necessarily optimized for the production plant needs and the maintenance costs can accrue too high. (Mäki 2010.)

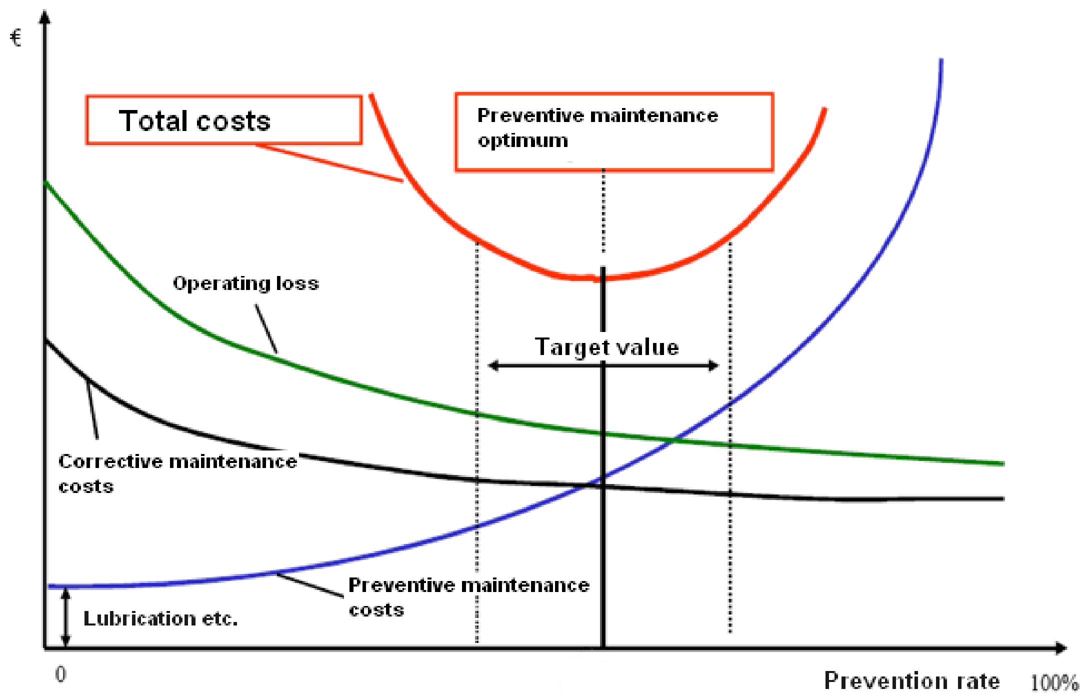

FIGURE 11. Maintenance optimization (Mäki 2010.)

RCM method utilization is often based on the management of the maintenance costs. Often it is believed that the prevention rate should be high. This is not true. It is impossible to prevent all failures. Figure 11 illustrates that the purpose of RCM is to rationalize the maintenance costs. It is a compromise between preventive maintenance costs, corrective maintenance costs and operating loss. (Mäki 2010.)

4.2.2 Phases of RCM

RCM-process is generally distributed in seven phases:

1. Specify the functions and system performance requirements in certain environment and conditions.
2. Specify the functional failures of the system
3. Identify failure modes
4. Identify failure mode effects

   FMEA
5. Specify the failure consequences
6. Specify the tasks for preventive and predictive maintenance
7. Specify the tasks if any proactive task cannot be found

(Moubray 1997, 7.)

The purpose of the first four phases is to define maintenance allocation. In other words it specifies the criticality of the equipment. Failure modes and effects analysis (FMEA) concentrates on the equipment and system performance. The analysis recognizes the failure modes of the equipment and their consequences for the system. (Kuntoon perustuva kunnossapito 2009, 128.) Safety, environmental and operational effects are defined in phase five. The purpose of the last two phases is to find out the most effective and the best applicable tasks to manage the failure modes and effects. (Moubray 1997, 8-16.)

4.2.3 Benefits of RCM

In theory there are several benefits that can be reached by the RCM method. But in reality most of the benefits of RCM can be detected afterwards. In the beginning of the analysis it is recommended to set a few indicators to monitor the success of the analysis. Below there are listed a few benefits and ambitions of the RCM analysis.

1. Increase the system performance and availability
2. Improve the safety and environmental aspects
3. Improve the cost efficiency of maintenance
4. Reduce the unexpected failures
5. Increase machinery and equipment operating lifetime
6. Coherent and explicit dependability database of equipment
7. Increase the cooperation and motivation of maintenance personnel

(Moubray 1997, 307-317.)

5 A RELIABILITY ANALYSIS FOR THE GRINDING PROCESS

This reliability analysis for the grinding process was based on the RAM – methodology. The analysis can be performed either in the quantitative or qualitative way depending on the wanted information of the research. In quantitative research the purpose is to solve cause-consequence relations and occurrences through numbers and statistical data contrary to the qualitative research which is emphasized more in order to minimize the consequences of failures. The purpose in this thesis was to examine the failure behavior of the system dependability by statistical failure data so the analysis is a quantitative assessment.

5.1 Process line presentation

The system under inspection of this thesis is a part of mineral concentration process of mining industry and the analysis was performed for a grinding process. The main function of this grinding process is to comminute the crushed aggregate to proper grain size for flotation and to grind limestone for the pelletize plant needs.

The system totally consist of three grinding lines, two similar grinding lines before the flotation unit and one additive grinding line for pelletizing plant needs. All these grinding processes are wet grinding processes. The process line can be seen in its entity in Figure 13.

5.1.1 Assembly

Two similar grinding lines before the flotation unit are parallel and both of them include two grinding mills (Primary and Secondary), conveyors, classifiers and different auxiliary systems. The additive grinding line is a bit different than these two lines. It consists of one ball mill, cyclone pattern, conveyors and auxiliary systems.

The main function of the classifiers in the grinding lines is to separate the particles by size or weight. There are also magnetic separators which classify the material by its magnetic properties.

5.1.1.1 Grinding lines 1 and 2

As mentioned the actual raw material grinding of the process is performed before the flotation unit. The material flow goes first from the grinding line feed via belt conveyors to primary grinding which is performed in the AG mill.

The very first material separation takes place in the AG mill trommel screen which separates particles by size. The material that is transmitted through the screen goes to the screw classifier via slurry pumps and the bigger particles go to the pebble screen.

The screw classifier separates the material by its weight, so the fine grades go to the first magnetic separator unit and coarse material returns to primary grinding.

The main function of the pebble screen is to pick up the pebbles for secondary grinding. The particles which are not suitable for pebble mill grinding media go back to primary grinding or pebble reject.

In both grinding lines there exist two magnetic separator units. Like mentioned before, the main function of the magnetic separator is to classify the valuable iron content material from the valueless gangue. The magnetic separator units are before secondary grinding and before the flotation unit. The gangue from magnetic separator reject is directed to a thickener so that all of the valuable particles could be exploited.

Secondary grinding is performed in the pebble mill. The pebble mills feed consists of the first magnetic separator unit output, pebble screen output and recycled material from the thickener.

After secondary grinding the slurry is pumped to the cyclone pattern, which consists of ten centrifugal cyclone separators. The basic idea of the cyclone is to separate the particles by particle size distribution. The conical shape of the cyclone generates two vortexes in the cyclone. Outer vortex presses coarse material back to secondary grinding and inner vortex lifts finer particles to the second magnetic separator unit. From the second magnetic separation, valuable product goes to flotation and valueless to the thickener.

5.1.1.2 Additive grinding

In additive grinding the process material is limestone so the process is a bit different. The mill feed system is quite similar like in the other grinding lines but the line assembly is much more simplified.

The raw material is fed by belt conveyors to the ball mill where the grinding is performed. After grinding the material is pumped to the cyclone pattern via slurry pumps. This cyclone pattern consists of three centrifugal cyclone separators. These cyclones are a bit larger than in the other lines but the operating principle is the same. From the cyclones the coarse material returns to the grinding mill and accepted material goes to the additive storage tank.

Additive grinding process has a storage tank which is the buffer storage for additive material. If the additive grinding fails the buffer tank ensures that the process can operate next 12 hours. If the restoration lasts longer than 12 hours the whole production line must be stopped.

5.2 Data acquisition

Information was collected by interviews. The interviews were made with Outotec specialists in Espoo campus and by email inquiries. Adding to these, a workshop was arranged between 14th and 15th of March. Overall five maintenance professionals and two technical specialists from Outotec participated in the workshop.

At the beginning of the workshop the purpose of the project was presented and the participants had a short conversation related to the agenda.

The whole process line and equipment in it were gone through with the reliability block diagram and fault trees which were done beforehand and also the validity of those models was checked. During these two days failure information and maintenance issues of every single device and component were inspected. The main emphasis of the inspection was on grinding mills and the auxiliary systems of them.

Required information was collected into a simple template (see Appendix 2.) by interviewing the maintenance personnel. The template in its entirety can be found in the appendices but the required information was the following: *Device, Failure mode, Mean time to failure, Mean time to repair, Maintenance resources and Maintenance costs*.

There came up totally about 100 different failure modes for each grinding line during this two-day workshop. Adding to this the interviews related to classifiers and thickener failure modes which were made in Espoo campus and by email exchange with Outotec technical specialists the total amount of system failure modes raised to 374 (see Appendix 3.).

5.3 Process line modeling

As mentioned, the system was modeled, and the fault trees and device hierarchy created before the interviews. During interviews there came up some differences in the system so the model was modified a bit. The device hierarchy was quite realistic so the actual modifying took place in the reliability block diagram and the fault trees of the system.

The grinding process was modeled in its entirety by ELMAS RAMoptim dynamic v4.4 –software. The modeling process can be divided into three main phases. The first phase was to make a reliability block diagram of the system which visualizes the behavior of the process material flow in the process line. The second phase was to create a device hierarchy and fault trees for every node in the reliability block diagram. The last phase was to add the failure data in the model.

5.3.1 ELMAS

ELMAS is an acronym for *Event Logic Modeling and Analysis Software*. It is the software to model and analyze logical relations between different events. An event can be any change in a certain object or situation. The model created by the event logic method can be utilized in different ways, for example in understanding the context, information analyses or documentation. (ELMAS 2011.)

The software can be adapted in modeling of any kind of subject. There are five different types to create a model in this software by default. These are Fault Tree, Block Diagram, Cause Tree, Cause-Consequence Tree and 2-level Process Diagram. In this thesis the interest was in failure behavior of the grinding process so the system was modeled by a reliability block diagram and fault trees. The software includes also a FMEA (Failure Modes and Effects Analysis) section, which is a tool for maintenance planning. (ELMAS 2011.)

Failure data input to software is quite simple. Data can be imported from an Excel file or it can be entered manually. The software can handle failure data versatility depending on the raw data and it is possible to mix estimations and data based on failure history. (ELMAS 2011.)

The model created by the software observes the functionality of the whole system. Model simulation gives specified information about risks and criticality of different functions. The simulation results are more reliable when the data input is extensive. Simulation results can be exploited in system availability and reliability improvements; for example, when considering new design solutions or maintenance allocation. The simulation result creates a good information base for a maintenance plan. Analysis results can be exported to a report in the Excel or HTML format. (ELMAS 2011.)

5.3.2 Reliability block diagram

Reliability Block Diagram (RBD) is a visual method to model system reliability. It is possible to describe the reliability structure of complicated systems by this method. The diagram can be made of parallel or consecutive blocks and different combinations of these. Blocks can describe the structure of the system function or device hierarchy. Generally the reliability block diagram is built by using two constructions. (Dhillon 2006. 29-32)

- Series connection, where a single sub-system failure stops the line
- Parallel connection, every sub-system must fail to stop the line

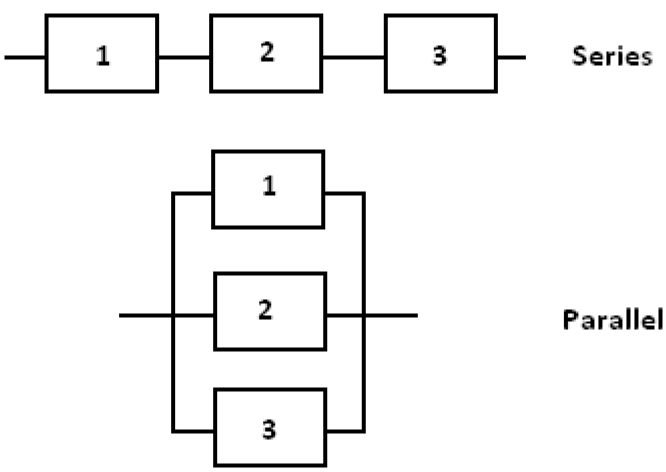

FIGURE 12. Reliability block connections

Simply the reliability block diagram is modeled by the flow of production material in the system. The diagram consists of different functions and subsystems which altogether ensure the operation of the system. (RBD 2011.)

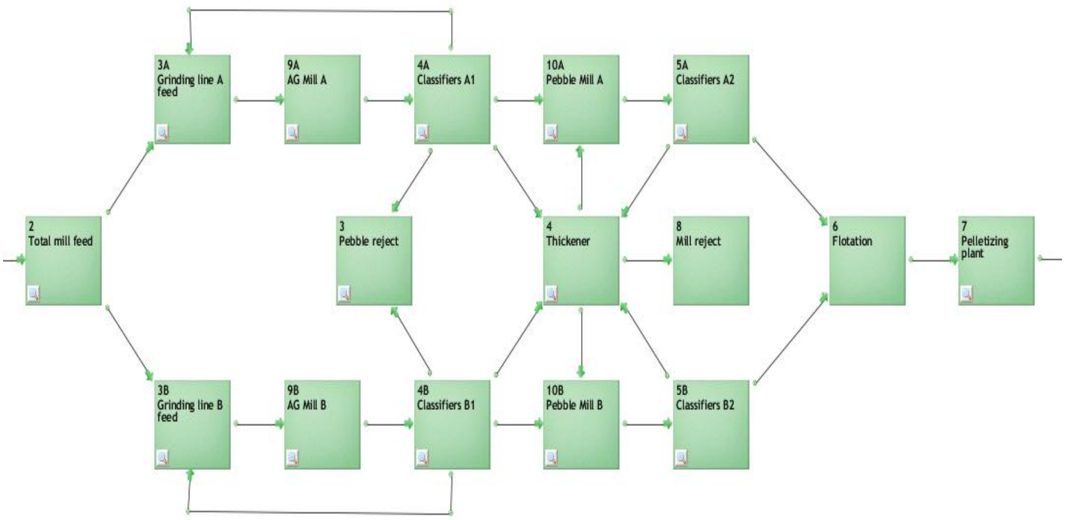

FIGURE 13. Reliability Block Diagram of the enrichment process

In Figure 13 the process flow of the enrichment unit is described by a reliability block diagram. As perceived from the reliability block diagram, the enrichment process stops when the Total mill feed, Flotation, Pelletizing plant or both of the Grinding lines fail. The purpose of this thesis was to examine the dependability of the grinding process so the Flotation unit and Pelletizing plant cannot fail by default. The additive grinding is as a sub-system of a pelletizing plant, so if that fails it sets pelletizing plant failure after twelve hours when the buffer tank gets empty. The specified list of reliability block devices is shown in Appendix 1.

5.3.2.1 Dynamic modeling

It is possible to model system dynamics with the software. The purpose of dynamic model is to illustrate the behavior of the system in certain situations. Dynamic modeling is commonly used to model the material flow of the system, the wait time before repair or capacity reduction in a certain failure situation. Dynamic modeling can be applied also in other purposes.

In this project the dynamic modeling was enforced in modeling the return loops of the system. This method was the easiest way to control the process flows and their consequences.

The return loop flow is not important for the process in this project but one of the thesis objectives was to test how it works. So the flow from magnetic separator reject to the pebble mill through the thickener was chosen. The thickener can return about 5% of the material that the magnetic separators feed to it, so the process flow from the thickener to the pebble mill is meaningless (less than 1%) when inspecting the total feed of the mill.

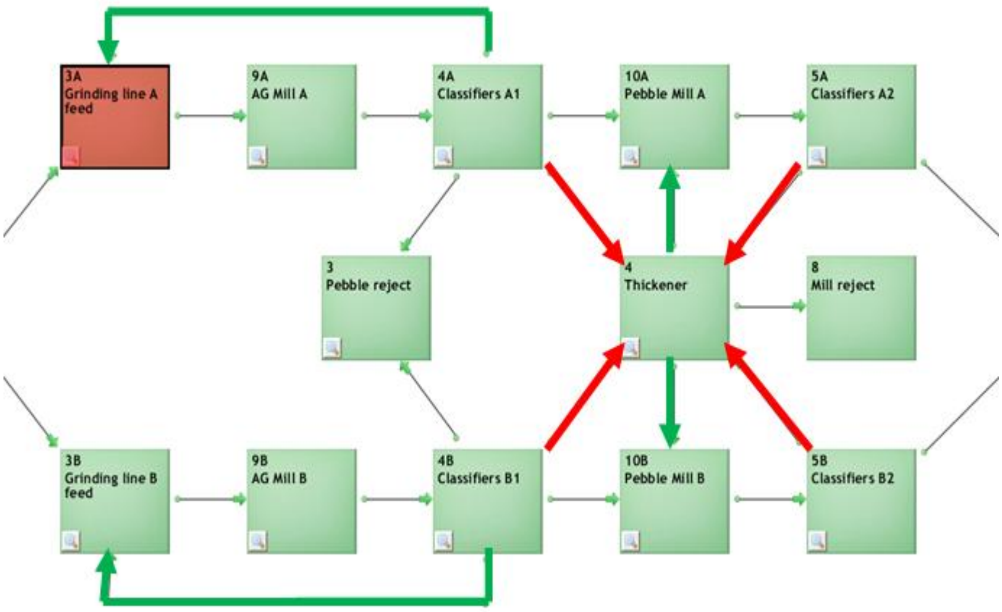

FIGURE 14. Return loops of the grinding process

Figure 14 describes the process flows of the return loop from the thickener and classifier unit one. The first classifier units (A1 and B1) encompass about 80% of the thickener total feed. If the thickener fails, this material flow is directed back to the grinding line feed system. If the thickener failure lasts longer than 12 hours it causes the production line shutdown. The modeling of the return loops needs Java programming so most of this programming work was made in cooperation with Ramentor Oy.

5.3.3 Fault tree analysis

Fault tree analysis is a method to examine the system reliability. In the fault tree model, the failure behavior is viewed in the graphic logic tree construction and the approach is top-down. The root node of the fault tree represents the unwanted event. There is no limitation for the scale of failure inspection. Failure behavior can be inspected in functional level or alternatively the inspection can extend to the root causes of an unwanted event. Fault tree analysis is a versatile and effective method to examine the system failure behavior and documentation. (FTA 2011.)

In the fault tree modeling there are gates used between events which define the rules of an event occurring. Most commonly used gates are OR, AND, XOR and Probability. Specified gate definitions are visualized in Figure 15. (Hecht 2004, 57-61.)

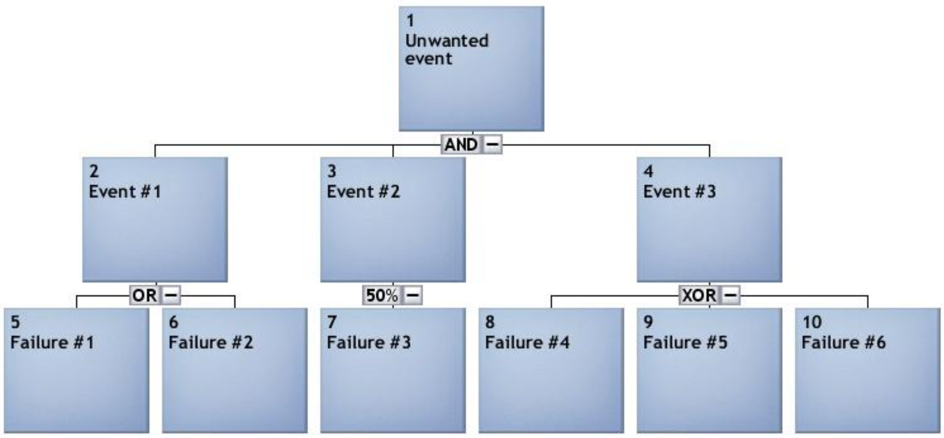

FIGURE 15. Fault tree gate definitions

Fault tree gates:

- **AND**, *Unwanted event* occurs when *Event #1, Event #2 and Event #3* occurs at the same time.
- **OR**, Event #1 occurs if either *Failure #1 or Failure #2* occurs.
- **Probability**, if *Failure #3* occurs there is 50% probability that Event #2 occurs.
- **XOR**, Event #3 occurs if exactly one of *Failure #4, Failure #5 or Failure #6* occurs.

Fault trees were made individually for all the equipment in the process line and the relations of the events in the fault tree were determined by these gate definitions. Some of the process line pieces of equipment are relatively large complexes so some of the system fault trees were very extensive.

5.3.3.1 Required information

When modeling the total dependability of a certain system it is very important for the final results that the failure information is documented well. The longer the period of failure information time is, the more reliable the analysis is. In the modeling phase it is required to adopt the operational principle of the system.

In the RAM analysis the required information is:

- Failure information
    - MTTF
    - MTTR
    - MWT (in some cases)
- Operational information
    - Operation methods
    - Process flows and process behavior
- Maintenance information
    - Maintenance resources
    - Special arrangements for maintenance task
- Cost information

    - Costs for lost production
    - Maintenance costs (Resource costs, Spares costs)
- Optional information (good to know)
    - Failure consequences (Safety, Operational, Environmental.)
    - Failure history data
    - Maintenance history data

6 RESULTS

In the analysis the simulated period was five years. The simulation calculates the probability that the grinding process fails during a five-year operational period. The analysis observes only the unexpected failures. The analysis does not account the unavailability of maintenance shutdowns or other planned shutdowns.

In the analysis results the reliability performance indicators are availability, reliability and maintainability. Availability can be measured separately for each sub-system or device that has affects on the system and it is reported by the percentage of a simulated period time. The reliability indicator is a probability to failure in a selected time from the system start-up. Maintainability is inspected from the *time to repair* point of view.

The model was simulated by the ELMAS RAMoptim dynamic software for 200 rounds. The software calculated the system events in every 10 minute steps in the five year operational period. Consequently the software calculated events for the system in 1000 years (five years per round). The long-term simulation guarantees the repeatability of the analysis.

6.1 Simulation results with given values

The reliability block diagram of the system shows that the production line stops if the total mill feed fails, the flotation fails (no failures defined), the pelletizing plant fails (the additive grinding line fails and the storage tank empties) or both of the parallel grinding lines fail. In addition to these a delay component for the thickener failure was defined. If a thickener failure lasts longer than twelve hours it will stop the production. The purpose of this thesis was to examine the total dependability of the grinding process, so the flotation unit is out of scope and it cannot fail by default. The total mill feed stops the production only when the thickener delay buffer time is reached. Thus the grinding process stops the line if both of the parallel grinding lines fail at the same time or the additive grinding fails and the additive storage tank empties (buffer time 12 hours).

Availability

The simulation results are based on reliability calculations. Calculations have certain range of variation. This section discusses about the average availability values of the calculation. The deviation between the best and the worst case scenario is represented in Figure 16. The results of the analysis show that the system availability variation is between 97.96% (the worst case scenario) and 99.12% (the best case scenario). The average availability for the whole system is 98.63%.

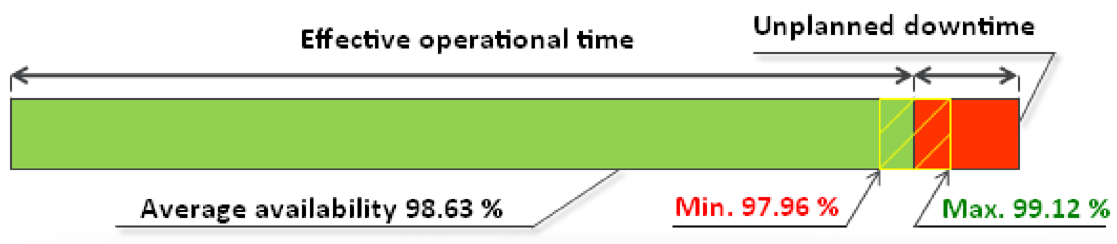

FIGURE 16. Availability deviation

The high availability is due to parallelism of the grinding lines. It is not possible directly to examine the availability of parallel grinding lines in this model because the lines have common pieces of equipment. Although it is possible to define the terms for simulation and that way it is possible to calculate the availability values for grinding lines separately.

During the five-year simulation period the production line has been stopped for 25 days and the total number of failures that caused the line shutdown has been about 260.

TABLE 1. System availability values

ID	NAME	Availability (%)	Failed (%)
1	**Mineral enrichment process**	**98,63**	**1,37**
2	Total mill feed	99,85	0,15
3	Pebble reject	99,80	0,20
3A	Grinding line A feed	99,80	0,20
3B	Grinding line B feed	99,79	0,21
4	Thickener	99,54	0,46
4A	Classifiers A1	98,41	1,59
4B	Classifiers B1	98,40	1,60
5A	Classifiers A2	99,85	0,15
5B	Classifiers B2	99,69	0,31
6	Flotation	100,00	0,00
7	Pelletizing plant (Additive grinding)	99,26	0,74
9A	**AG Mill A**	**96,36**	**3,64**
9B	**AG Mill B**	**96,31**	**3,69**
10A	**Pebble Mill A**	**95,96**	**4,04**
10B	**Pebble Mill B**	**95,97**	**4,03**

The mean times to failure and to repair for all the main components of the system during the simulation period are specified in Table 2. The average time for process shutdown is 5 days 17 hours and the restoration lasts 2 hours in average. It can be noticed that the AG and Pebble mills are the most prone to failure (less than 2 days in average).

TABLE 2. Failure information of the system main components

ID	NAME	MTTF (h)	MTTR (h)
1	Mineral enrichment process	137	2
2	Total mill feed	861	45
3	Pebble reject	3 119	6
3A	Grinding line A feed	3 254	7
3B	Grinding line B feed	2 465	5
4	Thickener	858	4
4A	Classifiers A1	282	5
4B	Classifiers B1	283	5
5A	Classifiers A2	8 759 998	2
5B	Classifiers B2	8 759 994	6
7	Pelletizing plant (Additive grinding)	2 719	20
9A	AG Mill A	35	1
9B	AG Mill B	35	1
10A	Pebble Mill A	34	1
10B	Pebble Mill B	34	1

Considering the total availability performance of mineral enrichment process it must be observed that only a bit over 5% of the system failure modes cause over 87% of the whole production line shutdowns. The failure modes that cause most of the shutdowns are specified in Table 3.

TABLE 3. The most critical failure modes (Shutdown)

	Failure mode	Shutdowns
1	Lubrication oil temperature measurement failure (AG & Pebble mills)	55,46 %
2	Inching unit failure (AG & Pebble mills)	6,24 %
3	Additive storage tank empty	5,64 %
4	Screw classifier wearshoe failure (2 classifiers)	4,46 %
5	Grease lubrication system signal loss	4,31 %
6	Blockage in lubrication cooling water line (AG & Pebble mills)	3,57 %
7	Grease lubrication valve blockage	3,53 %
8	Grease lubrication pump failure	1,96 %
9	Central compressor failure	1,85 %

Whereas considering the unavailability time of mineral enrichment process the individual failure modes that cause unavailability for the system, only 1% cause nearly 88% of the whole production line unavailability. Thus it can be assumed that these are the most critical components for the system. The individual failure modes that cause most of the production line unavailability are specified in Table 4.

TABLE 4. The most critical failure modes (Unavailability)

	Failure mode	Downtime
1	Additive storage tank empty	54,19 %
2	Water handling failure	12,49 %
3	Thickener failure over 12 hours	10,75 %
4	Central compressor failure	10,56 %

Like mentioned, it is possible to inspect the failure behavior of the grinding lines separately. The Grinding line A has been stopped for 161 days in average during the simulation period and the number of failures that caused the line shutdown has been approximately 2455. The time of the planned shutdowns is unavailable, so the production time is one calendar year (365 d) by default. Consequently the availability of the Grinding line A is:

$$A_{lineA} = \frac{5 * 365d - 161d}{5 * 365d} * 100\% = 91{,}18\%$$

TABLE 5. Grinding line A - TOP 10 failure modes

Equipment	Failure	Time (h)	Time (%)
Screw classifier	Wearshoe failure	520	13,42
AG Mill oil lubrication	Temperature measurement failure	453	11,68
Pebble Mill oil lubrication	Temperature measurement failure	452	11,67
Pebble Mill feed end	Wear ring failure	242	6,26
Pebble Mill feed end	Slinger ring failure	127	3,27
AG Mill feed end	Slinger ring failure	123	3,16
Pebble Mill	Inching unit failure	101	2,62
AG Mill	Inching unit failure	100	2,59
Screw classifier	Screw bearing failure	91	2,36
Pebble Mill	Head lining failure (Bolt breaks)	89	2,29
Total		**2298**	**59,33**

Top 10 failure modes of the Grinding line A cause 59.33% of the Grinding line A's unavailability.

The Grinding line B has been stopped for 163 days in average during the simulation period and the number of failures that caused the line shutdown has been approximately 2451. By these values the availability of the Grinding line B is:

$$A_{lineB} = \frac{5 * 365d - 163d}{5 * 365d} * 100\% = 91{,}07\%$$

TABLE 6. Grinding line B - TOP 10 failure modes

Equipment	Failure	Time (h)	Time (%)
Screw classifier	Wearshoe failure	518	13,25
Pebble Mill oil lubrication	Temperature measurement failure	454	11,63
AG Mill oil lubrication	Temperature measurement failure	450	11,51
Pebble Mill feed end	Wear ring failure	241	6,17
AG Mill feed end	Slinger ring failure	124	3,17
Pebble Mill feed end	Slinger ring failure	121	3,10
Pebble Mill	Inching unit failure	101	2,58
AG Mill	Inching unit failure	100	2,56
AG Mill	Head lining failure (Bolt breaks)	93	2,37
Screw classifier	Screw bearing failure	91	2,33
Total		**2292**	**58,67**

Top 10 failure modes of the Grinding line B cause 58.67% of the Grinding line B's unavailability.

The third grinding line is under the pelletizing plant and because the pelletizing plant fails only when the additive grinding fails it is possible to inspect the availability of the third grinding line as the availability of the pelletizing plant which is 99.26%. The high availability value of the additive grinding line is a consequence of the additive material storage tank. Without the storage tank the additive grinding line availability is 97.17%. During the five-year simulation period the additive grinding has been failed almost 51 days in average and the number of failures that caused the line shutdown has been about 303. The additive material storage tank was emptied and therefore the production line has been stopped for 13 days and 13 hours during the simulation period.

Reliability

The reliability of system can also be examined from the simulation results. The reliability is shown as a probability that the system fails during a certain period of time from the startup.

TABLE 7. System reliability during five days of operation from the startup

ID	NAME	Unreliability (%)
1	Mineral enrichment process	48,70
2	Total mill feed	1,18
3	Pebble reject	1,83
3A	Grinding line A feed	6,26
3B	Grinding line B feed	4,10
4	Thickener	17,64
4A	Classifiers A1	33,93
4B	Classifiers B1	37,19
5A	Classifiers A2	0,00
5B	Classifiers B2	0,00
7	Pelletizing plant (Additive grinding)	4,29
9A	AG Mill A	97,79
9B	AG Mill B	98,86
10A	Pebble Mill A	96,97
10B	Pebble Mill B	97,03

As perceived from Table 7 the probability for production line shutdown during five days' operation is almost 50%. The probability that the AG or Pebble mills can operate five days a row is very improbable.

Capacity

Analyzing the results it can be noticed that the biggest problem is not the availability of mineral enrichment process. The availabilities of the parallel grinding lines are significantly low. This means that when one of these grinding lines is stopped it decreases the production capacity to 50%, which is a huge risk for the production plant from the economical point of view.

Like mentioned, the whole production line is stopped for 25 days of the simulation period and 13 days and 15 hours of this time the line unavailability occurs of some other reason than parallel grinding lines failure. Therefore, it can be noticed that the parallel grinding lines coexistent failure caused 11 days and 9 hours of the production line unavailability. When inspecting the grinding lines one-to-one, the Grinding line A has been stopped for 161 days, and the Grinding line B 163 days of the simulation period. This means that the production plant operational capacity has been 50% for 312 days and 15 hours during the 5-year simulation period.

TABLE 8. Production line capacity during the 5-year simulation period

Production line capacity (5a)	Time	Time (%)
100 %	4a 27d 9h	81,50 %
50 %	312d 15h	17,13 %
0 % (Failed)	25d	1,37 %

Cost risks

In addition to availability values the simulation results give valuable information of the system cost risks. This is a very important part of the analysis. The cost risks of the system include information of the spare part costs, repair costs and lost production costs. Like mentioned, the biggest financial risks for the system are the production losses.

The process material is crushed iron ore, whose market price is approximately 2.14 € per metric ton (InfoMine 2011.). The end product of Grinding lines A and B is iron ore fines, whose market price is about 125.10 € per metric ton (InfoMine 2011.). The end product of the enrichment process is iron ore pellets, whose market price is about 134.10 € per metric ton (InfoMine 2011.). Consequently the increase in value of iron ore fines is about 123 € / t. The increase in value of iron ore pellets is about 132 € / t.

The risks for lost production are calculated separately for all the grinding lines. The lost production costs for the Grinding line A and the Grinding line B are 123 € / t. If the additive grinding failure stops the whole production line the cost for lost production is 132 € / t. Spare part costs are based on Outotec spares catalogue. Maintenance resource costs are 60 € / h per person.

During the 5-year simulation period the cost risk for lost production is 81.55% of the system total costs. Maintenance costs (spares and resources) are 18.45% of the total costs. The system total cost distribution is specified in Table 9.

TABLE 9. Total cost risk distribution

Type of risk	Risk (%)
Lost production	81,55 %
Spare parts	15,55 %
Maintenance resources	2,89 %

It is remarkable to perceive how a large amount of the system total cost risk is composed of the AG and Pebble mills costs, almost 75%. In its entity the parallel grinding lines cover over 90% of the system total cost risks. The cost risk distribution of equipment is specified in Table 10.

TABLE 10. Equipment cost risk distribution of the total costs

ID	NAME	Spares	Resources	Downtime	Total
10B	Pebble Mill B	3,41 %	0,50 %	15,64 %	**19,56 %**
10A	Pebble Mill A	2,64 %	0,47 %	15,61 %	**18,72 %**
9A	AG Mill A	3,10 %	0,47 %	14,66 %	**18,23 %**
9B	AG Mill B	3,11 %	0,48 %	14,50 %	**18,09 %**
7	Pelletizing plant (Additive grinding)	1,68 %	0,50 %	6,17 %	**8,34 %**
4B	Classifiers B1	0,71 %	0,18 %	6,19 %	**7,08 %**
4A	Classifiers A1	0,69 %	0,18 %	6,10 %	**6,97 %**
2	Total mill feed	0,00 %	0,01 %	1,13 %	**1,14 %**
3B	Grinding line B feed	0,07 %	0,10 %	0,79 %	**0,96 %**
3A	Grinding line A feed	0,07 %	0,09 %	0,77 %	**0,94 %**
5A	Classifiers A2	0,15 %	0,00 %	0,00 %	**0,15 %**
5B	Classifiers B2	0,14 %	0,00 %	0,00 %	**0,15 %**
3	Pebble reject	0,02 %	0,02 %	0,00 %	**0,04 %**

Maintenance resources

It is possible to examine the requirements for corrective maintenance personnel in unexpected failure situations. This inspection is a support function for maintenance planning, for example considering the reaction time in unexpected failure situations.

Almost four years of the operational period there have been none unexpected failure events that would have required corrective maintenance personnel. The most of the corrective maintenance tasks required one to four maintenance persons during five years.

TABLE 11. Maintenance resources in unexpected failure situations

Personnel	Count of need	Time of need (h)	Time of need (%)
0	-	3a 329d 6h	78,04
1	3467	109d 4h	5,98
2	1981	168d 10h	9,23
3	744	54d 2h	2,96
4	506	48d 7h	2,65
5	205	11d 7h	0,62
6	91	5d 18h	0,32
7	34	2d 2h	0,12
8	16	1d 1h	0,06
9	6	8h	0,02
10	2	3h	0,01
11	1	1h	0,00
12	0,30	26min	0,00
13	0,12	5min	0,00
14	0,03	2min	0,00
15	0,01	4s	0,00

6.2 Suggestions to improve system reliability

The most critical individual failure mode for the system is *Empty additive storage tank*. It causes over 54% of all the system unavailability time. The additive storage tank gets empty only when Limestone grinding failure lasts longer than 12 hours. And the most critical failure mode for additive grinding is the limestone feed bin blockages (winter and summer). So the easiest way to improve the system availability would be to increase the volume of the additive storage tank and try to decrease the repair time of feed bin blockages.

Also the oil temperature measurement failures of the mill bearing lubrication system cause the most of the production line shutdowns. If the real malfunction is the temperature measurement sensor and its functionality, it would be worth to consider the redundancy of the sensor. Adding one sensor per system is not a significant investment economically and if it reduces unwanted shutdowns, the financial benefit would be significant. But if the failure is really in the lubrication oil temperature, the oil cooling system is inadequate.

The focus should be on the parallel grinding line failures that cause unexpected shutdowns because the biggest economical loss comes from the lost production. The oil temperature measurement redundancy of the mill bearing lubrication system is one improvement that should be considered. The second biggest issue that causes unavailability of the grinding lines is the screw classifier wearshoe failure. The screw classifier itself is quite a large and expensive piece of equipment to duplicate so there should be consideration of improving the wearshoe lifetime. If the wearshoe lifetime would be 2 times longer, 28 days instead of 14 days, it would increase the availability.

6.2.1 Performed actions

The system parameters were edited by the suggestions of Chapter 6.2 and the model was simulated with the same time parameters as the original model. The parameters that were changed:

- Additive storage tank buffer time increased from 12 hours to 24 hours
- Maximum time to repair the limestone grinding feed bin blockage reduced from 48 hours to 24 hours.
- Lubrication oil temperature measurement duplication
- Screw classifier wearshoe mean time to failure increased from 14 days to 28 days

6.2.2 Improvement results

Availability

The system availability increased 0.57% as the result of improvements which means over 10 days more operational time. This is mostly a consequence of the increased additive storage tank volume but also the other improvements affect the system availability. During the 5-year simulation period the system has been stopped for 14 days and 16 hours and the failures that caused the production line shutdown has been approximately 88.

An important and noteworthy fact is the increased availability of the AG and Pebble mills. These values are discussed later in this chapter.

The lifetime extension of the screw classifier wearshoe can be seen in increased availability of the first classifier units. It increases the classifier unit availability approximately 0.60% which reduces the classifier unit downtime to half from the original.

TABLE 12. Effects on system availability

ID	NAME	Availability (%)	Change (%)
1	**Mineral enrichment process**	**99,20**	**0,57**
2	Total mill feed	99,86	0,01
3	Pebble reject	99,80	-0,01
3A	Grinding line A feed	99,79	-0,01
3B	Grinding line B feed	99,80	0,00
4	Thickener	99,55	0,01
4A	Classifiers A1	99,01	0,60
4B	Classifiers B1	99,01	0,60
5A	Classifiers A2	100,00	0,15
5B	Classifiers B2	100,00	0,31
6	Flotation	100,00	0,00
7	Pelletizing plant (Additive grinding)	99,68	0,42
9A	**AG Mill A**	**97,26**	**0,90**
9B	**AG Mill B**	**97,21**	**0,90**
10A	**Pebble Mill A**	**97,03**	**1,08**
10B	**Pebble Mill B**	**97,04**	**1,07**

As a result of these improvements, the Grinding line A has been stopped for 114 days during the 5-year simulation period and the failure events that cause the line shutdown have reduced to 784. So the availability of the line A has increased by 2.57%.

$$A_{lineA} = \frac{5 * 365d - 114d}{5 * 365d} * 100\% = 93{,}75\%$$

Analyzing the improvement results for the Grinding line B, the line has been stopped for 116 days and the failure events that cause the line shutdown have reduced to 786. Consequently the line B availability has increased by 2.58%.

$$A_{lineB} = \frac{5 * 365d - 116d}{5 * 365d} * 100\% = 93{,}64\%$$

The improvements affect also the mean times of the system. As perceived from Table 13, the mean times to failure have increased approximately three times from the original simulation, which means fewer shutdowns during the operational period.

TABLE 13. Effects on system mean times

ID	NAME	MTTF (h)	MTTR (h)
1	Mineral enrichment process	318	4
2	Total mill feed	867	36
3	Pebble reject	3 277	7
3A	Grinding line A feed	3 125	7
3B	Grinding line B feed	2 444	5
4	Thickener	865	4
4A	Classifiers A1	491	5
4B	Classifiers B1	494	5
5A	Classifiers A2	∞	∞
5B	Classifiers B2	∞	∞
7	Pelletizing plant (Additive grinding)	7 065	23
9A	AG Mill A	120	3
9B	AG Mill B	120	3
10A	Pebble Mill A	109	3
10B	Pebble Mill B	109	3

Reliability

Reliability of the system increases significantly as the result of these improvements. Comparing to the original results it can be perceived that during the five days of operation the whole system reliability increases over 32% and the risk for the process shutdown during five days from the startup is 16.23%.

The redundancy of the bearing lubrication oil temperature measurement of the AG and Pebble mills reduces the risk of the mill shutdown. Before this improvement the risk of the mill shutdown during five days of operation was nearly 100% and as the result of the improvement, it reduces the probability of shutdown over 35% for the AG mills and over 32% for the Pebble mills.

Reliability values and the changes are specified in Table 14.

TABLE 14. Effects for system reliability

ID	NAME	Unreliability (%)	Change (%)
1	Mineral enrichment process	16,23	32,47
2	Total mill feed	0,74	0,45
3	Pebble reject	3,44	-1,61
3A	Grinding line A feed	4,93	1,32
3B	Grinding line B feed	2,79	1,31
4	Thickener	13,53	4,10
4A	Classifiers A1	19,16	14,77
4B	Classifiers B1	23,98	13,21
5A	Classifiers A2	0,00	0,00
5B	Classifiers B2	0,00	0,00
7	Pelletizing plant (Additive grinding)	2,25	2,03
9A	AG Mill A	62,67	35,12
9B	AG Mill B	62,60	36,26
10A	Pebble Mill A	64,63	32,33
10B	Pebble Mill B	64,77	32,26

Capacity

Analyzing the effects of the improvements on the parallel grinding lines the advantage is very significant. The improvements that have effects on the failure behavior of the parallel grinding lines are the *Lubrication oil temperature measurement duplication* and *Screw classifier wearshoe lifetime extension*. Benefits of these improvements can be seen in decreased downtime, in other words increased availability and also the failure events of the grinding lines are reduced.

As a result of these improvements, the total downtime of the production line has decreased over 10 days, but the biggest profit is earned by the increased availability of parallel grinding lines. During the simulation period the mineral enrichment process downtime is 14 days 16 hours. The line shutdown occurs 8 days and 8 hours for some other reason than parallel grinding lines failure. This means that the parallel grinding line coexistent failure causes 6 days and 8 hours of the production line downtime.

These results show that the production capacity has been 50% for 221 days 16 hours during the operational period. Comparing to the original results the savings in production losses are huge. This means that the production line reduced capacity decreases 90 days and 23 hours and the total full capacity production increases 101 days and 7 hours.

TABLE 15. Capacity with improvements

Production line capacity (5a)	Time	Time (%)	Change (%)
100 %	4a 128d 16h	87,05 %	+5,55%
50 %	221d 16h	12,15 %	-4,98 %
0 % (Failed)	14d 16h	0,80 %	-0,57 %

Cost risks

These improvements increase the total maintenance costs of the system, but the attainable financial benefit in the decreased lost production is huge. Increased maintenance costs are the consequence of the lubrication oil temperature measurement duplication and the lifetime extension of the screw classifier wearshoe. The temperature measurement sensor itself is prone to fail. The redundancy of this sensor ensures that the grinding line can operate even though one sensor fails. Also it can be assumed that a better wearshoe is more expensive. In this case the price of the wearshoe is doubled.

TABLE 16. Total cost risk distribution

Type of risk	Risk (%)
Lost production	-29,62 %
Spare parts	+9,39 %
Maintenance resources	+3,01 %
TOTAL	**-22,61 %**

The financial benefit of these improvements is significant. The investment costs of these improvements decrease the profit a bit. But still the final result would be significantly profitable during the five years of the operational period. The coarse estimation is that the total cost risk benefit would be close to 20% in the five years of the operational period.

7 REQUIREMENTS FOR THE ANALYSIS AS A SERVICE PRODUCT

The strengths of Outotec have been so far that the company is a technology provider. However, the market situation in all fields of industry of the last few years has shown that new technology deliveries are decreasing and new solutions must be developed to keep up the competitiveness and business activity. The Company's Service Business area is increasing at the time and new innovative solutions are developed to enhance the business.

A reliability analysis as a company's service product is a very versatile entity and it serves many purposes. It is possible to apply the analysis almost on any kind of entity. The informative benefit of the analysis is very significant for the customer. The result of the analysis gives extensive information of the subjects' total dependability and it recognizes the biggest bottlenecks of the system. The analysis observes the failure behavior but also the cost risks of the system.

The starting point for doing the analysis and the scope of the target comes from the customer. The purpose of the work is to fulfill the customer requirements as well as possible. But from the service provider's point of view the gathered information in the analysis data acquisition phase gives very valuable information about the equipment failure behavior and it can be exploited in the service product processes and activity development. Properly documented, the information can be used in future projects and the results can be compared. The mandator should consider a database creation for the analysis information. The database enables easier utilization of the information. Thus the analysis establishing gets faster and it will be more reliable. In addition, the reliability information can be applied on technology development and design. RAM analysis is not exclusively a product for service business area on the contrary it serves also other corporate business areas and their development.

Like mentioned, the analysis can be performed for any kind of target. However, the biggest potential is in the process level inspection. It is possible to model large entities and dynamics of the system by the computer software, which is used in the work part of the analysis. Consequently the benefits of the service are significant for the customer and also for the service provider. The benefits increase if the scope is sufficiently extensive.

It requires a large amount of work to perform the service in embryo. Participants of the project vary depending on the scope of the target. When experience and information base increases the time usage will decrease substantially. It requires about one month work contribution of the software supervisor to perform one analysis. In addition there will be several supporting participants included in this project. Roughly estimated it takes about 30-40 persons' daily workload to perform one analysis, depending on the scope of the system.

The customer must commit in data acquisition phase of the analysis. Required data for the analysis is based on estimates of specialists if there is not failure or maintenance history data available. These specialists are the maintenance personnel and plant operators. The attendance of operators in the data gathering workshop is primarily important. Operators have such information that the maintenance personnel might not have. In addition to failure information the information of process functions and cost information are required. A proposal for improvement will be created based on the analysis results. The proposal is a support function for decision making in maintenance and production risk management. The benefits of the proposal are to improve the system availability performance and to decrease the operation and maintenance costs of the customer.

8 CONCLUSION

New investments in industry are decreasing and the demand for different supporting solutions for maintenance is growing in various industry fields. Today the plant investments are increasingly centralized in the maintenance section. The past few years have shown that the downward trend of new technology deliveries hasten the service business growth of many companies. This is already evident in the mining and metallurgical industries.

The purpose of this reliability analysis was to examine the failure behavior of the system dependability and try to find the most critical equipment for the system. The objectives of this thesis were to create a reliability analysis for the mineral enrichment process grinding circuit and to examine the possibilities for the analysis as the company's new service product. The scope for this thesis was chosen by the employer. The subject of this thesis was considered internally in the company, but the lack of resources prevented the start of the investigation.

As to the title of the thesis, a reliability analysis was very interesting and motivating because it corresponds to the education. My opinion is that the objectives of the thesis were achieved and the results were conspicuous. The biggest challenge during this thesis was the lack of knowledge about the mining industry technologies and their operational principles. Anyhow, I had a huge support from Outotec process specialists with this issue which made possible to carry out the analysis successfully.

A reliability analysis is a support function for maintenance and its focus is to inspect the selected subject's reliability, availability and maintainability. The analysis can be assumed to be a criticality inspection when considering the maintenance allocation or planning a new effective maintenance plan. The methods of this analysis work are based on familiar themes of maintenance like reliability modeling and reliability calculations. The analysis gives extensive information about the failure behavior of the system and it shows the biggest bottlenecks of the system. The base information used in the analysis is the system functional features, failure information and cost information. The purpose is to create a certain kind of optimized criticality inspection based on this information.

Although, lots of maintenance information is applied in the analysis, it does not mean that the analysis is only a tool for maintenance planning. The results of the analysis can be utilized also in product development and design.

Personally I see the reliability analysis, a remarkably potential option as a part of the corporate service product portfolio. The financial benefits of the analysis can be significant from the customer’s point of view. It is possible to examine easily different scenarios about the system failure behavior and the consequences of them by the computer software which is used in the analysis. The information we get as a result of the analysis is very valuable also from the technology manufacturer’s point of view. As the results are based directly on the actual use of the equipment, the information is more reliable than based on the design view considerations. It is possible to evolve the technologies of the company by the results of the analysis so the reliability of the company as a technology provider can be improved. This also improves the reputation of the company.

REFERENCES

Blanchard, B. 2004. Logistics Engineering and Management. 6th edition. Upper Saddle River: Pearson Education, Inc.

Damsten, L. 2011. Spare part cost definition. Interview April 5, 2011.

Dhillon, B. S. 2006. Maintainability, Maintenance, and Reliability for Engineers. Boca Raton: CRC Press.

Domenico, J. 2011. Magnetic separator spare part cost information. Email message on April 11, 2011. Receiver P. Tolvanen.

Hecht, H. 2004. Systems Reliability and Failure Prevention. Norwood: Artech house, Inc.

Hokka, H. 2011. Notification related to grinding process. Interview March 24, 2011.

InfoMine 2011. Iron ore market prices. Accessed on May 26, 2011. http://www.infomine.com/, Charts & Data.

Jäppinen, R. Notification related to thickener functions. Interview April 12, 2011.

Järviö, J., Piispa, T., Parantainen, T., Åström, T. 2007. Kunnossapito. Kunnossapidon julkaisusarja N:o 10. Helsinki: KP-Media Oy.

Järviö, J. 2000. Luotettavuuskeskeinen kunnossapito. Kunnossapidon julkaisusarja N:o 4. Rajamäki: KP-Tieto Oy.

Lehtinen, T. 2011. ELMAS training at Espoo campus. February 28, 2011.

Lehto, H. 2011. Introduction to grinding – training seminar. April 20, 2011.

Lukkarinen, T. 1984. Mineraalitekniikka 1, Mineraalien hienonnus. Helsinki: Insinööritieto Oy.

Lukkarinen, T. 1987. Mineraalitekniikka 2, Mineraalien rikastus. Helsinki: Insinööritieto Oy.

Lynch, A. J. 1977, Mineral crushing and grinding circuits. Amsterdam: Elsevier.

Lyytikäinen, A. 2010. RAM-analyysi. Promaint 5/2010, 6 September 2010, 40-42.

Moubray, J. 1997. Reliability-centered Maintenance. 2nd edition. Oxford: Butterworth-Heinemann.

Mäki, K. 2010. Study material: Ennakoivan kunnossapidon suunnittelu, Jyväskylä University of applied sciences, Optima study environment.

Outotec Oyj. 2011. Annual Report 2010.

Outotec Oyj. 2011. Corporation website. Accessed on February 25, 2011. http://www.outotec.com, About us.

Outotec Oyj. 2009. Regional training seminar about grinding. Outotec internal training material.

Outotec Oyj company overview. n.d. Accessed on February 24, 2011. http://www.jamk.fi/kirjasto, Nelli-portaali, Marketline.

Promaint. 2009. Kuntoon perustuva kunnossapito. Helsinki: KP-Media Oy.

Pukki, K. 2011. Notification related to classifiers. Interview March 23, 2011.

Ramentor Oy, 2011, Corporate website, ELMAS, Accessed on April 5, 2011. http://www.ramentor.com/etusivu, Tuotteet, ELMAS.

Ramentor Oy, 2011, Corporate website, FTA. Accessed on April 6, 2011. http://www.ramentor.com/etusivu, Tuotteet, ELMAS, Vikapuu.

Ramentor Oy, 2011, Corporate website, RBD. Accessed on April 5, 2011. http://www.ramentor.com/etusivu, Tuotteet, ELMAS, Luotettavuuslohkokaavio.

Svoboda, J. 1987. Magnetic methods for the treatment of minerals. Amsterdam: Elsevier.

Tuomisalo, A. 2011. Introduction to grinding. February 24, 2011.

Wills, B. A. 2006. Mineral processing technology. Oxford: Butterworth-Heinemann.

Workshop, 2011. Outotec maintenance specialists interviews, March 14-15, 2011.

APPENDICES

Appendix 1. List of equipment

ID	NAME
1	**Mineral enrichment process**
2	Total mill feed
3	Pebble reject
3A	Grinding line A feed
3B	Grinding line B feed
4	Thickener
4A	Classifiers A1
4B	Classifiers B1
5A	Classifiers A2
5B	Classifiers B2
6	Flotation
7	Pelletizing plant (Additive grinding)
8	Mill reject
9A	AG Mill A
9B	AG Mill B
10A	Pebble Mill A
10B	Pebble Mill B

Appendix 2. Information template

Equipment	Failure mode	MTTF	MTTR	Resources		Spare part costs

Appendix 3. System failure information

AG Mills

Failure	MTTF	Min (TTF	Max (TTF	Frequenc	MTTR (h	Min (TTR	Max (TTR	Resource
Bearing failure (Radial bearing)	10a				48,0			4
Manufacture failure (Axial bearing)	50a				14,0			4
Misalignment (Axial bearing)	50a				14,0			4
Mill sleeve surface failure	50a				12,0	10,0	14,0	4
LP Pump 1 failure	0,5a	0,1a	1a		2,0			2
Sequence valve blockage	0,5a				1,0			2
Hydraulic accumulator sealing failure	5a				1,0	0,5	1,5	2
Slurry V-ring failure				2 / a	1,5	1,0	2,0	1
RPM Sensor electric failure	1a				2,0			1
Contaminated oil	1a				16,0			2
Temperature measurement failure	2d	1d	7d		0,5			1
Filter 1 holder failure	5a				8,0			1
Filter 2 holder failure	5a				8,0			1
Filter 3 holder failure	5a				8,0			1
Filter 4 holder failure	5a				8,0			1
LP Pump 2 failure	0,5a	0,1a	1a		2,0			2
Induct transmitter failure	2a				1,0			1
HP Pump 1 failure	1a				2,0			2
HP Pump 2 failure	1a				2,0			2
HP Pump 3 failure	1a				2,0			2
Heat exchanger failure	10a				8,0			2
Blockage in incoming water line	30d				1,0	0,5	2,0	1
Cooling water temperature failure	2a				8,0	2,0	48,0	1
Check valve blockage	4a				2,0			2
Discharge trunnion lining failure	12a	10a	15a		16,0			4
Trommel failure	0,5a				6,0			2
Main pump failure	1a				4,0	0,5	12,0	2
Stand by pump doesn't wake up	1a				8,0			2
Wear ring failure				4 / a	4,0			2
Slinger ring failure				5 / a	5,0	4,0	6,0	2
Feed trunnion lining failure	12a	10a	15a		16,0			2
Distance ring failure				5 / a	2,0			2
Whole shell lining failure	10a				36,0	24,0	96,0	5
Head lining failure (Bolt breaks)				3 / a	6,0			4
Part of lining failure	5a				24,0			4
Drive motor failure	10a				18,0	16,0	24,0	2
Gearbox failure	10a				24,0			3
Main drive coupling failure	10a				24,0			3
Inching unit failure				20 / a	1,0			1
Inching coupling failure	10a				24,0			3
Inching lubrication pump failure	0,5a	0,1a	1a		2,0			2
Heat exchanger failure	10a				8,0			2
Cooling water supply failure	10a				0,0			1
Lubrication pump 1 failure	0,5a	0,1a	1a		2,0			2
Lubrication pump 2 failure	0,5a	0,1a	1a		2,0			2
Filter 1 blockage	2a				1,0			1
Filter 2 blockage	2a				1,0			1
Ring gear felt seal failure	5a				48,0			4
Pinion seal failure (Whole pinion)	13a	10a	15a		168,0			3
Pinion shaft failure	20a				60,0			3
Fixed bearing failure	10a				48,0			3
Floating bearing failure	10a				16,0			3

Pebble mill A

Failure	MTTF	Min (TTF	Max (TTF	Frequen	MTTR (h	Min (TTR	Max (TTR	Resource
Bearing failure (Radial bearing)	10a				48,0			4
Manufacture failure (Axial bearing)	50a				14,0			4
Misalignment (Axial bearing)	50a				14,0			4
Mill sleeve surface failure	50a				12,0	10,0	14,0	4
LP Pump 1 failure	0,5a	0,1a	1a		2,0			2
Sequence valve blockage	0,5a				1,0			2
Hydraulic accumulator sealing failure	5a				1,0	0,5	1,5	2
Slurry V-ring failure				2 / a	1,5	1,0	2,0	1
RPM Sensor electric failure	1a				2,0			1
Temperature measurement failure	2d	1d	7d		0,5			2
Induct transmitter failure	2a				1,0			1
Contaminated oil	1a				16,0			1
Filter 1 holder failure	5a				8,0			1
Filter 2 holder failure	5a				8,0			1
Filter 3 holder failure	5a				8,0			1
LP Pump 2 failure	0,5a	0,1a	1a		2,0			2
Filter 4 holder failure	5a				8,0			1
HP Pump 1 failure	1a				2,0			2
HP Pump 2 failure	1a				2,0			2
HP Pump 3 failure	1a				2,0			2
Heat exchanger failure	10a				8,0			2
Blockage in incoming water line	30d				1,0	0,5	2,0	1
Cooling water temperature failure	2a				8,0	2,0	48,0	1
Check valve blockage	4a				2,0			2
Discharge trunnion lining failure	12a	10a	15a		16,0			4
Trommel failure	0,5a				6,0			2
Main pump failure	1a				4,0	0,5	12,0	2
Stand by pump doesn't wake up	1a				8,0			2
Wear ring failure	30d				4,0			2
Slinger ring failure				5 / a	5,0	4,0	6,0	2
Feed trunnion lining failure	12a	10a	15a		16,0			2
Distance ring failure				5 / a	2,0			2
Mill lining failure	18a	15a	20a		24,0			5
Head lining failure (Bolt breaks)				3 / a	6,0			4
Drive motor failure	10a				18,0	16,0	24,0	2
Inching unit failure				20 / a	1,0			1
Inching coupling failure	10a				24,0			3
Inching lubrication pump failure	0,5a	0,1a	1a		2,0			2
Gearbox failure	10a				24,0			3
Main drive coupling failure	10a				24,0			2
Heat exchanger failure	10a				8,0			2
Cooling water supply failure	10a				0,0			1
Lubrication pump 1 failure	0,5a	0,1a	1a		2,0			2
Lubrication pump 2 failure	0,5a	0,1a	1a		2,0			2
Filter 1 blockage	2a				1,0			1
Filter 2 blockage	2a				1,0			1
Ring gear felt seal failure	5a				48,0			4
Pinion seal failure	13a	10a	15a		168,0			3
Pinion shaft failure (Manufacture)	20a				60,0			3
Fixed bearing failure	10a				48,0			3
Floating bearing failure	10a				16,0			3

Pebble mill B

Failure	MTTF	Min (TTF	Max (TTF	Frequen	MTTR (h	Min (TTR	Max (TTR	Resource
Bearing failure (Radial bearing)	10a				48,0			4
Manufacture failure (Axial bearing)	50a				14,0			4
Misalignment (Axial bearing)	50a				14,0			4
Mill sleeve surface failure	50a				12,0	10,0	14,0	4
LP Pump 1 failure	0,5a	0,1a	1a		2,0			2
Sequence valve blockage	0,5a				0,0			2
Hydraulic accumulator sealing failure	5a				1,0	0,5	1,5	2
Slurry V-ring failure				2 / a	1,5	1,0	2,0	1
RPM Sensor electric failure	1a				2,0			1
Temperature measurement failure	2d	1d	7d		0,5			2
Induct transmitter failure	2a				1,0			1
Contaminated oil	1a				16,0			1
Filter 1 holder failure	5a				8,0			1
Filter 2 holder failure	5a				8,0			1
Filter 3 holder failure	5a				8,0			1
LP Pump 2 failure	0,5a	0,1a	1a		2,0			2
Filter 4 holder failure	5a				8,0			1
HP Pump 1 failure	1a				8,0			2
HP Pump 2 failure	1a				8,0			2
HP Pump 3 failure	1a				8,0			2
Heat exchanger failure	10a				8,0			2
Blockage in incoming water line	30d				1,0	0,5	2,0	1
Cooling water temperature failure	2a				8,0	2,0	48,0	1
Check valve blockage	4a				2,0			2
Discharge trunnion lining failure	12a	10a	15a		16,0			4
Trommel failure	0,5a				6,0			2
Main pump failure	1a				4,0	0,5	12,0	2
Stand by pump doesn't wake up	1a				8,0			2
Wear ring failure	30d				4,0			2
Slinger ring failure				5 / a	5,0	4,0	6,0	2
Feed trunnion lining failure	12a	10a	15a		16,0			2
Distance ring failure				5 / a	2,0			2
Mill lining failure	5a				24,0			5
Head lining failure (Bolt breaks)				3 / a	6,0			4
Drive motor failure	10a				18,0	16,0	24,0	2
Gearbox failure	10a				24,0			3
Main drive coupling failure	10a				24,0			3
Inching unit failure				20 / a	1,0			1
Inching coupling failure	10a				24,0			3
Inching lubrication pump failure	0,5a	0,1a	1a		2,0			2
Heat exchanger failure	10a				8,0			2
Cooling water supply failure	10a				0,0			1
Lubrication pump 1 failure	0,5a	0,1a	1a		2,0			2
Lubrication pump 2 failure	0,5a	0,1a	1a		2,0			2
Filter 1 blockage	2a				1,0			1
Filter 2 blockage	2a				1,0			1
Ring gear felt seal failure	5a				48,0			4
Pinion seal failure	13a	10a	15a		168,0			3
Pinion shaft failure	20a				60,0			3
Fixed bearing failure	10a				48,0			3
Floating bearing failure	10a				16,0			3

Ball mill

Failure	MTTF	Min (TT	Max (TTF	Frequen	MTTR (h	Min (TTR	Max (TTR	Resource
Additive buffer tank empty					0,0			
Grease lubrication pump failure	1a				1,0			1
Grinding media failure	1a				4,0	1,0	15,0	0
Discharge grate blockage				2 / a	8,0			2
Trommel failure	0,5a				6,0			2
Main pump failure	1a				4,0	0,5	12,0	2
Stand by pump doesn't wake up	1a				8,0			2
Feed bin blockage / Winter	30d				8,0	3,0	48,0	3
Feed bin blockage / Summer	60d				2,0	0,5	8,0	2
Wear ring failure				4 / a	4,0			2
Slinger ring failure				5 / a	5,0	4,0	6,0	2
Feed trunnion lining failure	3a				16,0			2
Feed chute blockage	30d				2,0	0,1	8,0	2
Distance ring failure				5 / a	2,0			2
Mill lining failure	5a				36,0			5
Drive motor failure	10a				18,0	16,0	24,0	2
Gearbox failure	10a				24,0			3
Main drive coupling failure	10a				24,0			3
Inching unit failure				20 / a	1,0			1
Inching coupling failure	10a				24,0			3
Inching lubrication pump failure	0,5a	0,1a	1a		2,0			2
Heat exchanger failure	10a				8,0			2
Cooling water supply failure	10a				0,0			1
Lubrication pump 1 failure	0,5a	0,1a	1a		2,0			2
Lubrication pump 2 failure	0,5a	0,1a	1a		2,0			2
Filter 1 blockage	2a				1,0			1
Filter 2 blockage	2a				1,0			1
Ring gear felt seal failure	5a				48,0			4
Pinion seal failure	13a	10a	15a		168,0			3
Shaft failure	20a				60,0			3
Fixed bearing failure	10a				48,0			3

Auxiliary systems

Grease lubrication system

Failure	MTTF	Min (TTF)	Max (TTF)	MTTR (h)	Min (TTR)	Max (TTR)	Resources
Central compressor failure	1a			12	8,0	24,0	1
Valve blockage	0,5a			2			1
Divider blockage	2a			1			1
Grease pump failure	1a			1			1
Signal loss	150d	120d	180d	1,5	1,0	2,0	1

Water system

Failure	MTTF	Min (TTF)	Max (TTF)	MTTR (h)	Min (TTR)	Max (TTR)	Resources
Water handling failure	5a			72	24	336	1

Screw classifiers

Failure	MTTF	MTTR (h)	Min (TTR)	Max (TTR)	Resources
Screw bearing failure	0,5a	9,0	8,0	12	2
Wearshoe failure	14d	4,0			2

Magnetic separators

Failure	MTTF	MTTR (h)	Min (TTR)	Max (TTR)	Resources
Rubber surface damage	3a	1,5	0,5	3	2
Magnetic support failure	5a	4,0			2

Thickener

Failure	MTTF	Min (TTF)	Max (TTF)	Frequency	MTTR (h)	Min (TTR)	Max (TTR)
Hydraulic drive failure (55m)				5 / a	3,0	1,0	8,0
Pinion failure (55m)	15a	10a	20a		96,0		
Planetary gear 1 failure	15a	10a	20a		48,0		
Planetary gear 2 failure	15a	10a	20a		48,0		
Planetary gear 3 failure	15a	10a	20a		48,0		
Hydraulic drive failure (35m)				5 / a	2,0	1,0	8,0
Planetary gear failure	15a	10a	20a		48,0		
Pinion failure (35m)	15a	10a	20a		96,0		
Thickening failure +12h	Thickener failure more than 12h stops production						
Thickening failure max. 12h	System can operate						

Main belt conveyors

Failure	MTTF	MTTR (h)	Resources
Motor failure	10a	16,0	3
Pulley failure	5a	12,0	1
Drive failure	10a	16,0	3
Idler failure	0,5a	4,0	1
Belt tensioner failure	4a	6,0	2
Belt failure	10a	24,0	3

Smaller belt conveyors

Failure	MTTF	MTTR (h)	Resources
Motor failure	10a	16	3
Pulley failure	5a	12	1
Drive failure	10a	16	3
Idler failure	0,5a	4	1
Belt tensioner failure	4a	6	2
Belt failure	10a	24	3

Feed system

Failure	MTTF	MTTR (h)	Resources
Hydraulic gate failure	1a	0,5	1
Vibrating feeder failure	5a	0,25	1