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Cost Analysis for Crushing and Screening – Part I

Development of a cost model for determination of the production cost for product fractions

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Preface

The Master's thesis was performed at Sandvik SRP AB in collaboration with the Division of Production and Materials Engineering, Lund University at the company Sandvik SRP during the spring of 2014.

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Title: Cost analysis for mineral processing – Development of methodology for determination of production cost for mineral fractions

Abstract

The purpose of this paper is to introduce a new production cost-model within the world of comminution. There are many ways to determine different production costs in the industry but there has thus far been no previously published efficient way to calculate the cost per product and metric ton. In order to be able to test and validate the model the current research has been conducted in collaboration between Sandvik SRP and the Faculty of Engineering at LTH.

The base for this proposed new model is the macroeconomic generic cost-model, previously developed and published by Ståhl. The proposed model has been adapted to fit the currently investigated process of crushing and screening of different mineral and aggregate fractions.

Several factors had to be introduced or alternated in order to adapt the model to the current application. Different product factors were introduced in order to be able to distribute and trace the costs for different product fractions. In order to adjust the previously published generic cost-model to fit the intended comminution process a new cycle time had to be introduced, that represents the time for processing one metric ton of raw material. Potential balancing losses have also been reviewed and are defined as the individual balancing loss for each production station investigated. The attained results presented as a part of the current paper and the input into the proposed production cost model has been based on information from four main sources: lectures at Sandvik, literature studies, Sandvik's internal simulation software, and crushing and screening plant visits, including interviews, information systems, testing and observations. To achieve the required level of accuracy and enhance the validity of the attained results, simplistic Monte Carlo-simulation has been used where needed.

The result obtained as part of the current research is a new production cost-model intended to calculate the cost for producing different mineral fractions as part of the comminution industry. The attained accurate result indicates that the proposed model may be considered as an important tool to attain an accurate production cost and the distribution of it.

The result is a new production cost-model to calculate the cost for producing in the comminution industry. It indicates an improved tool to get a more precise result for cost per ton of product and delivers a good approach to decide the profitable or non-profitable product on a more detailed scale. However, due to different circumstances the model has only been tested at one live C&S site and the statistical data is not sufficient. The model needs further verification before proven.

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1. Introduction

The aim of this chapter is to give the reader an introduction and background of the thesis, to better be able to understand and follow the report.

1.1 Report structure

Introduction	• Company introduction • Thesis background • Deliverables
Methodology	• Work steps • Collection of information • Model verification
Theory	• Dynamic simulation • Sampling methods • Generic Production Cost Model • Adapted Production Cost model
Results	• Production cost results
Conclusions	• Validity of results • Error sources • Future work and possibilities

Figure 1: Report Structure.

1.2 The company

Sandvik AB is high-technology engineering group involved in five business areas; Sandvik Mining, Sandvik Machining Solutions, Sandvik Materials Technology, Sandvik Construction and Sandvik Venture. Each business area is responsible for production, sales and research and development.[1]
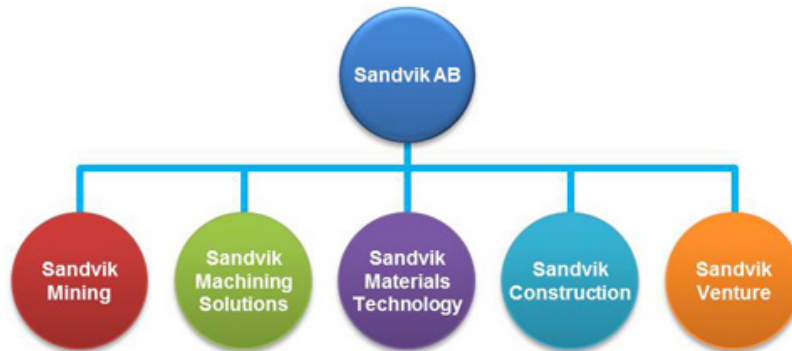
Figure 2: Sandvik business areas**.**

Sandvik's goal is to develop, manufacture and sell products and services mainly within three areas:

- Tools and tooling systems for metal cutting as well as components in cemented carbide and other hard materials.
- Equipment and tools for the mining and construction industries as well as various types of processing systems.
- Products in advanced stainless steels, special alloys and titanium as well as metallic and ceramic resistance materials.

The company was founded by Göran Fredrik Göransson in 1862 and focused, like today, on high quality, research and development and close customer contact. Today Sandvik has evolved into a large global company with activity in over 130 countries worldwide.

This project was performed at Sandvik SRP AB in Svedala, Sweden where the focus is within the areas of mining and construction.

1.3 The Process

The mining and construction processes contain several different operations. This thesis has focus on the process of comminution, which consist of crushing and screening (C&S), with the purpose of reducing the particle size. All C&S operations are made at plants, containing a mixture of machines, such as crushers, screens, and transport units, optimized for prevailing circumstances.[2]

1.3.1 Mining basics[3]

In short mining is extraction and beneficiation of single or multiple minerals or coal from Ore. Ore is described as a mineral or minerals with a content high enough to make exploration economically valuable. Whether an Ore can be exploited profitably or not is influenced by several factors[4]:

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[1] http://sandvik.com/en/about-sandvik/
[2] Sandvik Rock Processing Manual, 2011
[3] Interview: Hedvall, Per

- Location.
- Composition.
- Size of deposit.
- Mining methods.
- Mineral beneficiation.
- Cost levels.
- Market prices.

Once extracted the Ore is reduced to particles that can be separated into valuable mineral and waste, called mineral processing or mineral beneficiation. This is achieved through different beneficiation processes such as:

- Comminution.
- Sizing.
- Froth flotation.
- Gravity concentration.
- Electrostatic separation.
- Magnetic separation.

C&S accounts for about 4% of the total mining costs, all costs are presented in figure 2 below.
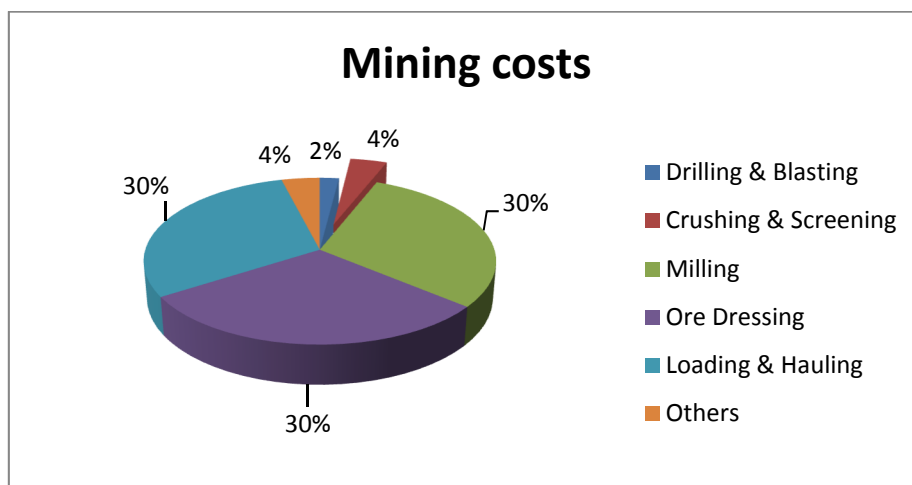
Figure 3: Split over mining costs.

Mineral exploration is expensive but the mineral products claim a high price per unit weight.

1.3.2 Construction basics

Construction material such as aggregates and cement are a prerequisite for almost all types of modern construction[5]. It is used for building of roads, bridges, tunnels, dams, railways and airports for example. Within construction the raw material is blasted and drilled, or in forms of sand and gravel, so called natural fines. The raw material is processed, downsized to fit the requirements of the product in question, in two or three steps depending on which kind of raw material that is used, shown in figure 3 below

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[4] Sandvik Rock Processing Manual, 2011
[5] Sandvik Rock Processing Manual, 2011
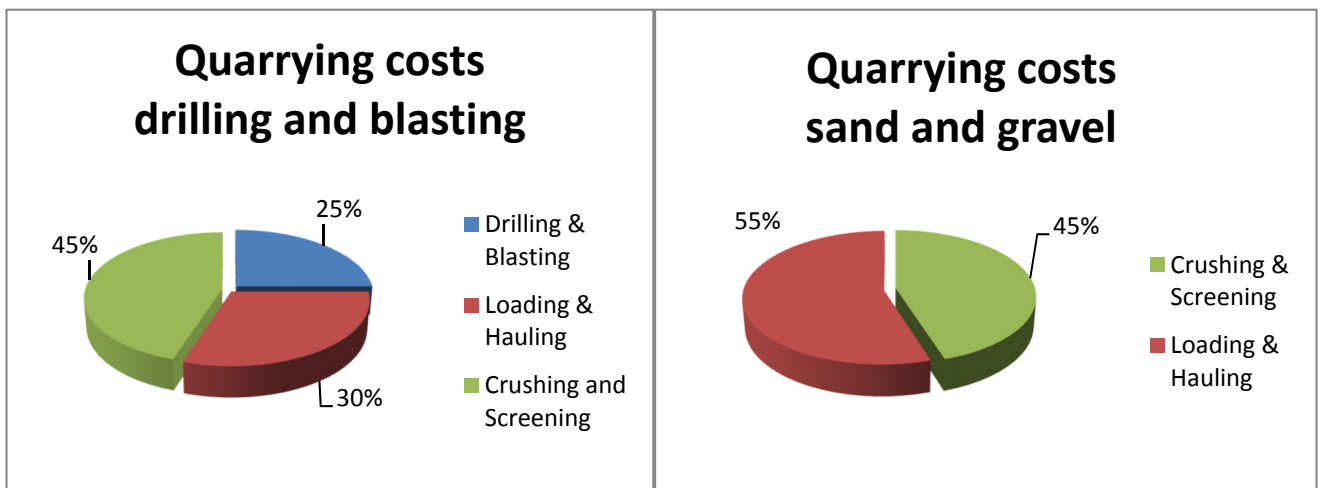
Figure 4: Split over quarrying costs, construction.

Within construction the requirements on the quality of the products are very high, especially in terms of particle sizes and shapes. For example the importance of cubisity, the ratio between length, width and thickness of the particles is often emphasized.

In contrary to mining, the final product is usually finished after the size reduction in the C&S steps and hence leads to a much smaller cost than for minerals, but also provides much less income per unit weight.

Another important thing to emphasize is the presence of multiple products within construction, in contrary to mining where only one product is the most common.

1.3.3 Crushing and Screening equipment[6]

As a group Sandvik is producing a wide range of different products. The focus of the thesis is C&S hence the focus of the products is Sandvik Mining's portfolio. The main equipment of a C&S plant is listed below:

- Jaw crushers.
- Gyratory crushers.
- Cone crusher.
- HIS and VSI crushers.
- Screens.
- Conveyors.

All of these are available in many different versions but the basic function is similar.

1.3.3.1 Jaw crushers
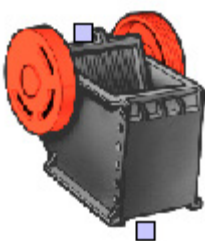
Jaw crushers are one of the most common machines in the comminution industry, often used in primary or secondary stage. It is known for high durability, flexibility and a high reduction ratio. It mainly consists of two vertical jaws, one connected to a flywheel, and one connecting rod. Its performance is affected by four main features: nip angle, width, the gape and flywheel speed. The Ore is crushed, at intermittent speed, between the two

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[6]http://mining.sandvik.com/sandvik/0120/Internet/Global/S003713.nsf/Alldocs/Portals*5CProducts*5CCrushers*and*screens*2AJaw*crushers/$FILE/Jaws.pdf

jaws and as the gape is reduced from top to bottom the Ore is reduced in size. Even though the size of a jaw crusher can vary, between around 1 and 300 tons, the principle stays the same.

1.3.3.2 Gyratory crushers

The gyratory crusher consists of a rotating cone surrounded by a mantle. Gyratory crushers have a large feed opening and offers great reduction rate for most particle sizes. It can be used both for primary crushing but also offers great possibilities for later stages. All gyratory crushers are equipped with Automatic Setting Regulation, which allows for fine tuning of the setting for the crusher during load.

1.3.3.3 Cone crushers
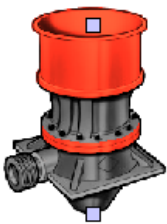
The cone crusher basically consists of a rotating cone surrounded by a mantle. The area between these two creates a crushing chamber where the Ore is squeezed between the gyratory spindles. It is often used in secondary or later stages and has a large versatility easily adapted to of any kind comminution process. Some of the advantages are robust design and easy to maintain. Sandvik offers a large range of different sizes ranging from 7 to 80 metric tons.

1.3.3.4 HSI and VSI Crushers
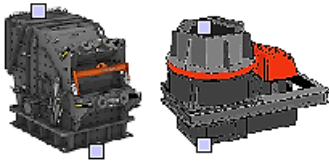
High Speed Impact crushers and Vertical Shaft Impact crushers rely on crushing with the use of kinetic energy. The raw material is hurled and when impact occurs, either with other raw material particles or crusher chamber it is downsized by this impact.

1.3.3.5 Screens
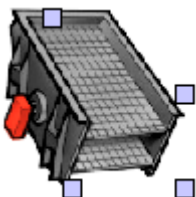
Screens are used to separate different particle sizes of the Ore, and are generally divided into two different categories; wet- and dry screening. In comminution dry screening is the most common one and screens can range between many different versions. It consists of a drive which induces a vibration, splitting the particles and drives them through a screen which provides particle separation, and decks that gather the different particle sizes and drives the bed to a correct channel for further transportation. The selection of the right screen media is essential for an optimally working screen.

1.2.3.6 Conveyors

An important part of a C&S plant are conveyors, they account for all of the transportation of material between the different C&S stages. They consist of belts, rollers, frames, pulleys and belt cleaners, safety and control devices, and dust control systems, and the reliability is the most important thing. Conveyors come in many shapes and sizes depending on the current conditions.

1.3.4 The Crushing and Screening process

This part aims to go through the most important steps using a fictive model of a C&S plant, created in PlantDesigner. Since the process is very important to this project it is of high priority to have a great

understanding of it. This model was created to make the reader more familiar with the C&S operations using a simple example.
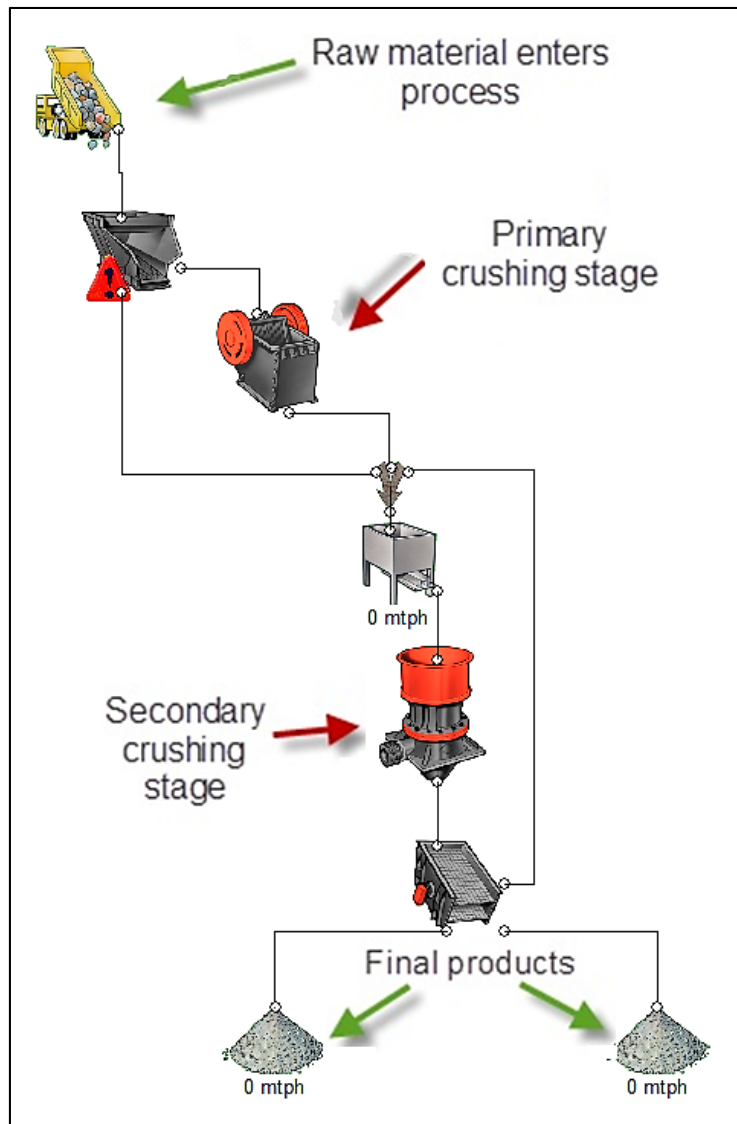
Figure 5: Flow chart of typical C&S process.

The C&S process starts at the top of the figure, where blasted rock (raw material) is fed into a grizzly feeder. This feeder separates the material and the larger fraction goes for crushing in the primary crusher while the smaller fraction is transported to the secondary crushing stage to avoid unnecessary load of material already ready for the next stage. Most material transports are performed by conveyor belts. From the grizzly feeder, the larger fraction is fed into the primary crushing stage, in this case a jaw crusher. The jaw crusher reduces the particle size through crushing between two tiles. After this the material is fed into another stockpile with a feeder, along with the smaller fraction. The feeder then feeds the succeeding cone crusher, called the secondary crushing stage. If there are more crushing stages in series the next one is called tertiary, the one after that quaternary.

After the secondary stage the crushed material is fed onto a screen that separates the incoming material into three fractions, each with a different range of particle sizes and distribution. In this case

the two smaller fractions are considered final products and the largest one is sent in a closed loop back to the secondary crushing stage. When the final products have entered the stockpiles at the bottom the C&S process is over. Once again, this is only an example, a plant can come with many different machines and setups.

For this project it is important to know a lot about all the processes and to be able to extract all data needed to use the generic cost model.

1.3.5 Cost Sources
Parameters inducing costs at a C&S plant are many and are listed below[7].

- **Rent or cost for Crushing and Screening site**
  C&S sites generally induce a cost for the operating company, whether it comes as rent or installment and depreciations.
- **Raw material**
  A prerequisite for mineral extraction is the raw material, which for the C&S process is blasted rock. This is one of the major costs since the flow of material is in the range of hundreds of metric tons per hour.
- **Mechanical equipment**
  A C&S plant contains many different kind of machines and equipment. The most common machines are; crushers, screens, feeders and conveyor belts.
- **Additional equipment**
  More equipment is mainly needed for a working plant, in addition to the equipment directly involved in the C&S process. Examples of such equipment are wheel loaders and mining trucks.
- **Facilities**
  Buildings such as warehouses for the incoming, or outgoing, material or staff facilities.
- **Payroll costs**
  Wages for the operating staff. In some cases also costs for on site management.

1.4 The objective
The purpose of this thesis is to develop a methodology to be able to determine the production cost for each material-fraction within a C&S plant. To develop a cost calculation tool for the Mining and Construction areas and express each material-fraction in cost per ton as well as account for the value flow throughout a C&S plant.

1.5 Focus and delimitations
The focus of this project is limited to the production cost for the C&S part of the mining and constructions processes. All processes before and after, like drilling, blasting and transport, are neglected.

1.6 Target groups
If the outcomes of the project are reliable and accurate the aim is to include the cost model developed into PlantDesigner (PD). PD is a Sandvik simulation software, for C&S plants, used as an application tool by engineering houses and consultants. It is also used both internally for

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[7] Interview: Hedvall, Per, 2014.

development and externally for testing by Sandvik's customers. Today PD is frequently used and has a lot of advantages but still lack information, especially regarding production costs. If the results of this thesis are reliable this presents a great opportunity in the development of PD regarding production economy. It will lead to more accurate and more information available for the user of the software. It will be beneficial for the customers and thus for Sandvik in the end.

The purpose of the project is also to test and verify the production cost model developed by Ståhl for current applications.

1.7 Deliverables

This thesis will result in a production cost model with the purpose of delivering the complete production cost, for the C&S steps, for material-fractions within the mining and construction industry. The model should be applicable in different situations, with different sites and varying materials. The cost model will show a better and more accurate to delicate different costs and be a part of the NEXT STEP theory. A report will be written of all the essential work made and consist of a thorough examination of all the costs associated with crushing and screening processes. The model is to be used as a cost comparison between the new and old technology and present a more equitable result. Two presentations will be made, one at internally Sandvik SRP, Svedala and one at the Faculty of Engineering, Lund University.

Another goal with thesis is to be accepted to be part of the Swedish Production Symposium[8]. The theme of the Swedish Production Symposium 2014 is Sustainable and Competitive Production. This is the 6th conference held like this and will take place in Gothenburg in September 2014. As application an abstract of the thesis will be submitted for acceptance to the scientific committee. If accepted, a full report of the thesis results will be made and sent to be part of the book where all SPS participants' reports will be gathered and published.

2. Methodology

This chapter aims to explain the methods used for reaching wanted and accurate results. The reader will get an overview of the thoughts behind all methods in this project.

2.1 Work steps

The most important task of this thesis is the modification and adaptation of The Generic Production Cost Model[9] later referred to as the generic production cost model, mainly developed by Professor Ståhl at Lund University, to current application. The baseline of this project consists of the following seven steps.

1. Mapping of process-flow for the whole C&S plant.
2. Calculation and estimation of machine costs, including planned maintenance and service costs, expressed in SEK/h for each machine, as well as the plant in whole.
3. Calculation and estimation of production rate, in terms of product flow, expressed in ton/h.
4. Calculation and estimation of downtime for each machine, as well as the plant in whole.
5. Calculation and estimation of balancing losses for each machine.

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6. Calculation of the cost/ton for each product respectively.
7. Validate the results from the newly developed production cost model.

2.2 Collection of information

The level of difficulty is high and a lot of information is needed and the sources of information might prove difficult to get hold of and prove unreliable.

2.2.1 Lectures

To get knowledge of the company, their operation areas and especially about mining and constructing lectures took place, performed by Sandvik staff.

2.2.2 Literature studies

Literature studies, mainly books, articles, papers and other academic work, such as other master's theses and doctoral theses, has been the major source for knowledge.

2.2.3 C&S plant visits

During the project work two visits at C&S plants, at Sandvik's customers, were made. That was a great way to get further insight in the actual work of C&S but also presented a great opportunity to bring home valuable data. Numbers of importance for the future work were derived, for example investment costs, costs for raw material, yearly product output and particle size distribution. Prior to the visits information forms were sent to the plants to get the information needed. One of these forms can be viewed in appendix 4.

2.2.3.1 Interviews

In order to gather information that was not possible to get on or own and to get a wider view of C&S plant operations several interviews took place. Also interviews at Sandvik in Svedala were made with the purpose to get a greater insight in the organization and in certain operations.

2.2.3.2 Testing and sampling

In addition to the interviews, performed at the C&S plant visits, sampling, and later testing, took place. An important factor was the properties of the raw material used.

2.2.3.3 Information systems

In some highly developed sites the information systems could provide a reliable information source. The parameters may not be exactly comprehensive with the ones in the production cost model, but a modification and adaptation could be made.

2.2.3.4 Observations

One step to increase the understanding of the different processes and their functions were pure observations. In many processes there is a lack of information systems and the work had to be done manually. The lack of information leads to certain insecurity and to enhance the validation of the data simulations were made.

2.3 Computer Software

To make this thesis viable different kind of software were used which are presented in short below.

2.3.1 PlantDesigner

PlantDesigner is Sandvik's own tool for process simulation. 1978 was the start of simple computer based calculations of crushing and screening processes and in 1994 the first Graphic User Interface

was presented with the introduction of PlantDesigner. It comes in three versions, normal, professional and expert for Sandvik personnel only. The latest version appeared in 2007 and in 2009 the software had over 400 users. The simulation tool can be used as assistance and a guiding tool when a customer is interested in new stationary or mobile equipment or upgrading of existing equipment. The software is used to develop a rock processing solution and flow charts and helps to present things such as: production rate, process tuning, equipment of choice and process balance. The input to PlantDesigner is often a combination of field studies and laboratory testing. The result is based on the input and many years of experience from Sandvik. In progress the software simulates the process 11 times to produce a steady flow. When used for professional purpose, to make business proposal to a customer, the result is based on three different scenarios; worst, average and best. The main use of PlantDesigner in this thesis is to extract material flows in the process and capacity of each machine. The results from site visit tests were fed into the software to acquire a valid result which is later used in the production cost-model. PlantDesigner can also be used as a guideline for verification of the end result.

2.3.2 Mathcad[10]

Mathcad was initially introduces in 1986 by Allen Razdow at MIT as an engineer calculation tool. It is nowadays owned by PTC and included and integrated in their wide portfolio. The main focus is an easy-to-use interface to handle advance calculation, analysis and live solving. Its interface is created like a worksheet and design to bring calculation capabilities into easy human read form. It allows the user to calculate advanced equations and to plot and illustrate the results in simple manners. In this thesis the possibilities of Matchad is only scratch on the surface and it is used mainly for two reasons: main calculation of the production cost model and Monte-Carlo Simulations.

2.3.3 MLOC

Machine Lifetime Operating Costs, MLOC, is a Sandvik developed software used to calculate and estimate the lifetime operating cost for Sandvik's Machines[11]. In this thesis the main purpose to use the software is to evaluate and estimate the costs of wear for the machines used in the process. These costs will be extracted and later on inserted in the production cost-model. The figures were earlier based on the old model consumptions model, but have been develop to follow the new Reliability Centered Maintenance Model guidelines to emphasize on additional uptime.

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[10] http://www.ptc.com/product/mathcad/about/, 2014
[11] Interview: Svennelid, Albin, 2014
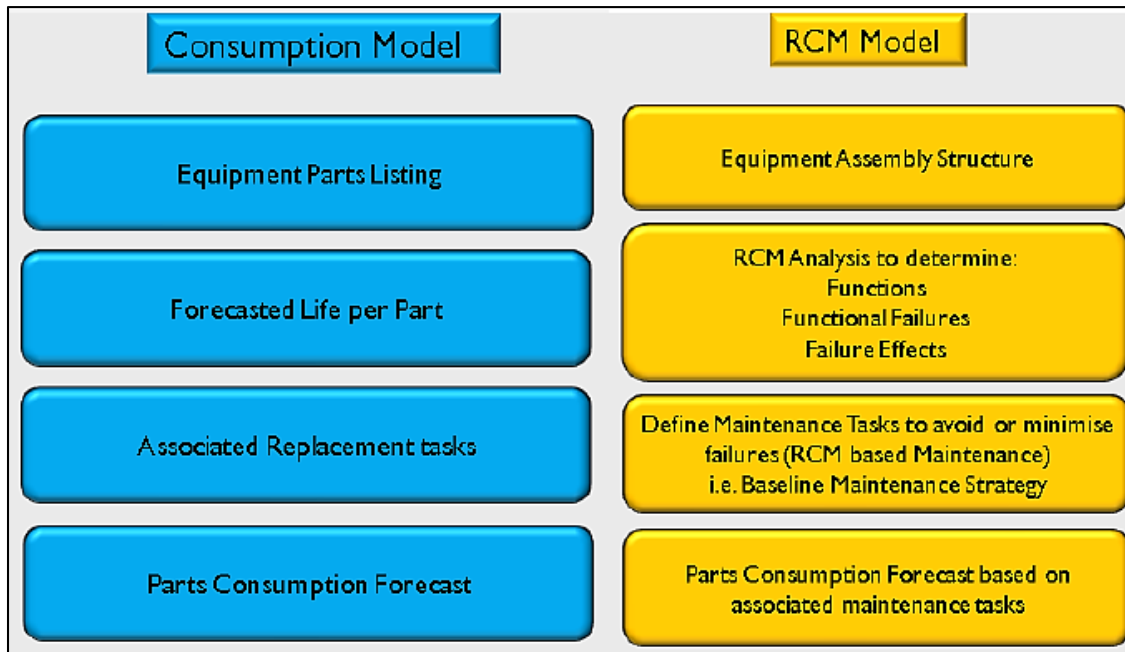
Figure 6: Build-up of MLOC, Old and New model.

The attained results are a combination of expert analysis and Weibull distributions.

MLOC is still in the developing stage and could only be used as a guideline, but the results attained from the software are sufficient enough throughout the project. For internal use it is possible to identify and create gap models. The gap models are a comparison between what Sandvik could be able to sell to the costumer, in terms of spare and wear parts, and what they actually sell to the costumer and could result in revenue for Sandvik.

2.4 Production Performance Matrix PPM[12]

In order to do an analysis of a production or process you need different sources of information and ways to handle all gathered data. One of these could be a Production Performance Matrix. All processes or productions can often be related to three different result parameters: rejection rate, downtimes and production or processing rate. The intention of the matrix is to analyze how different factors affect the cost model, but it can also be used for further analysis and improvement of the process.

Downtime parameters are downtime caused by process-related events and can occur for many different reasons. Primarily the downtimes could be separated into planned and unplanned and can be caused by both external and internal factors, for example due to unknown material in the feed or a power breakdown.

Production or processing rate parameters are measurements in time for when the process are either working at a higher or lower speed. It is based on the nominal setup time and can for example depend on factors like bad weather or harder material than expected. The nominal rate could either be based on PD, observations or interviews.

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[12] Industriella Tillverkningsystem Del ll, 2012

At the beginning of this project the plan was to use a Production Performance Matrix. This method is still viable but in order to get a representative PPM the follow up must take place during a longer period or the use of information systems can make up for the lack of time. Since the time spent at chosen production sites was limited and no information system used, the decision became to scrap the use of this matrix. This lead to a disadvantage when analyzing the production but since the main focus lies upon proposing an adapted production cost model the loss was acceptable. With this mentioned the aim for future recommendation should still be to use a PPM.

2.5 Verification of developed production cost model and information sources

2.5.1 Fictive test

In order to be prepared for the real testing at the C&S plants a fictional test of all the contents of the thesis that far was carried out. This was done to verify the new modified and adapted production cost model. It was also done to make sure that all information sources were providing sufficient information.

The test was carried out according to the previously mentioned steps:

1. **Mapping of process-flow for the whole crushing and screening plant.**
   - A fictional C&S plant was created in the simulation software PlantDesigner. See appendix 3 for process flow chart.

2. **Calculation and estimation of machine costs, including planned maintenance, expressed in SEK/h for each machine, as well as the plant in whole.**
   - Numbers for cost of raw material, staff size, payroll costs etc. were based on internal requests and relevant historical data.

3. **Calculation and estimation of production rate, in terms of product flow, expressed in ton/h.**
   - These numbers were extracted from the model in PD.

4. **Calculation and estimation of downtime for each machine, as well as the plant in whole.**
   - Were calculated and extracted from a software called MLOC.

5. **Calculation and estimation of balancing losses for each machine.**
   - These numbers were extracted from the model in PD.

6. **Calculation of the cost/ton for each product respectively.**
   - A Mathcad program with the adapted production cost model was created.

7. **Validation of the results and adaptation of the newly developed production cost model.**
   - Manual verification of Mathcad production cost model program.

2.5.2 Result from fictive test

The result presented values within reasonable limits and provided a good first indication of the model's validity .The test was only fictional which mean that the changes made as a result from the test were mostly mathematical. The cost-model was reviewed and the initial model was changed to better fit the application. This means that some of the initial parameters where either changed or removed and some new parameters were introduced. The adapted cost model will be further introduced in the theory section.

3. Theory

3.1 Dynamic simulation or simplistic Monte-Carlo Simulation[13][14]

In order to be able to present results with a strong connection to reality it was early on decided to use simulation on parameters where exact results were difficult, or even possible to obtain. The goal was to present all part costs of the adapted cost model with simulated costs with confidential intervals or with histograms and frequency. As a tool Monte-Carlo simulation was used, which is a simulation method using statistical distribution to decide uncertain variable parameters. First appeared in 1930:s the method developed throughout time and was used in the Manhattan Project. The method described below includes three different steps:

1. Determine the statistical distribution function, Weibull or Normal distributions are both suitable and often chosen.
2. Determine the parameters included in the statistical distribution function.
3. Create adequate number different outcomes using the decided function.

If a large historical data exists an empirical distribution function and a frequency function can be computed and the empirical distribution function can later on be fitted to one or more analytical distributions. In most cases there is a lack of historical data and a series of qualified assumptions need to be made. Ståhl describes the process to decide the function of use to pose five different questions:

1. Is the frequency function symmetric or asymmetric?
2. What value does the most frequently occurring result for the parameter in question?
3. What is the lowest value for the parameter in question, which is found to occur?
4. What is the highest value for the parameter in question, which is found to occur?
5. What is the average value obtained for the parameter in question?

At least two out of questions 2-5 needs to be answered and depending on whether the function is symmetric or asymmetric some of the answers could coincident.

Due to the easiness in deciding the parameters α and β, Weibull distributions, exponential distributions and normal distributions are often chosen. In cases were a large data exists the parameters could be decided using the least square or the Most-likelihood method. To evaluate the result the relative error could be calculated with an error function were the relative error corresponds to the number of data points. When the historical data does not exist or is insufficient a

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[13] Development of Manufacturing Systems, 2013
[14] Sannolikhetsteori & statistikteori med tillämpningar, 2005

number of different methods can be used to select the constants or parameters. If the frequency function has a maximum, one option is to extract the most commonly occurring value in the vector, set the distribution function equal to zero and calculate the parameters. Another option is to use the largest and smallest known outcome but then the probability for these two must be known. The frequency function is then set to that probability and maximum and minimum are obtained. The constants are then solved from these values.

The last step is to use a random vector to simulate a large number of different outcomes. The obtained values can then later on be inserted into different equations and used to calculated and estimate different results.

To obtain parameters such as α and β it was chosen to use the method of maximum and minimum value. The method and the calculations are further explained in the section; Creation of the production cost model in Mathcad.

3.2 Sampling methods[15][16]

In order to achieve a good result it is important to get relevant input, therefor on-site testing was a big factor. The result acquired from these tests will hence be used in Sandvik's own simulation tool, which is used to get valuable data input to the production cost model. The samples are carefully attained according to European standards:

EN 13285 Unbound Mixtures

EN 931-1 Methods for sampling

EN 931-2 Methods for reducing laboratory samples

EN 933-1 Determination of particle size distribution – sieving method

EN 933-2 Determination of particle size distribution – test sieves, nominal size

EN 933-3 Determination of particle shape – Flakiness Index

EN 933-4 Determination of particle shape – Shape Index

This will prevent deviation in the results and provide reliable data. To be able, in a correct way, to collect the samples different basic equipment is needed: shovel, length gauge, tachometer, buckets, packaging material and markings. Additional to sampling equipment, precautions regarding safety standards and the necessity for use of safety equipment needs to be accounted for. The first step in the procedure is to bring the process up to normal speed and calculate the belt speed using the tachometer. The belt is then stopped by pressing the emergency button and represented samples are gathered at chosen locations. The samples needs to be of sufficient size and the material over the whole width must be collected in order to get a correct representative sample. The minimal weight of sampling size is described in the standards and presented below.

$$minimal\ sample\ weight = 6\sqrt{P * D}$$

P=Maximum particle size (mm)

---

[15] Interview: Hedvall, Per. Linderoth, Lars-Ola
[16] Lindström, Anders,2010

D=Bulk density of tested material (metric tons/m^3)

 Both feed and product of each chosen location must be gathered and the test must be packed and marked in a correct way. To get validity of the tests additional information such as energy consumption, weather, CSS etc. must be noted. The tests are repeated five times at each time to enhance the result and thereafter sent to Sandvik's laboratory for further examination.

When operating with different samples it is important to achieve consistent and reliable results. Using European standards in the tests ensures a unified method and a better result. Sandvik has a large database with different materials from all over the world. Three different measurements and properties are the goal for the tests; crushability (Work Index, WI), abrasiveness (Abrasion Index, AI), particle size distribution.

When samples first arrive to the laboratory it is important that the moisture is reduced to a minimum, therefor the wet samples are dried in an oven according to standard for at least 8 hours. The second step in the test procedure is to measure the samples density by help of a scale and Archimedes principle. A test run usually starts with a Work Impact Index analysis.

Work Index is a parameter in comminution, which describes the materials resistance to grinding and crushing. The theory was developed by Fred C. Bond in 1951and is a derivate from two earlier theories by Rittinger and Kick xx. "According to this theory, the work input is proportional to the new crack tip length produced in particle breakage, and equal the work represented by the product minus that represented by the feed. In particle of similar shape, the crack tip length is equal to the square root one-halt the surface area, and the new crack length is proportional to 1/√p-1/√f." W is calculated with the equation:

$$W = 10W_i(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}).$$ Equation 1: Work Impact Index.

Impact Work Index (WI) is calculated according to standards and in Sandvik's test lab a Pendulum Impact tester is used, see appendix 2, and was done for the first time in Svedala 1966. The principle is to test a quantity of similar samples of such measurements to fit the template. These are placed between two hammers of known weight and the stone is smashed between at a known drop angle. The angle is then raised until 20 percent of the stone has been separated from original sample. The kinetic energy is then calculated and the Impact Work Index can be computed.

Abrasion Index is a measurement for indication on how much a rock will wear on steel and to estimate a wear part life. The test method was first developed by Pennsylvania Crusher CO in 1950 and later on enhanced by Bond in 1956 and was conducted for the first time in Svedala 1968. The test involves a spinning drum, a Cr-Mo-Ni Special Alloy paddle, a precise scale and for different samples of equal weight. The total weight of the sample should be equal for each different material and is hence adjusted with a factor and the density. Each sample is between 12.5- 19 mm in particle size and is placed inside the drum for 15 minutes. The paddle is attached inside the drum and rotating at a higher speed (about 10 times higher). To be able to calculate the AI the paddle is weighted with high precision.

To plot a particle size distribution curve it is necessary to screen the material. Depending whether it is feed or product different sizes on the screens will be used, for feed larger and product finer. The

material is to be screened a sufficient time until the sample is considered fully separated and the sample is weighted and the different fractions are summed up to reach full weight. The result will be shown in a plotted particle size distribution curve later used in PD.

3.3 The Generic Production Cost Model
3.3.1 Generic Production Cost Model

A concept, and a possible successor to Lean Production, is Next Step[17], mainly developed by Ståhl, professor at Lund University. Ståhl emphasizes the connection between economy and technology as the most important factor for success.

By using an easy to use, yet very advanced, cost-model for calculating the part cost the goal is to break down the part-cost to be able to identify all the different parts of the costs and exactly what causes them. For example one can identify the cost of downtime, and how it affects the total part-cost compared to other factors. Other important factors are for example cost for material waste and setup times.

Another key in the Next Step concept is to involve operators in a more extent way, so that they get a better understanding of the production. With more understanding the goal is to get the operators more involved in which areas the improvements to the production will have the best effect and how it might affect the part cost.

In order to establish this link between the technology and economics, Ståhl emphasizes the importance of setting up manufacturing goals. Goals that will take advantage of the benefits from the cost model and make it a powerful tool for increasing company development.

The generic production cost model is a macroeconomic model[18] used to calculate the production cost per part, below presented in its original state.

$$
k = \frac{k_B}{N_0} \left[\frac{N_0}{(1 - q_Q)(1 - q_B)} \right]_b + \frac{k_{CP}}{60 N_0} \left[\frac{t_0 N_0}{(1 - q_Q)(1 - q_P)} \right]_{c1}
$$
$$
+ \frac{k_{CS}}{60 N_0} \left[\frac{t_0 N_0}{(1 - q_Q)(1 - q_P)} \frac{q_S}{(1 - q_S)} + T_{su} + \frac{1 - U_{RB}}{U_{RB}} T_{pb} \right]_{c2}
$$
$$
+ \frac{k_D}{60 N_0} \left[\frac{t_0 N_0}{(1 - q_Q)(1 - q_P)(1 - q_S)} + T_{su} + \frac{1 - U_{RB}}{U_{RB}} T_{pb} \right]_d
$$

Equation 2: Generic Production cost model[18].

K is the production cost per part [SEK/part]. In order to get this cost, all four different terms has to be calculated.

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[17] Industriella Tillverkningsystem Del ll, 2011
[18] Development of Manufacturing Systems, 2013

3.3.1.1 Material cost term; *b*

Accounts for the material cost per part. k_b is the cost for raw material used for one part. N_0 is the nominal batch size which is divided by *(1-q_b)*, where q_b is the material spill rate, and *(1-q_Q)*, where q_Q is the scrap rate. Material spill occurs if parts of the raw material used for one part is removed during the process of getting the finished part. Scrap is when a whole part must be discarded for some reason.

3.3.1.2 Machine cost during production; term *c1*

Deals with the cost for the machines, when running, for one part. k_{CP}, is the hourly cost for machines during production. t_0 is the ideal cycle time per part which is multiplied by the nominal batch size and divided by the scrap rate and *(1- q_P)* where q_P is the production loss rate which occurs when a machine is working with reduced speed for some reason.

3.3.1.3 Machine costs during downtime; term *c2*

Is the cost per part, for machines during downtime. As an example when machines are down due to breakdown, maintenance or setup. k_{CS} is the hourly cost for machines during downtime, it is almost the same as k_{CS} but does not include variable costs like electricity to run the machines. t_0 and N_0 are multiplied with the downtime rate q_s and divided by *(1- q_Q)*, *(1- q_P)and (1- q_P)* and added to all this, before multiplied with k_{CS}, is the setup time for a batch T_{su} and $T_{su}*(1-U_{RB})/ U_{RB}$ and. $T_{su}*(1-U_{RB})/ U_{RB}$ which is the free capacity of the manufacturing facilities calculated using the degree of utilization, U_{RB} and the time it takes to produce one batch, T_{pb}.

3.3.1.4 Payroll costs; term *d*

Is the cost per part in terms of wages and other staff expenses?

3.3.2 The adapted Production Cost Model

In order to get the generic model applicable with the current processes of C&S for mining and construction a lot of parameters in the model must be changed and adapted. One major concern is the fact that the generic model presents the result in cost per part and mining and construction measures the final products by weight. The proposed adapted production cost model is presented below.

$$k_j = \frac{1}{PF_j}\left[[k_B \cdot PF_j]_b + \sum_1^i \frac{k_{CPi}}{M_0}\left[\frac{t_{mfi} \cdot pf_{ij} \cdot M_0}{(1-D_i)(1-q_{Pi})}\right]_{c1}\right.$$

$$+ \sum_1^i \frac{k_{CSi}}{M_0}\left[\frac{t_{mfi} \cdot pf_{ij} \cdot M_0}{(1-D_i)(1-q_{Pi})}\frac{q_{Si}}{(1-q_{Si})} + T_{sui}\right.$$

$$+ \frac{1-U_{RB}}{U_{RB}}\left(\frac{t_{mf} \cdot pf_{ij} \cdot M_0}{(1-D_i)(1-q_{Pi})(1-q_{si})} + T_{sui}\right)\bigg|_{c2}$$

$$+ \frac{k_D}{M_0}\left[\frac{t_{mfS} \cdot PF_j \cdot M_0}{(1-D_S)(1-q_{Ps})(1-q_{Ss})} + T_{suS}\right.$$

$$\left.+ \frac{1-U_{RB}}{U_{RB}}\left(\frac{t_{mfS} \cdot PF_j \cdot M_0}{(1-D_S)(1-q_{Ps})(1-q_{Ss})} + T_{suS}\right)\bigg|_d\right]$$

<p style="text-align:center">Equation 3: Adapted production cost model.</p>

In the following paragraphs this proposed model is described along with relevant changes made.

3.3.2.1 Cost per metric ton of product j; kj

When doing analyses on the production cost for mining and construction it was early on found that the generic model would not be sufficient for this application. One reason for this is the fact that there often is a presence of multiple products at a C&S-plant, at least in construction. The generic model is made for a production system with only one product and to make to work for the current application changes were needed.

The goal was to be able to choose either product at a plant and to present the cost for this particular one. Two things were altered from the generic model; the most important issue was how to distribute the different costs between the different product fractions. To make the cost distribution fair it was decided to look into the flow for each product fraction in every stage of the process. PF_j is defined as the fraction of one product fraction j at the end of the process. For example, consider two products and that one ton of raw material is run through the process and from this one ton there is 650kg of product one, that will lead to a PF_1 of 0,65 and hence to a PF_2 of 0,35. The sum of this factor is equal to one and can be found in material cost term b and personnel cost term d and distributes these costs in desired way on to the different products.

The second issue was how to distribute the machine costs in a good way. The decision was to find the ratio of each product in every machine and through this divide the cost on each product fraction. This is done by monitoring the distribution of particle size through every machine in the process, and thus makes every product account for as much of the machine cost as it is utilizing each machine. These factors are called pf_{ij} and is denoted as the flow of product j in machine i.

When doing like the previous paragraphs propose, the cost of a product is presented as a ratio of one metric ton, and in order to get the cost per ton the whole cost must be divided with PF_j which can be found at the very beginning of the proposed model. An important thing to remember is that when having multiple products is the difficulty to compare one product cost with another straight off. It is important to remember that all products are related to each other through specific ratios. For example, if two products are processed one ton of product one also brings a certain amount of product number two which also accounts for a cost per ton and cannot be neglected. It is thus important to have all the products in mind when performing these calculations to present a valid result.

3.3.2.2 Cycle time t_0

Another example where changes need to be made is the cost for machines, which is defined as the cycle time t_0 multiplied by the hourly machine cost k_{CP}. A parameter, $t_{mf}=1/m_f$ that is introduced, represents the time for processing one metric ton of raw material where the material flow m_f is described in metric tons per hour. This resulted in the replacement of the parameter t_0 being replaced by t_{mf} and the result ends up to be a cost per metric ton, which was the original intention.

3.3.2.3 Batch size N_0

The batch size is present in all terms in the generic model and must be changed since mining and construction products are measured by weight and not in number of parts. The solution chosen was to switch N_0 for M_0 which is defined as one metric ton of raw material entered in the process. In mining processes there is often a single product and then the batch size is of minor importance since the production will remained with the same settings. Thus have M_0 been set to 1 in calculations regarding mining processes. In construction processes will the batch size inflict when the production is set up between different products and therefor it is interesting to examine the effect of set up times.

3.3.2.4 Material spill rate q_B

Since C&S in general does not separate material from a main product but rather only downsize entered material into different fractions there is no material spill rate to consider except for a few ppm that disappears as dust. C&S deals with great weights and volumes and most products command a value, either positive or negative, they all need to be accounted for. Due to this fact the choice was to remove the spill rate in the proposed model.

3.3.2.5 Reject rate q_Q

There are no rejects in mining and construction, a product cannot be destroyed or be required to be scrapped. In some cases there is material, such as sand or gravel of some kinds are considered scraps. But they still command a value, a negative one and is considered a product that is already accounted for. This has led to the removal of the reject rate in the proposed model.

3.3.2.6 Production rate loss q_P

The production rate loss in C&S is very difficult to monitor without information systems or long time observations. Due to the limited access to these possibilities the decision was made to set the rate

losses equal to zero. An assumption that is far from reality but focus has been put on other parameters where more information has been available and should not impact the results too much.

3.3.2.7 Balancing losses D

An important parameter in C&S processes is the presence of balancing losses. Balancing loss is defined as the downtime due to a previous station, caused by different cycle times. An example is when a crusher is waiting for material from a slow feed. Crushers are designed to run at maximum capacity when running, it is either down or running at 100 % of capacity. However the aim is to have a grade of utilization for a crusher at around 80 % depending on which step in the process it belongs to, for example the grade of utilization should be high, preferably close to 100%, at the last crushing stage.

3.3.2.8 Multiple stations

The generic model is designed to focus on the steering station, or bottleneck, of the process. This means that all calculations are based on this station and all other stations are adapted to this one. In order to increase the accuracy and quality of the results in this thesis the decision was made to make calculations for each station or machine in the process. This means that both term *c1* and *c2* will be changed into the sum for all stages in the C&S process. By making these changes it will lead to more precise information being available, making the results even more accurate than with the generic model.

3.3.2.9 Description of cost model parameters

k_{CP} is denoted as the cost for operating a station or machine during processing. It includes costs only for uptime. It is defined according to the following equation:

$$k_{CP} = \frac{a_f K_0 r_a \left(1 + \overline{k_{ren}} N_{ren}\right) + Y k_y + T_{plan}\left(\frac{k_{UHh}}{h_{UH}} + k_{ph}\right)}{T_{plan}}$$

Equation 4: Operating cost for a machine or station during uptime, adapted production cost model.

Where a_f, the annuity factor is calculated with the following equation:

$$a_f = \frac{p(1+p)^n}{(1+p)^n - 1}$$

Equation 5: Annuity, adapted production cost model.

Where p is the internal rate and n is the expected technical lifetime.

K_0 is the original investment, including costs for transportation, installation and all other costs associated with getting new equipment operable.

The original model does not take into account any form of residual value of the equipment. In many cases in high-tech industrial companies' equipment is sold when the economic lifetime has passed. To take into account the residual value it was decided to insert a residual value factor r_a into to the k_{CP} and k_{CS} calculations. Through interviews it was decided that it was possible to get around 15 % back of the original investment cost after the expected lifetime of both screens and crushers. With

this knowledge the residual value factor r_a was denoted according to the following equation using the present value method:

$$r_a = \left[1 - \frac{r_{\%}}{(1+p)^n}\right]$$

Where $r_{\%}$ is the residual value in percent of the original investment, p is the internal rate and n is the expected technical lifetime. Using this factor gives a better connection to reality and a more valid production cost per metric ton.

$$\overline{k_{ren}} = \frac{\sum_1^{N_{ren}} \frac{k_{renk}}{(1+p)^{n_{renk}}}}{K_0 N_{ren}}$$

This is the average cost for a renovation based on all renovations done during a machines lifetime. It is calculated as a fraction of the original investment and N_{ren}, an integer of the number of renovations done during the machine lifetime. It is calculated according to the following equation:

$$N_{ren} = integer\left(\frac{n\frac{T_{plan}}{h_y}}{n_{syren}}\right)$$

Where T_{plan}/h_y is the planned production time per year, in hours, divided by the number of hours per shift per year. And n_{syren} is the number of shift-years between renovations.

Yk_y is the cost for the C&S plant or facility in terms of rent or depreciations.

$$\left(\frac{k_{UHh}}{h_{UH}} + k_{ph}\right)$$

This part of the equation is the maintenance cost per hour divided by the number of hours of operation per hour maintenance. Added to this there are the variable machine time costs, which consists of cost for electrical consumption etc.

After adding all the uptime costs for the equipment the total cost is divided by the planned production time per year, hence presenting the cost per metric ton product.

k_{CS}, or the machine costs for downtime is denoted according to the following equation:

$$k_{CS} = \frac{a_f K_0 r_a \left(1 + \overline{k_{ren}} N_{ren}\right) + Yk_y}{T_{plan}}$$

The cost for downtime consists of the exact same parameters as the cost for uptime except for the last term that is removed.

The cost parameter K_D is the costs for all personnel connected with the plant at hand. It includes costs for salary, social security costs and holiday compensation. The parameter is presented in the equation below:

$$k_{D=\frac{n_{op}l\ddot{o}n(1+socavg)}{T_{plan}}}$$ **Equation 11: Cost of personnel, adapted production cost model.**

n_{op} is the number personnel connected to the production line, "*lön*" is their average salary and "*socavg*" is equal to the social security costs.

3.4 The creation of the adapted Production Cost Model in MathCad

A significant part of this thesis, in addition to the creation of the adapted production cost model, is the creation of a fully working cost model in Mathcad. The purpose of this model is to be fully functional and easy to change input in order to get valid results from different C&S plants. The work behind this is substantial with a lot of theory behind. In this section all calculations and things concerning creations of working equations and simulations are brought up for each of the cost terms.

Within mining and construction it is often difficult to determine exact figures on different parameters since the processes are very comprehensive and complex. Hence a selection of parameters with high insecurity and great fluctuation was made, listed and simulated with available data. All cost terms are brought up below along with the parameters simulated using Monte Carlo simulation.

3.4.1 Cost term b, Raw material

Before entering the crushing and screening stage the raw material is drilled, blasted and transported. The costs for these operations are not always easy to put exact figures on and have a large impact on the total production cost for crushing and screening. Thus it was decided to use Monte Carlo simulation on this parameter.

The cost for raw material has a large impact on the production cost for C&S but is not very complex to get hold of. This cost has been recovered through interviews of both internal staff at Sandvik as well as staff at the local C&S sites. As mentioned earlier generally C&S does not separate main product from waste material but rather downsize the entered material the entered material and the finished product has a ratio of 1 to 1. This lead to that the calculation of raw material cost was easy and just entered as cost per metric ton. But there were questions raised regarding the validity of the attained costs for raw material. Therefor it was decided to simulate this cost, to make up for wrong estimations of this cost.

The simulations were carried out by creating a simulation tool in Mathcad, Weibull distribution was used and in the figures 6, 7 and 8, below a Monte Carlo simulation is presented along with descriptions of the calculations.

SIMULATION FOR RAW MATERIAL (KB)

$n_R := 2000$ Number of simulations $y := 50$ Number of classes in histogram

Determination of statistical parameters

Given

$x := 0, 2 .. 1500$

$G_{max} := 0.99$ $G_{min} := 0.01$ G_{max} represents 99% (0.99) probability the the cost for raw material falls below KB_{max}. G_{min} represents 1% (0.01) probability that KB falls below KB_{min}.

$k_{Bmax} = \beta \cdot \left(-\ln\left(1 - G_{max}\right)\right)^{\frac{1}{\alpha}}$

Equation system with 2 unknown parameters.

$k_{Bmin} = \beta \cdot \left(-\ln\left(1 - G_{min}\right)\right)^{\frac{1}{\alpha}}$

Weibull distribution where "z" as a function of probability in the case where z = K_0.

$\begin{pmatrix} \alpha_{k.B} \\ \beta_{k.B} \end{pmatrix} := \text{Find}(\alpha, \beta) \rightarrow \begin{pmatrix} 6.68710111999126265543 \\ 19.895605881721757846 \end{pmatrix}$

Solving of the equation system

Value of α and β respectively

Definition of vectors for raw material

$k_{BW} := \text{runif}\left(n_R, 0, 1\right)$

Built in function to generate a random number between 0 och 1.0

$j := 0 .. \text{last}\left(k_{BW}\right)$ Range-variabel, integer from 0 to the position for the last value in the vector k.BW = n_R -1

$k_{B_j} := \beta_{k.B} \cdot \left(-\ln\left(1 - k_{BW_j}\right)\right)^{\frac{1}{\alpha_{k.B}}}$

$k_{Bs} := \text{sort}\left(k_B\right)$ $S_{k.B_j} := \dfrac{j}{n_R}$

Figure 7: Determination of statistical parameters and definition of vectors, Mathcad.

Creation of frequency Histogram and Distribution graph

$H_{k.B} := \text{histogram}\left(y, k_B\right)$

$e_{k.B} := \dfrac{n_R}{y} \cdot \left(\max\left(k_B\right) - \min\left(k_B\right)\right) = 341.351$

$k_{Bm} := \text{mean}\left(k_B\right) = 15.248$

Figure 8: Creation of frequency histogram and distribution graph, Mathcad.
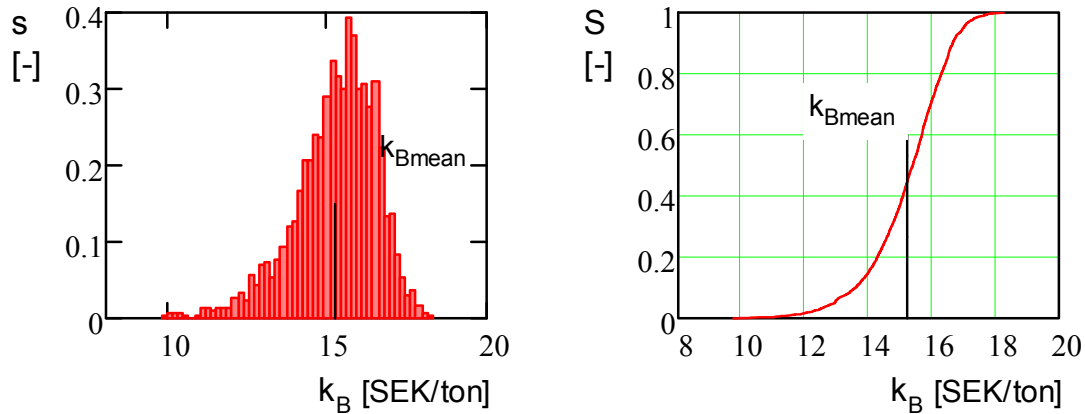
Figure 9: Frequency histogram and distribution graph, Mathcad.

The number of simulation points was chosen to 2000, fewer point leads to a discontinued probability curve and more points does not improve the result, only demands better computer hardware. 2000 simulation points provides smooth results in both the histogram and probability function. The number of classes in the histograms was chosen to be 50 in order to get good visual results. These numbers were consequent throughout all the simulations carried out. The decision was also to perform the calculations with a 95 % certainty.

In the definition of vectors for raw material section a 2000 long vector of draws from the Weibull distribution are sorted in the section and a distribution function is created. After that a normalized histogram is created through dividing the histogram function with range of simulation outcomes multiplied by number of simulation points and divided by the number of classes in the histogram. Along with the histogram a probability function is presented.

Similar simulations have been carried out for the rest of the parameters chosen for simulations in the other cost terms.

3.4.2 Cost term d, payroll costs

Cost term d contains many different parameters and it is showed below as it is calculated in the adapted production cost model.

$$\frac{k_D}{M_0} \cdot \left[\frac{t_{mfS} \cdot PF_j \cdot M_0}{(1-D_S)(1-q_{Ss})} + T_{su} + \frac{1-U_{RB}}{U_{RB}} \left(\frac{t_{mfS} \cdot PF_j \cdot M_0}{(1-D_S)(1-q_{Ss})} + T_{suS} \right) \right]_d$$

Equation 12: Cost term d, adapted production cost model.

At first there is K_D which is the hourly cost for staff connected to the C&S operations. This hourly cost is calculated according to the following equation:

$$k_D = \frac{\left[n_{op} \cdot l\ddot{o}n(1 + socavg) \right]}{T_{plan}}$$

Equation 13: Cost of personnel, adapted production cost model.

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Where n_{op} is the number of operators working with C&S and *lön* is the average yearly salary of an employee. These two numbers are multiplied by (*1+socavg*) where *socavg* is social fares[19] in addition to salary, like payroll taxes. This number is then divided by T_{plan}, the total number of yearly planned production hours. This presents the total cost for the whole C&S staff.

In order to get the salary cost in the desired unit, cost per metric ton, the rest of cost term is needed. The term t_{mfS} earlier described as the time for processing one ton of material at the steering station. This parameter is received from the simulation software PlantDesigner after creating a plant with correct equipment setup and raw material properties. This time for the processing of one metric ton is divided by (*1-D_S*) where the balancing loss for the steering station also is obtained from PlantDesigner. The downtime for the steering station q_{sS} is very difficult to obtain without advanced information systems or observations over a long period of time. Therefore it was also simulated and the max and min values used were obtained through interviews.

Setup times T_{su} occur from time to time but are hard to monitor without information systems and they account for such a small amount of the total planned production time and hence it has been decided to have all setup times equal to zero.

Regarding the grade of utilization due to demand U_{RB} it has been decided have it equal to one. Through interviews it has been found that the production is almost consequently aimed at a maximum level and that over production due to low demand is very rare i.e. the production is always aimed to be at a maximum level.

The above paragraphs lead to the fact that the second part of the cost term d is equal to zero and can thus be neglected.

One parameter in payroll costs that has the potential of variations is the material flow in metric tons per hour for the steering station. Two other parameters chosen for simulation were balancing losses D and downtime q_s, both for the steering station just like the material flow.

3.4.3 Cost term c1 and c2, Cost of machines during production and downtime
The main machines used for C&S are crushers and screens and a parameter that is very difficult to determine is the technical lifetime of the machine. Many things have a great impact on the lifetime, such as particle size distribution, machine load, environment and service. The cost terms in the adapted production cost model regarding K_{CP} and K_{CS} are the following:

$$\frac{k_{CPi}}{M_0}\left[\frac{t_{mfi} \cdot pf_{ij} \cdot M_0}{(1 - D_i)}\right]_{c1}$$

Equation 14: Cost term c1, adapted production cost model.

[19] http://www.finfa.se/Avtalad-forsakring/Arbetsgivarens-ataganden/Vad-kostar-det/

$$\frac{k_{CSi}}{M_0} \left[\frac{t_{mfi} \cdot pf_{ij} \cdot M_0}{(1 - D_i)} \frac{q_{Si}}{(1 - q_{Si})} + T_{sui} + \frac{1 - U_{RB}}{U_{RB}} \left(\frac{t_{mf} \cdot pf_{ij} \cdot M_0}{(1 - D_i)(1 - q_{si})} + T_{suS} \right) \right]_{c2}$$

<div align="center">Equation 15: Cost term c2, adapted production cost model.</div>

Another important parameter identified based on the impact for current processes is balancing loss. alancing losses vary significantly and was as a result chosen to be one of the parameters simulated.

$$k_{CPi} = \frac{a_f K_0 \left(1 + \overline{k_{ren}} N_{ren} \right) + Y k_y + T_{plan} \left(\frac{k_{UHh}}{h_{UH}} + k_{ph} \right)}{T_{plan}}$$

Equation 16: Operating cost for machine or station i during uptime, adapted production cost model.

$$k_{CSi} = \frac{a_f K_0 \left(1 + \overline{k_{ren}} N_{ren} \right) + Y k_y}{T_{plan}}$$

Equation 17: Operating cost for machine or station i during downtime, adapted production cost model.

The two contents of the equations are the same except for the part with the variable costs during production, with costs for energy consumption for example. The annuity factor a_f is calculated with the following equation:

$$a_f = \frac{p(1 + p)^n}{(1 + p)^n - 1}$$

Equation 18: Annuity, adapted production cost model.

The annuity factor varies with cost of capital p and the lifetime n. The cost of capital varies between different companies but can be said to be around 10-15 %. Through interviews and other information sources it was decided that the lifetime for a crusher varies between 8 and 30 shift years and a screen between 2 and 7 shift years. The simulations led to two figures for the machine lifetime were decided to be used for all of the machines of the specific kind. Meaning that all crushers each had the same lifetime which was simulated, the same principle was used for the screens.

In addition to the lifetime of the equipment and the balancing losses, the cost for renovation k_{ren} was chosen for simulation. The reason for this was the difficulty of finding old data for renovation costs, only costs for one crusher was available. The decision was therefore to simulate a renovation cost per year for this machine and then divide it by the original investment to get a fraction that was later used for the other crushers correlated to each original investment respectively. Through interviews and data search it was decided that the renovation and service cost was around 20-30% of the original investment for screens.

The parameters $Y \cdot k_y$ and T_{plan} were acquired through interviews at the local C&S sites.

As mentioned in earlier sections the cost during production and the cost during downtime were made for each piece of equipment to get a more accurate value. After building a formula for each piece of equipment they were summarized at the end to get the total cost.

3.5 Company visit; Company 1

This plant is often used by Sandvik for testing of their products and new technology. Therefor it was an easy plant to get access to to perform testing and sampling. The site itself is relatively small and the ability to acquire samples and adjusts the settings of the crushers is high. The site is a stationary mining site with only one product. The time was limited and the sample was acquired during a one day session. The aim was to gather material in order to verify and feed the PlantDesigner tool with real data. The site consist of three crushing stages; one primary jaw crusher, one secondary S-type cone crusher and two tertiary cone crushers, Vibrocone and H-type. The site accounts for five screens, including grizzly feeder, which in total is nine machines, see appendix 3. At this specific site there was only one product so the ratio between feed and product was equal to one. The analyzed facilities were all located at the production site.

The tests were undertaken before and after the Vibrocone, with different setups. Additional input to PlantDesigner is received from historical, but relevant, sample sessions. The tests follow previously mentioned standards and guidelines and the results were sent to Svedala for analysis. During the site visit an interview were conducted with the crush manager, see appendix 5. The results from the laboratory analysis were fed to PlantDesigner and the process was simulated in the program. The figures attained from the simulation tool combined with the information received from interview and other additional information sources were fed into Mathcad and the proposed production cost-model. Some information did not reach desire reliability level and were therefore simulated with Monte Carlo simulation. When all information was obtained and presented in an appropriate manner the cost was calculated using the proposed production cost model.

3.6 Error Sources/Validity of information

The C&S processes are complex and few studies like this have been made before. These processes vary with so many external and internal factors. External factors such as raw material properties, like moisture level, Work Index, compressive strength can for example make huge impact on the lifetime of the equipment by years. Internal factors such as settings on the equipment make huge impact on the processes, such as material flow rate and other parameters. Many error sources and questionable sources of information can be identified through this process. Due to the limited time and extent of the thesis and the handing of huge amounts of data and information many information sources had to be accepted as is. Below these sources are listed along with an estimation of their validity.

3.6.1 Software

3.6.1.1 PlantDesigner

PlantDesigner is, as mentioned earlier, simulation software used both internally at Sandvik as well as by their customers. The results from PD are no exact values and are based on years of testing, data and experience. The results are far from reality, for example when rock has been drilled and blasted the particle size distribution is very different from the beginning and the end of the blasting round. PD makes a number of simulations until the process reaches a steady state to present viable information for the user. It can be said that PD is advanced software with a lot of useful information. However the results cannot be taken as exact, but is the only information provider available for acquiring this kind of process information.

3.6.1.2 MLOC

Machine Lifetime Operation Cost[20] is software developed by a team of experts from different areas. As a tool to calculate the lifetime costs it acts as a good indicator but the extracting of decisive numbers is connected with problems. The values extracted from MLOC are simulated, simulations based on expertise and experience at Sandvik.   In the production cost model MLOC was used to get data for k_{ren}. As earlier mentioned only one crusher's cost were available and therefor k_{ren} was simulated in Mathcad. The result is a simulation of simulated values and lowers the accuracy. It is very hard to estimate the lifetime costs since it is very dependent on the application. When operating in very hard materials is will increase the costs and vice versa when operating in more fragile materials. There are also many other uncertainty factors such as, location, machine failures and lack of operators expertise. Altogether the simulated value could be considered to be a good estimation for a general production cost model but each plant application could differ as previously shown in the increase or decrease in k_{ren}.

3.6.1.3Weibull Distribution

In this thesis it was decided to use the Weibull distribution. It can be discussed if this is the right distribution of use. Weibull distribution is often used to simulate lifetimes and breakdowns etc.[21]. This indicates that it could be discussed if it is applicable for all parameters used in the production cost model. There is other distribution such as Rayleigh distribution exponential distribution which could have been a better fit to some parameters simulated. Since focus lay upon the production cost model these areas have yet to been examined, but Weibull distribution is used in the comminution industry and for parameters much alike the ones in the model. Therefore the authors considered the distribution to be adequate for this project[22].

3.7 Methods of verification

There are many different ways to verify the production cost model and the results. It is an important step to compare the results attained from the model with previous methods or figures. This is a complicated part of this thesis. First of all there is a conflict of interest from the customer to reveal the costs of production in the C&S process. It could be difficult to attain exact figures and there is also an uncertainty in the way the costs are calculated and the result will therefor deviate. Previous methods in estimating the cost are not fully developed. Presented below are different methods of model verification.

3.7.1 Black Box

Black box testing is a very simple testing method often used when testing software.. In this project it is applicable to test if the costs attained from the production model will correspond to the costs attained from the interview at the site. First of all the boundaries of the black box are decided. Thereafter the input and the output are to be defined. In the case of crushing and screening the black box is considered to be all activities from input of raw material to output from the last screen in the C&S system.

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[20] Interview: Svennelid, Albin
[21] Sannolikhetsteori & statistikteori med tillämpningar, 2005
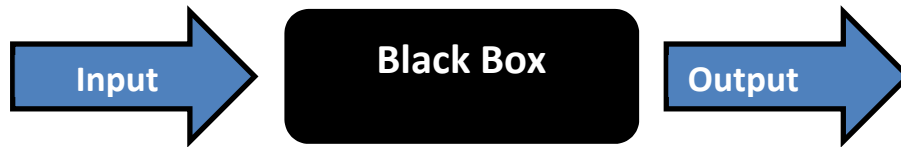[22] Applied Life Data Analysis, 2004

Figure 10: Black box verification model.

As mentioned the input is the cost of raw material and the output the total cost of the black box, added the raw material cost. This could provide a good indication of the models validity.

3.7.2 TCO Plantdesigner

There have been done some previous work regarding the cost of C&S. This resulted in a cost-module[23] in Plantdesigner and used a method called Total Cost of Ownership. It is a method to decide all cost associated to a product. The issue in using this TCO module is that is yet to be fully developed and the application have been used for limited number of plants.

3.7.3 Crushing and screening cost percentage

There is a possibility to compare the relation between the cost attained from the model and the cost from the Sandvik's rock processing manual. This could only act as an indication and should not be considered as precise comparison. As seen in the diagram below the C&S process accounts for 4 % of the mining costs. The Drilling & Blasting i.e. raw material costs accounts for 2 % of the total mining costs; this means a ratio of 1/3.
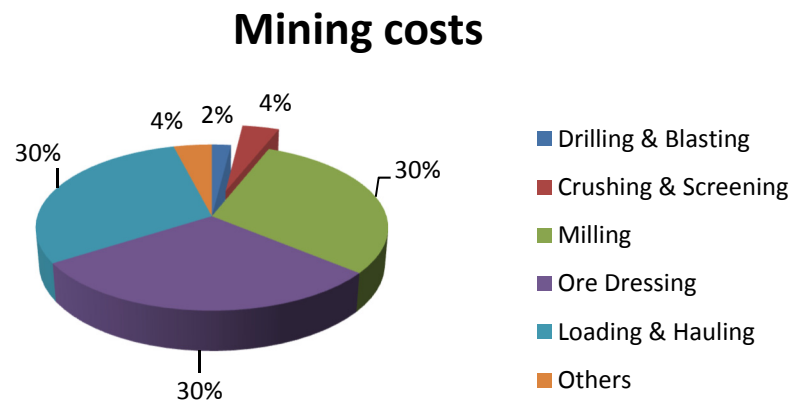
Mining costs

Figure 11: Split over quarrying costs, construction.

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[23] Crushing & plant optimization, 2012

4 Results

Presented in this chapter are the results from the calculations using the adapted production cost model at company 1.

4.1 Company 1

4.1.1 Cost for raw material

- **Mean cost of raw material k_B 15.25 [SEK/ton]**
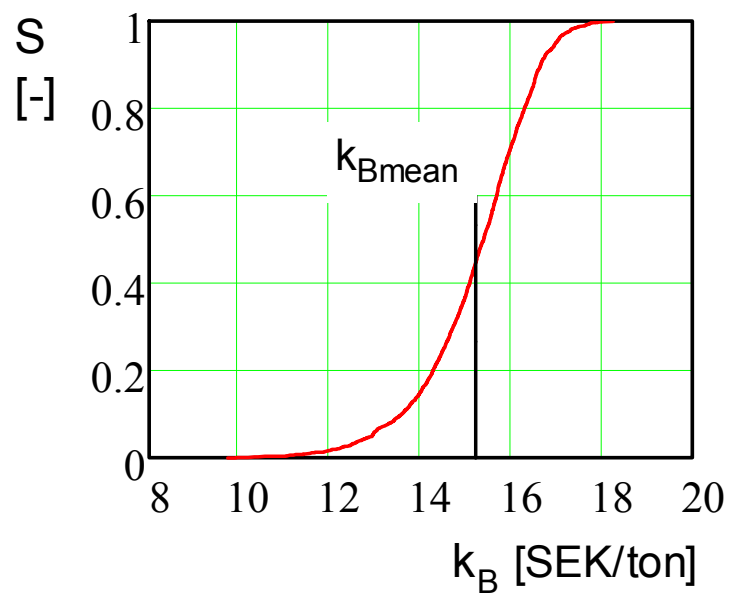
Figure 12: Distribution function of raw material cost represented by a Weibull distribution.
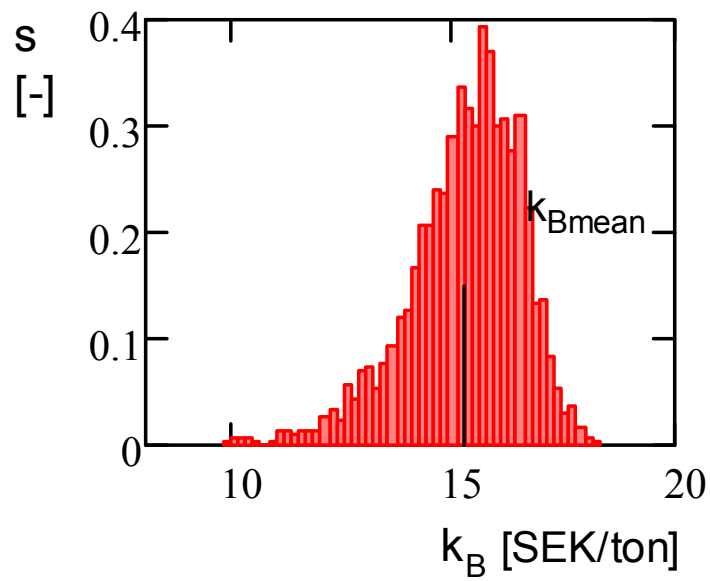
Figure 13: Distribution function of raw material cost represented by a normalized frequency function.

4.1.2 Payroll costs

- **Mean Payroll costs k_D 5.22 [SEK/ton]**
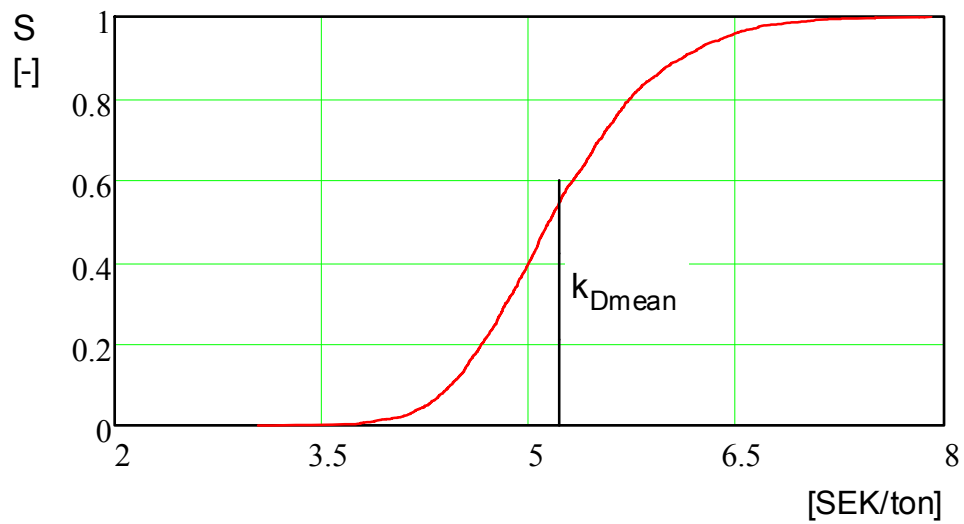
Figure 14: Distribution function of payroll costs represented by a Weibull distribution.
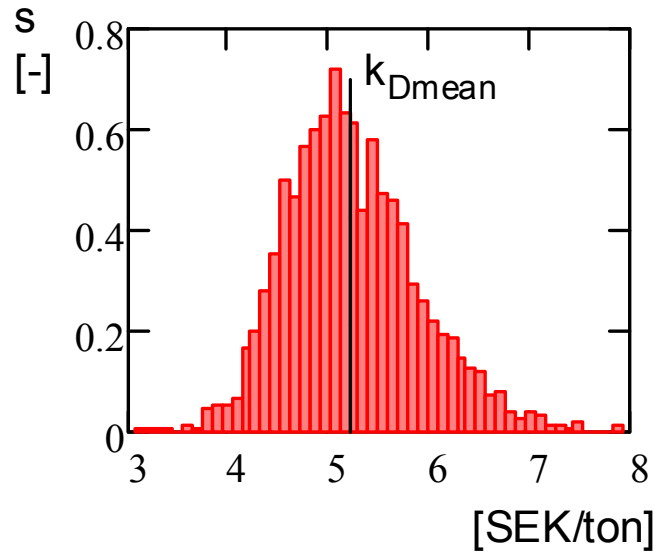
Figure 15: Distribution function of payroll costs represented by a normalized frequency function.

4.1.3 Machine costs during uptime

- **Mean machine cost during uptime 24.16 [SEK/ton]**
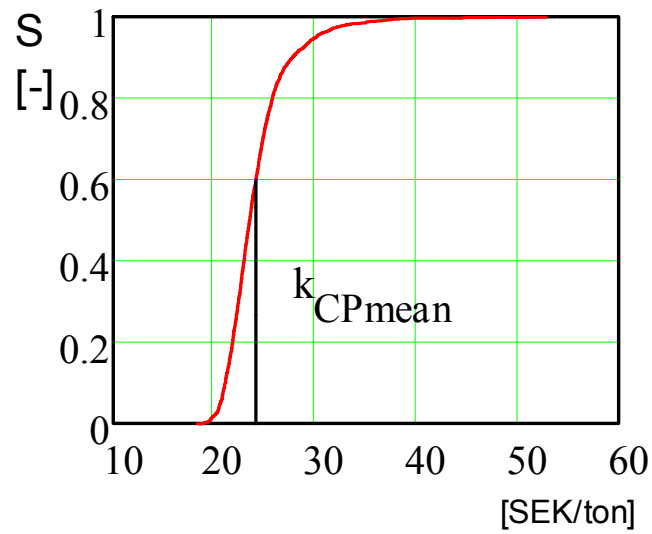
Figure 16: Distribution function of machine costs during uptime represented by a Weibull distribution.
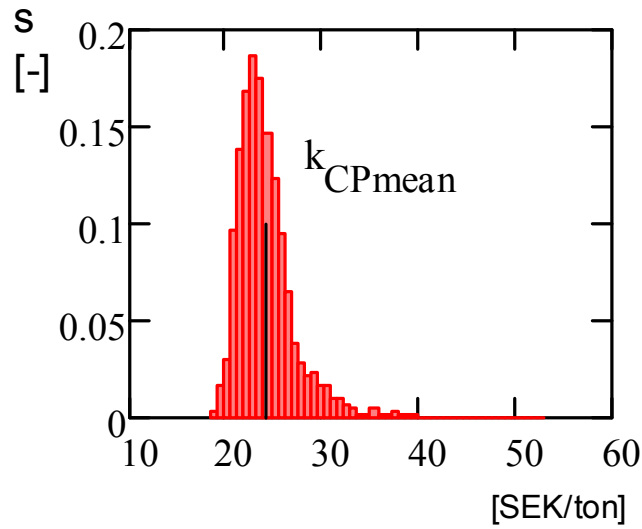
4.1.4 Machine costs during downtime

- **Mean machine cost during downtime 3.19 [SEK/ton]**
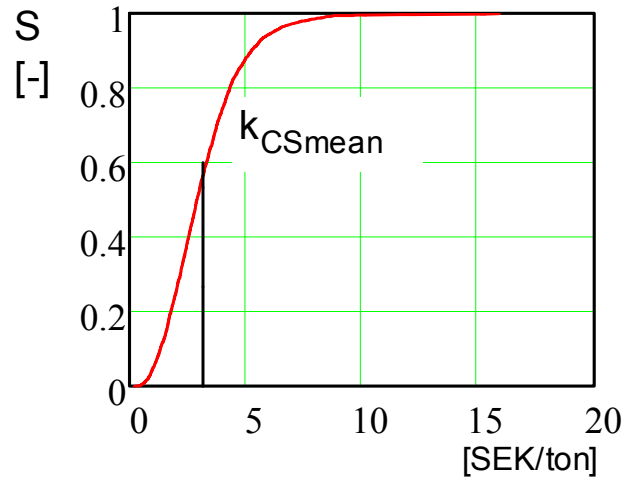
Figure 19: Distribution function of machine costs during downtime represented by a normalized frequency function.

4.1.5 Total production cost per metric ton processed material

- **Mean total production 47.82 [SEK/ton]**
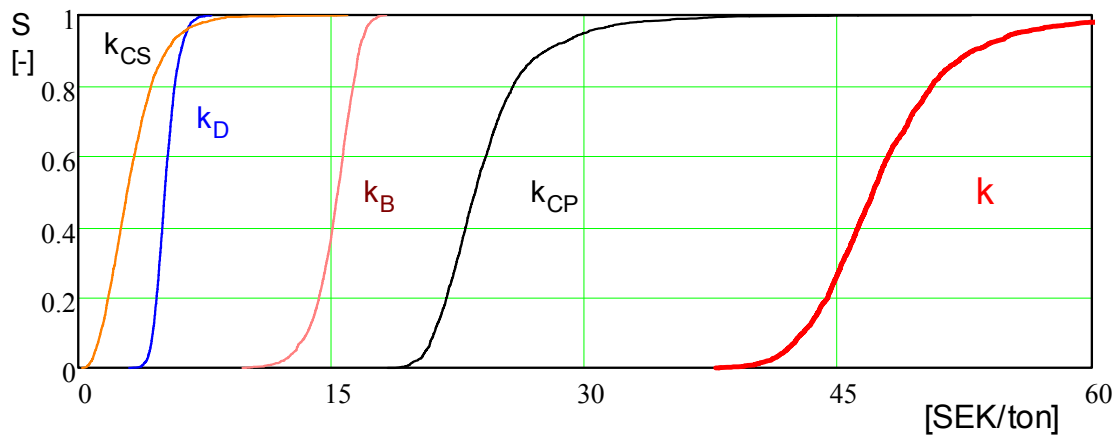
Figure 20: All cost term Distribution functions Weibull distributions with the total added cost at the far right.
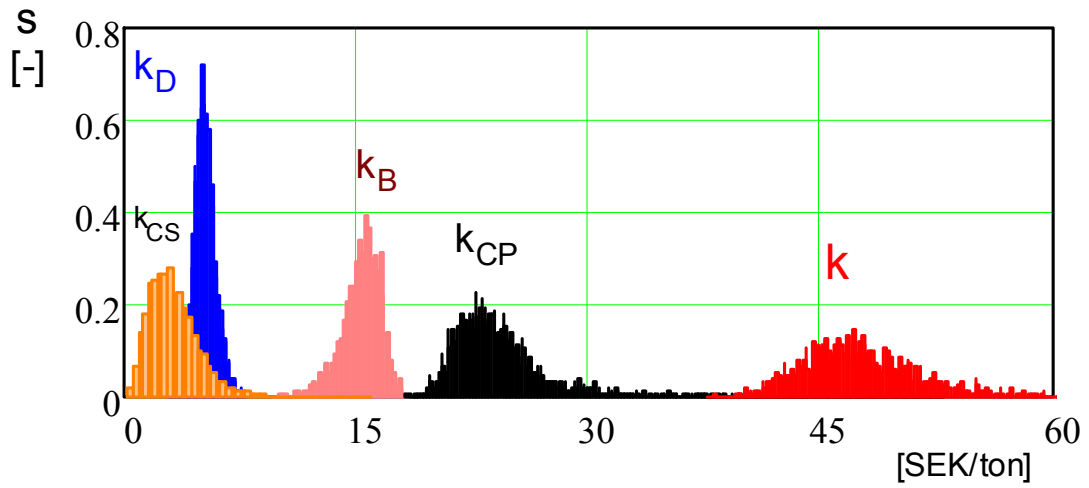
Figure 21: All cost term frequency functions Weibull distributions with the total added cost at the far right
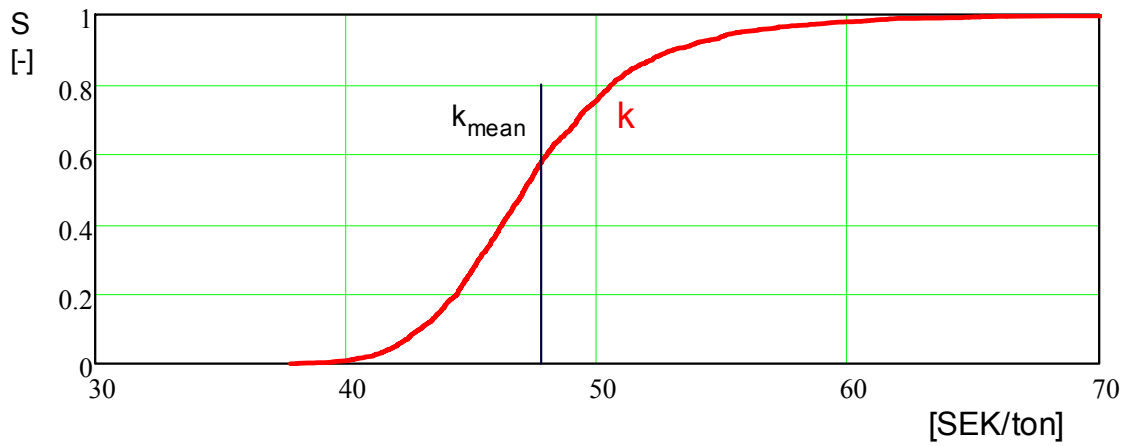
Figure 22: Distribution function of total production cost
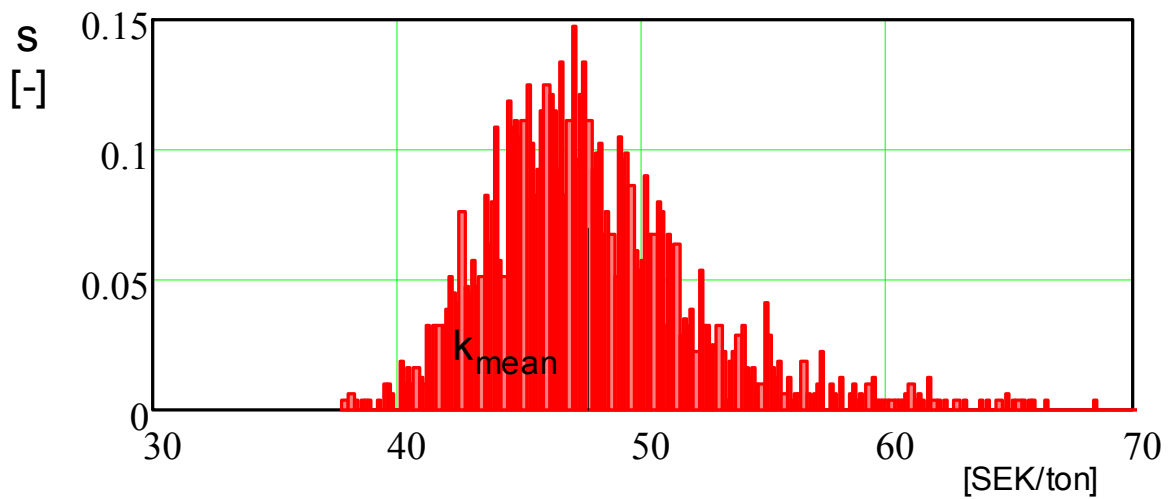
Figure 23: Frequency distribution of total production cost

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4.2 Sensitivity analysis

In the making of models, of any kind, it is always important to undertake sensitivity analyses. Since a large input data are based on Monte-Carlo simulations to enhance the result and the reliability of the model, this can be used as an uncertainly analysis. The main goal of a sensitivity analysis is to analyse how the output varies when certain input is changed. The strategy applied in this project is called one-factor-at-time[24] (OFAT) approach.

The main downside in using this method is that it does not show interactions between different factors. The relation between different factors is often very high since the whole systems are often connected and there are more advanced methods in analysing[25]. Due to the constraints and the time limit for this project, the authors have considered OFAT to be the most applicable method. In an OFAT analysis a baseline is chosen to act as a nominal value and thereafter one factor changed at a time. Not all variable are usually included in the analysis, but often the ones considered most important. The variable output can thereafter be presented and compared presented in visual manner.

In this project a couple of parameters were chosen to be analysed in order to see the models sensitivity. The baseline was set to be the Monte-Carlo simulated production cost obtained from the Mathcad software. The result was presented in a histogram but the outputs compared are presented as the mean value of total cost per metric ton. Ten different simulations were made when the parameters are alternated and the mean value of the production cost is presented as a percentage of the baseline value.

Parameters chosen:

- D, balancing losses.
- n_s and n_c, the lifetime of the equipment.
- K_0, original investment.
- p, internal rate.

4.2.1 D, balancing losses

When interpreting the model it was obvious that balancing losses or utilization grade had a big impact on the result. When alternating this value it was also possible to see the cost of balancing losses i.e. a possibility to improve the production line since in a perfectly ideal process the balancing losses could be minimized to zero additional information was the production cost when increased balancing losses. The value range between D=0 and $\lim_{D \to 1} D$.

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[24] Global Sensitivity Analysis, 2008
[25] Design and Analysis of Experiments, 2013
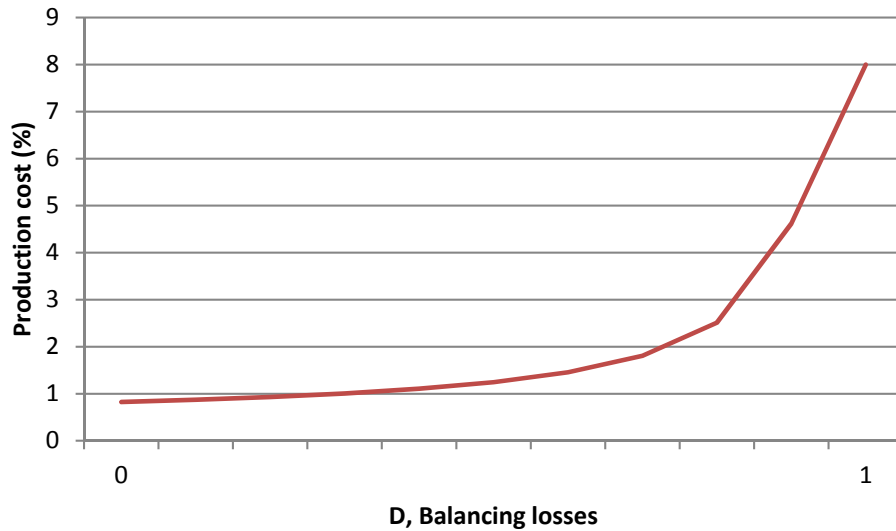
Figure 24: Sensitivity analysis of balancing losses.

As could be seen in the graph above, balancing losses have a large impact on the production cost. When minimizing the balancing losses the production cost can be reduced by up to 20 %. This could be considered to be a small percentage but in a sector with high volumes it represents a large cost saving. When balancing losses approach one, the cost increased and deviated to infinity. In a case of total downtime there will be no production and the cost of producing one metric ton of product was rising accordingly. All results could be considered an indication to validate the model.

4.2.2 n, lifetime

Lifetime was interesting because it affects the production to a large extent. It was also an interesting value to look at because it is related to the production quality, and it was interesting to see what would happen if the lifetime for example was to be increased or decreased two times. The decision was to make three separate analyses; first one with fixed screens lifetime and changing only the crusher's lifetime, then one the other way around and last one where both were changed. Conveyors were neglected since they only stands for a small part of the total production cost. The decision was to make a factor x_n and alternating this between $\lim_{x_n \to 0} x_n$ and 2, which means a percentage of simulated lifetime.

$$n_{C_j} = x_n \left[\beta_{n_C} \left(-ln \left(1 - n_{CW_j} \right) \right)^{\frac{1}{\alpha_{n_C}}} \right]$$

Equation 19: Lifetime sensitivity factor.
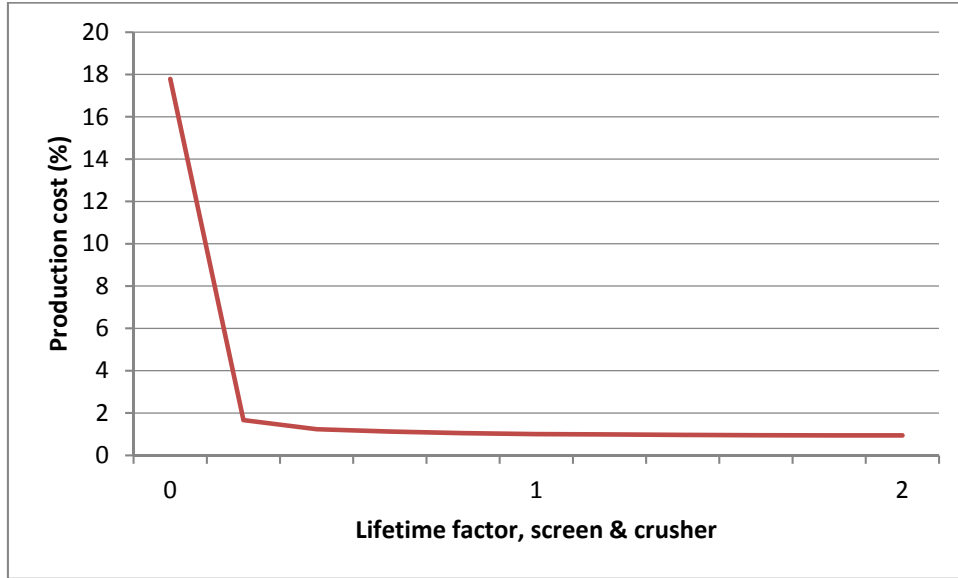
Figure 25: Graph of sensitivity analysis of lifetimes, n.

The graph indicates an approach to infinity when the lifetime is approaches zero. Off course when investments are made for equipment without lifetime the production cost will only increase. As the lifetime approaches 2 the production cost is below 1. The small decrease is explained with the annuity and that the sensitivity is made on simulated results.

4.2.3 K_0, original investment

The analysis was performed in order to investigate the outcome when the original investment for all equipment, was either reduced or increased. It could be valuable to know what would happen to the model and the production cost if suppose Sandvik would take a higher or lower price for their equipment. The sensitivity analysis was done as previously by introducing a new factor, x_K. The factor was inserted in both K_{CP} and K_{cs}. The value was alternated from 0 to 2.

$$KCP_J = \left[\frac{a_j K_0\left(1x_K + k_{ren}n_j\right) + Yky + T_{plan}\left(k_{ph} + \frac{k_{UHh}}{h_{UH}}\right)}{T_{plan}}\right]\left[\frac{t_{mf}}{\left(1 - D_j\right)\left(1 - q_p\right)}\right]$$

Equation 19: Original investment sensitivity factor, KCP**.**

$$KCS_J = \left[\frac{a_j K_0\left(1x_K + k_{ren}n_j\right) + Yky}{T_{plan}}\right]\left[\left[\frac{t_{mf}q_{s_j}}{\left(1 - D_j\right)\left(1 - q_{p_j}\right)\left(1 - q_{s_j}\right)}\right] + T_{su}\right]$$

Equation 19: Original investment sensitivity factor, KCS.
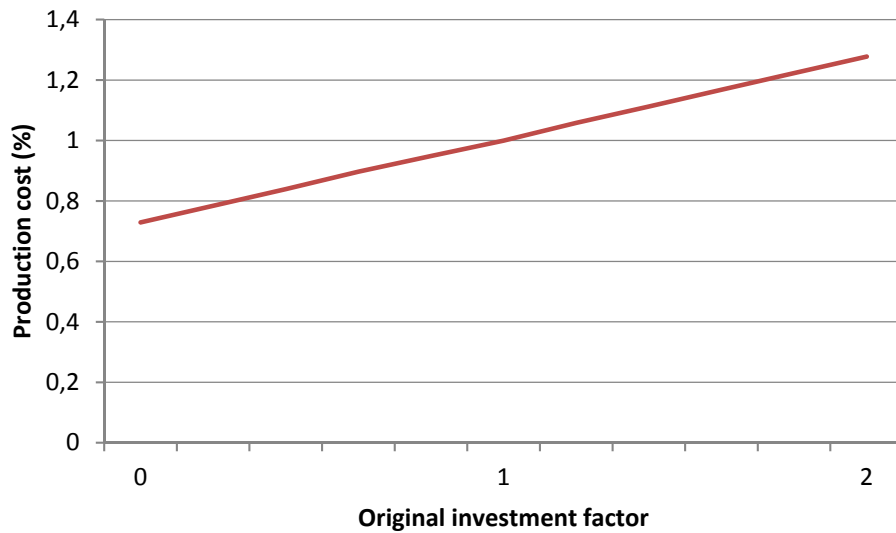
Figure 26: Graph of sensitivity analysis of original investment, K_0.

In analysing of the graph it was possible to extract the increase and decrease in production cost. This was a likely result and indicates the validity of the model. The production cost varies from 0.77 % to 1.27 % of the original production cost. This could was considered to be a reasonable value since all investments cost are multiplied with the annuity.

4.2.4 p, internal rate

The variation internal rate was interesting to examine since it has a big affection on the annuity and it is also a factor which is varied between many companies and industries. In this thesis it was chosen to 10 %. In this analysis the rate was alternated with plus/minus five percentages.
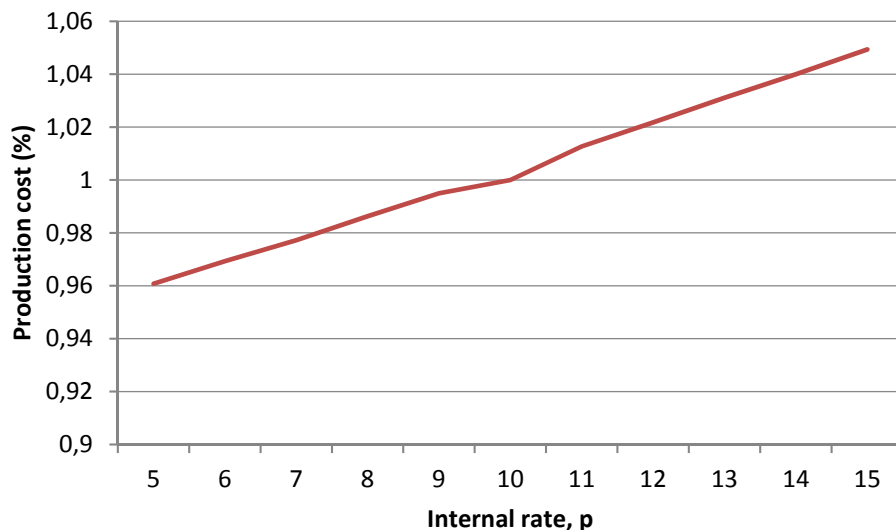
Figure 27: Graph of sensitivity analysis of internal rate, p.

As seen in the graph presented above the production cost only varies with up to 10 % when alternating the internal rate. The correlation is almost linear, and it is considered to be valid variation.

The conducted sensitivity analysis contains gaps and could be done in a more accurate and thorough way. Some on the indicated problems with the analysis are:

- The interaction between different parameters.
- More alternated parameters.
- Another approach and different method of analysis.
- Some of the analyses were performed on simulated value, which smoothen the results.
- There could be some interest in analysing the impact on parts of the equation, i.e. K_{CP} and K_{CS} to see the impact on these.

In the aim to further examine and analyse the model some of the above mentioned problems are recommended to take into consideration. This could lead to enhance the certainty of the result and further validation of the model.

5 Conclusions

5.1 The production cost
The total production cost of 47.8 SEK/ton is an interesting figure if you look into it. The figure received from company 1, was 18 SEK/ton for C&S operations plus the cost for raw material of around 15 SEK/ton ads up to a grand total of 33 SEK/ton for their calculations/estimations of the C&S costs. If company 1's cost is compared to the one acquired through this thesis there is difference of around 11 SEK. This can however be explained by the fact that company 1's costs does not include investment costs for the C&S equipment, which is the case in the adapted production cost model. To test the validity of the model the investment cost was removed and the total production cost was reduced to 31.93 SEK/ton, if the cost for raw material is deducted from that number you and up with a cost only for C&S of almost exactly the same cost as Company 1. This does not prove the validity of the model but it does place the results in an acceptable range.

Another reflection is that the whole proposed adapted production cost model was not tested entirely. The possibility to use the model at a construction C&S plant with multiple products was unfortunately lost due to lack of time.

5.2 Setbacks
One major setback in this thesis was that only one C&S plant vas visited and thus the model was only tested one time with real figures. The goal was to validate the model using one or two additional cases but due to the complex processes of getting data from Sandvik customers and the lack of time unfortunate led only to one plant visit.

5.3 Future work & possibilities
Although a lot has been achieved during this thesis it has only been a scratch on the surface. There are a numerous possibilities and areas of use for this new production cost model. There is a lot of room for improvement and changes in the future.

- **Increase level of user friendliness**

  One problem with the new model is the high level of complexity; it takes a lot of knowledge of it to be able to use it in a correct way. For the model to be successful there is a need for a simpler way of use, by now the model is in need of manual adaptation between different sites. The model is currently only created in Mathcad and demands a lot of work. One possibility is to create a script in Excel where all data needed could be entered easily and later imported into the model in Mathcad, which would be a much more efficient way of use.

- **Possibility for PlantDesigner implementation**

  In theory the model could prove to be a powerful tool for engineers at Sandvik when developing new projects or doing research on existing plants. The same goes for engineering houses and consultants. It would be a great way of getting a good indication of the operating costs for C&S.

- **Extended Sandvik professional sales tool**

  If the model was made to be easy to use and present the result in a visually appealing way it would be a great way of presenting costs for customers. For customers in this industry, where production costs are very hard to calculate, it would be a great sales pitch to be able to give them a good indication of probable production costs.

- **Adapt model to milling and ore dressing**

  The model could be extended and thereby applicable to some of the other areas in the mining and construction industries. Areas suitable for application are the milling processes and the ore dressing processes. An extension of the model over these areas would create an interesting connection between them and a lot of valuable information would be available.

Complementary work

Although very accurate results have been achieved during this thesis a few questions are still unanswered. The most relevant one is the validity of the model. It has only been tested at one site and for it to be considered viable it is in need of further testing. For example there has been no testing of the possibility of multiple products. Our recommendation of future work will be the following, preferably through another master thesis:

- · Test at a mineral site with high grade mineral ore.
- · Test at two construction sites with multiple products.

If this would be done a much more fair evaluation of the model and its validity could be done.

5.4 Final words

At last it can be said that the model has shown great and precise results and has great potential. However it is in need of verification through tests from other C&S sites.

The model is in need of getting more users friendly, but once it is, there are great ways to use it to obtain powerful tools that will help Sandvik and their customers in their future development.

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6.3 Interviews

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Linderoth, Lars-Ola. *Laboratory Engineer* (02 2014).

Lundström, Peter. *Crush Manager, Company 1* (04 09, 2014).

Paravac, Marijan. *Market & Sales Manager* (03 01, 2014).

Ståhl, J-E, interview by A Lindström E Rading Heyman. *Professor at Lund University* (continously).

Svedensten, Per. *Manager Crushing Chambers and Materials Development* (03 13, 2014).

Svennelid, Albin, interview by E Rading Heyman A Lindström. *Reliability Specialist* (04 23, 2014).

Appendices

Appendix 1
Abbreviations

a_f	Annuity	-
AI	Abrasion Index	kg/kWh
$C\&S$	Crushing & Screening	-
CSS	Close Side Setting	mm
D	Balancing loss for station	-
F_{80}	The 80 % passing size of the feed	µm
HIS	High Speed Impact	-
h_{UH}	Number of hours of operation per hour maintenance	-
h_y	Number of hours per shift per year	hours/year
k	Production cost of product	SEK/part
K_0	Original investment of equipment	SEK
k_B	Cost of raw material per ton	SEK/ton
k_{CP}	Hourly cost of machine during production	SEK/hour
k_{CS}	Hourly cost of machine during downtime and setup times	SEK/hour
k_D	Payroll costs	SEK/hour
k_{ph}	Variable machine time cost	SEK/hour
k_{ren}	Average renovation cost	SEK
k_{renk}	Renovation cost	SEK
k_{UHh}	Maintenance cost per hour	SEK/hour
k_y	Cost per square meter	SEK/m^2
$lön$	Average salary	SEK/year
M	Tons of raw material used for 1 ton of main product	tons
M_0	1 ton of main product at end of process	ton
mf	Material flow	ton/hour
MIT	Massachusetts Institute of Technology	-
$MLOC$	Machine Lifetime Operating Cost	-
n	Expected length of time in use	year
N_0	Batch size	number
n_{op}	Number personnel connected to the production line	number
N_{ren}	Number of renovations during lifetime	-

N_{ren}	Number of renovations	number
n_{ren}	Year of renovation, from present time	years
n_{syren}	Number of shift-yeas between renovations	years
OFAT	One Factor At Time	-
p	Internal rate	-
P_{80}	The 80 % passing size of the ground product	µm
PD	PlantDesigner	-
PF	Product factor at end of process	-
pf	Product factor for station and product	-
PPM	Production Performance Matrix	-
PTC	Parametric Technology Company	-
q_B	Rejection rate	-
q_P	Production-rate loss	-
q_S	Downtime rate	-
$r_\%$	Residual value	-
r_a	Residual value factor	-
socavg	Social security costs	-
SPS	Swedish Production Symposium	-
t_0	Cycle time	min/part
T_{free}	Free capacity	hours
t_{mf}	Time to process 1 ton of material	hour/ton
T_{plan}	Planned production time per year	hours
T_{su}	Setup time for machine	hours
U_{RP}	Machine utilization	-
VSI	Vertical Shaft Impact	-
W	Work Impact Index	kWh/ton
Wi	Bond work index	kWh/ton
Yk_y	Cost for the C&S plant or facility in terms of rent or depreciations	m^2

SANDVIK	Routine / Instruction				SA 1368en	
	Uppgjord/Prepared	Fastställd/Approved	Publiserad/Published	Datum/Date	Utgåva/Edition	Sida/Page
Sandvik Rock Processing	KP/BTj	KP/BTj	BKS/Tla	2004-11-04	01	1 / 3

Determination of Impact Work Index for rocks

Test method

General

The test method has been developed by Fred C. Bond at Allis-Chalmers Corporation, U.S.A..

The test is performed in order to indicate the crushability (toughness) of a rock and to establish the work index that is used to calculate the energy consumption during crushing. The result is used internally within Sandvik Rock Processing, primarily for application engineering.

Apparatus

- Test apparatus according to drawing No. 2.606.0710.

- Pattern with the square holes 75x75 mm and 55x55 mm.

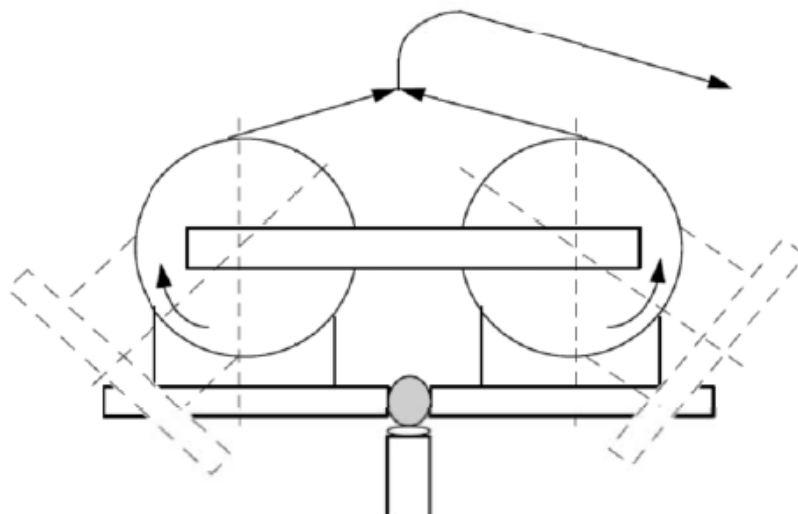- Measuring stick with graduation in mm up to minimum 100 mm.

Figure. Test apparatus (principle).

SANDVIK

Sandvik Rock Processing

Routine / Instruction

SA 1368en

Uppgjord/Prepared	Fastställd/Approved	Publiserad/Published	Datum/Date	Utgåva/Edition	Sida/Page
KP/BTj	KP/BTj	BKS/Tla	2004-11-04	01	2 / 3

Preparation

Select twelve stones which are passing a 75x75 mm opening but are retained on a 55x55 mm opening. They should be as cubical as possible and have a shape which enables them to stand steady in the test apparatus. The specimen length shall not exceed three times the thickness.

Position the stones, one at the time, on the support in the test apparatus. The stone should be oriented with its smallest dimension (the thickness) in the same direction as the movement of the two hammers. Adjust the hammers so they both touch the stone. Measure the distance between the end surfaces of the hammers at the same level as the centre of the hammers. This dimension is further called the thickness of the stone. Record the thickness, which should be between 45 and 70 mm.

Exception: If the stones received do not fulfil the requirements on dimension and/or shape and it is not an alternative to send a new sample, a deviation from the above is permitted. The distance between the hammers (the thickness of the stones) may in exceptional cases be minimum 40 mm and maximum 80 mm. Less stones than twelve are also permitted. The number and sizes are shown in the test report.

Method

When the stone is positioned on the support and the thickness is measured, the hammers should be lifted by turning the pair of wheels in the test apparatus. The rotation angle should be chosen small enough to avoid crushing the stone at the first trial. The experience from the type of rock and measured thickness are determinant. In doubtful cases, 30 degrees is chosen. Maximum three stones which have broken at the first hit , is allowed to be included in the test results, and maximum two if the amount of tested rocks is from six to nine and only one if the number of tested rocks is five or less.

The hammers are then released and the stone is hit repeatedly until the stone finally breaks. The stone is considered to be broken if at least 20 % of its original volume is removed. For each new trial the rotation angle is increased by five degrees. Tested angles is recorded in a protocol (blanket 1793)
The angle when the stone broke is recorded together with the previously measured thickness.

The procedure is repeated with each of the twelve stones.

Calculation

Calculate the kinetic energy in the hammers (and in other parts of the apparatus that is moving) when the stone was crushed with the formula

$$W = 129.64 \times (1 - \cos \phi)$$

where W is the energy in Nm and ϕ is the rotation angle of the wheels in radians when the stone was crushed.

Divide W by the measured thickness in mm for each of the twelve tested rocks. The quotient is the impact strength (toughness) for the stone.

Omit the results with the highest and lowest impact strength. Calculate the average impact strength for the remaining ten results.

Calculate a confidence interval for the impact strength with the confidence coefficient 0.90 using the formulas

Lower confidence limit = average impact strength - $t_{0.1\div2}(n-1)$
Upper confidence limit = average impact strength + $t_{0.1\div2}(n-1)$

where n = the number of tested stones and $t(\alpha,n)$ is (the statistical) t-distribution.

Then calculate the Impact Work Index with the formula

$$WI = 0.0485 \times \text{average impact strength} / \text{density}$$

where the measured density is given in g/cm^3.

Calculate the confidence interval for Impact Work Index by using the impact strength confidence limits in the same formula.

The results shall be archived in the Access-database "Datamaster" on the company's computer network a paper copy shall be printed immediately and archived in separate binders.

	Routine / Instruction			SA 1367en	
	Uppgjord/Prepared KP/BTj	Fastställd/Approved KP/BTj	Publiserad/Published BKS/Tla	Datum/Date 2004-11-04	Utgåva/Edition Sida/Page 01 1 / 3

SANDVIK

Sandvik Rock Processing

Determination of Abrasion Index for rocks

Test method

General

The test method has been developed by Pennsylvania Crusher Division within Bath Iron Works Corporation in U.S.A..

The test is performed in order to indicate how much a rock will wear on steel and to estimate a wear part life. The test result is used internally within Svedala Crushing and Screening, primarily for application engineering.

Apparatus

- Test apparatus according to Sandvik SRP AB drawing No. 1.606.0740.
- Test paddle according to Sandvik SRP AB drawing No. 606.0750-02.
- Scale with accuracy ± 0.00005 g for weighing of the paddle.
- Plate sieves with the following square hole sizes: 12.5 and 19 mm.
- Wire sieves with the following square holes: 16, 11.2, 8, 4, 2 & 0.5 mm.
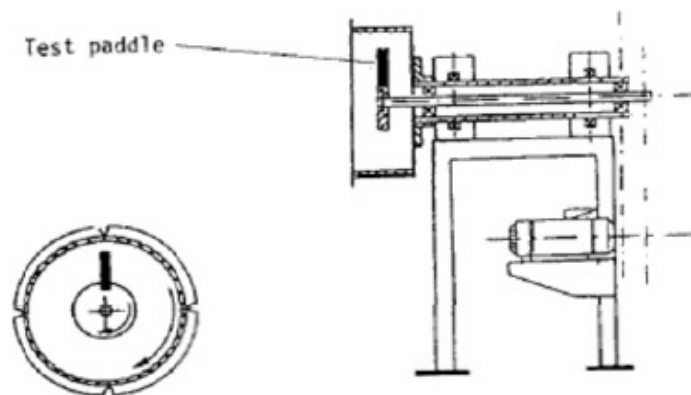- Other equipment for sieve analysis according to SS-EN 933-1 with changes according to E 200.008.

Figure. Test apparatus (principle).

SANDVIK

Sandvik Rock Processing

Routine / Instruction

SA 1367en

Uppgjord/Prepared	Fastställd/Approved	Publiserad/Published	Datum/Date	Utgåva/Edition	Sida/Page
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Preparation

Calculate required amount of stone with the formula

$$Q_{tot} = 4 \times 400 \times d \div 2.65 \ (g)$$

where Q_{tot} is the total amount in grams and d is measured solid density in g/cm^3.

Prepare the amount Q_{tot} of fraction 12.5-19 mm by screening on plate sieves the product from crushing of +19 mm in a single toggle jaw crusher R 2513 at C.S.S. 15 mm.

Exception. If the sample received for testing is not coarse enough for the crushing (smaller than 30 mm), is it allowed to sort out the fraction 12.5-19 mm from the sample.

Split the material in four parts, each weighing $Q = 400 \times d \div 2,65 \ (g)$. Maximum deviation allowed from this weight is $\pm 2 \%$. Adjust by adding or removing a stone.

A test paddle can be used for two determinations of Abrasion Index. If the paddle is not used, then weigh it on a scale with a minimum accuracy of $\pm 0,00005$ g and check its measured hardness. A new paddle may be used if the weight is in the interval 93,85 - 96,85 g and if the hardness is in the interval 48,0 - 51,5 HRC. If the paddle is used once, it may be used a second time without any action.

Method

Attach the test paddle in the test apparatus.

Add the amount Q of the material into the drum and attach the cover tight to prevent emission of dust. Start the apparatus with the outer drum surface moving at 70 - 72 m/min and the paddle rotating at the speed 630 - 680 r/m in the same direction. Let the apparatus run for 15 minutes ± 10 seconds. Remove the material in the drum and collect it in a bowl. Repeat the actions above three times, which results in a paddle operation during totally 60 minutes ± 40 seconds.

Wash off stone dust from the test paddle with diluted hydrochloric acid and let it dry. Weigh the paddle on a scale with a minimum accuracy of ± 0.00005 g.

Calculation

Calculate the Abrasion Index:

AI = Paddle weight before the test - paddle weight after the test   (g)

If the amount of material received is too small to enable four tests, the Abrasion Index can be estimated by using the following formulas:

$$K = 0{,}025 \times t - 0{,}00017 \times t^2 - {}^{10}\log(M)$$

$$\text{Estimated AI} = 10^{0{,}888 - K}$$

where K is a constant, t is the time that the test paddle has been running (15, 30 or 45 minutes) and M is the mass in grams which have been worn off the paddle. The calculated value should be given with two decimals and it should be stated in the test report that AI is estimated.

Draw the particle size distribution curve according to the sieve analysis and compare it with normal curves for material with different Impact Work Index.

The results shall be archived in the Access-database "Datamaster" on the company's computer network a paper copy shall be printed immediately and archived in separate binders.

Appendix 3

Company 1, Plant 1, PD model
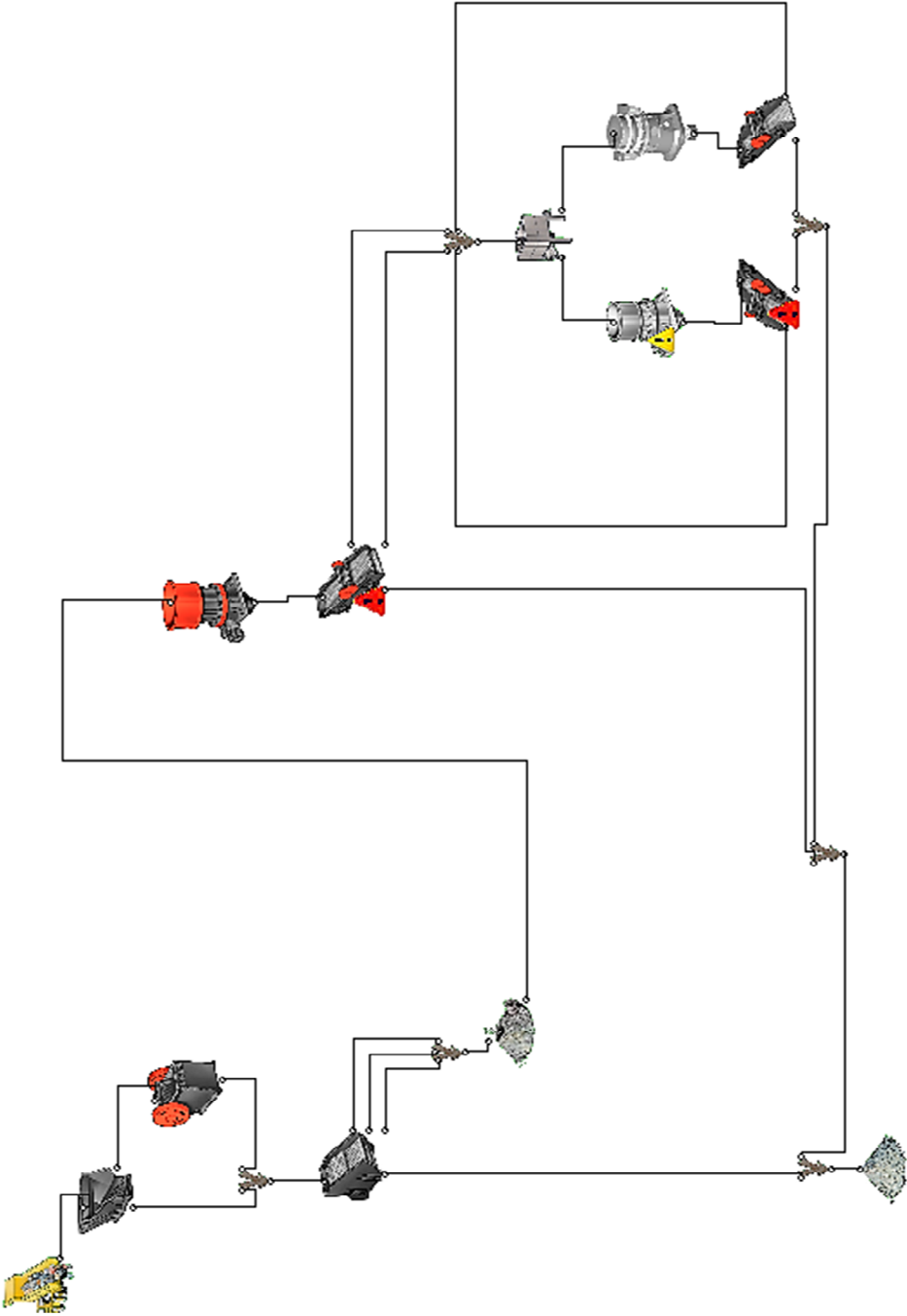
Appendix 4
Frågeformulär anläggning 1 (utan svar)

Råmaterial och produkter

Vad är kostnaden för råmaterialet som går in i primärkrossen, per ton?   _____ SEK/ton

Hur många produkter/fraktioner har ni efter sista station?   _____ st

Process-kapacitet

Hur stor är den årliga produktionen i ton/hur många ton processeras per år?   _____ ton/år

Hur ser er överkapacitet ut, har ni inplanerade stillestånd för att inte överskrida efterfrågan, om ja, hur ser denna planering ut?

Planerad produktion och personal

Hur många planerade produktionstimmar per år?   _____ h/år

Hur många skift används, samt hur ser de ut?   _____ st _____ h/skift

Hur många anställda är knutna till krossning och siktning på denna anläggning?   _____ st

Vad ligger snittlönen hos de anställda på?   _____ SEK/månad

Används intern eller extern kompetens vid underhåll/reparationer av krossar och siktar?

Intern ☐   extern ☐

Om extern arbetskraft används vid service, vad är kostnaden per timme för inhyrda servicetekniker?

_____ SEK/h

Övriga frågor

Vad är den årliga kostnaden för att använda anläggningen i form av hyra eller räntor och avskrivningar?

_____ SEK/(månad/år)

Vilken kalkylränta används vid investeringar?   _____%

Appendix 5
Frågeformulär C&S-anläggning 1 (modifierad med svar)

Råmaterial

Vad är kostnaden för råmaterialet som går in i primärkrossen, per ton?   *15 SEK/ton*

Process-kapacitet

Hur stor är den årliga produktionen i ton/hur många ton processeras per år*?   1,308426/1,486 Mton/år*

Hur ser er överkapacitet ut, har ni inplanerade stillestånd för att inte överskrida efterfrågan, om ja, hur ser denna planering ut? *35% ÖK rep/förebyggande underhåll*

Finns det några data/erfarenhet angående eventuella ställtider för de olika maskinerna?

4*24+3*18 krosstid -100 hela krossanläggningen. 100-115 krosstimmar/7dagar

200 timmar borta från normal krosstid CO-kross

Planerad produktion och personal

Hur många planerade produktionstimmar per år?   *5200* h/år

Hur många skift används, samt hur ser de ut?   *2/4 st   4*12 & 3*9* h/skift

Hur många anställda är knutna till krossning och siktning på denna anläggning*?   12-14* st

Vad ligger snittlönen hos de anställda på?   *22-27 utan tillägg 28-32 med tillägg* SEK/månad

Används intern eller extern kompetens vid underhåll/reparationer av krossar och siktar?

Intern ☒   extern ☒

Både och 2 interna och 1 extern

Om extern arbetskraft används vid service, vad är kostnaden per timme för inhyrda servicetekniker?

450 SEK/h

Övriga frågor

Använder ni någon form av informations/process-övervakningsprogram i anläggningen? Om ja, går det att få tag på dessa data för oss?

Vad betalar ni för en kWh?   *50-60 öre* SEK

Appendix 6
Product Performance Matrix

This was the initial PPM that was created early on during the project but was later scrapped.

Factor groups		Process parameters — Production loss in hours				
		S — Downtime		P — Production Rate	URB	Σ
		S1: Planned downtime	S2: Unplanned downtime	P1: Production rate	URB	Sum of factor groups
A. Raw Materials	A1 Wrong dimensions					
	A2 Wrong material properties					
	A3 Dampness					
B. Process and process data	B1 Wrong settings					
	B2 Insufficient feed					
	B3 Setup Time					
	B4 Unknown material					
C. Personell and organization	C1 Break					
	C2 Handling					
	C3 Instructions					
	C4 Meeting					
	C5 Lack of personell					
	C6 Waiting for repairman					
D. Maintenance and service	D1 Machine maintenance					
	D2 Machine renovation					
E. Special/external factors	E1 Bad weather					
	E2 Low demand					
	E3 Power failure					
F. Peripheral equipment	F1 Wheel loader breakdown					
	F2 Feeder breakdown					
G. Unknown factors	G1 Unknown 1					
Sum of process parameters	Σ					

Appendix 7
Particle size distribution test site 1

Circumstances
Ore: Granodiorite with quartz
Bulk weight: 1.7 t/m^3
Impact Work Index (WI) = 22
Abrasion Index (AI) = 0.2
CO 865 M
Capacity 210 MTPH
Effect :380 kW
DO = 70 mm
RPM 860

Circumstances
Ore: Granodiorite with quartz
Bulk weight: 1.7 t/m^3
Impact Work Index (WI) = 22
Abrasion Index (AI) = 0.2
CH 660 M
Capacity 270 MTPH
Pressure: 5,4 mPa
High Dampness