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IN

PRODUCT AND PRODUCTION DEVELOPMENT

REAL-TIME OPTIMIZATION OF CONE CRUSHERS

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To Johanna and Theander

ABSTRACT

Cone crushers are used in the mineral, mining, and aggregate industry for fragmentation and production of rock materials. Cone crusher control systems are widely used for machine protection, wear compensation and, to some extent, increasing production. These systems ordinarily focus on the crusher and not the yield of production process.

In this thesis real-time optimization is explored to the control of eccentric speed and on-line CSS adjustment based on information from the process. The objective is to develop theories, models, software and hardware that enable real-time optimization of a single crushing and screening stage. The main hypothesis is that fixed parameters can never be optimal over time because many things in the process vary continuously.

The eccentric speed in a cone crusher determines the number of times a material is compressed and thus the particle size distribution of the product. The speed of the crusher is usually fixed since speed change by changing pulleys is a labor intensive activity. By applying a frequency converter to the crusher motor power supply, it is possible to continuously adjust the eccentric speed. The cost for frequency converters has decreased significantly over the last decade.

By applying mass-flow sensors to the process, e.g. conveyor-belt scales, the crusher result can be monitored and the result can be fed back to an operator or a computer. To analyze data from the process and automatically calculate the appropriate value for the Closed Side Setting (CSS) and eccentric speed, algorithms have been developed. The goal for the algorithms is to maximize the product yield in a given moment. The algorithms are loaded into computer systems that can communicate with sensors and crushers.

The developed algorithms are tested and evolved at full-scale aggregate crushing plants. Crushing stage performance increased 3.5% in terms of production yield compared to a fixed CSS when the algorithm was implemented in addition to the existing control system. The algorithm automatically compensates for changes in the feed material and also decreases the need for calibration of the CSS. The crushing stages where the speed algorithm were tested increased their performance by between 4.2% and 6.9% compared to a good fixed speed. In real life however, the performance was increased by almost 20% since an inappropriate speed was selected during installation. As a bonus, on one of the test plants for the dynamic speed, the lifetime of the manganese wear parts increased 27% on the evaluated crusher, as a consequence of changed crusher dynamics.

In conclusion, real-time optimization has been demonstrated to be feasible and increases the production yield with significantly numbers and should thus be of commercial interest to the industry.

Key words: cone crusher, crushing, real-time optimization, process optimization, CSS, eccentric speed.

PUBLICATIONS

This thesis contains the following papers.

Paper A: Hulthén, E. and Evertsson, M., *A Cost Effective Conveyor Belt Scale*, Presented at 11th European Symposium on Comminution, Budapest, October 9-12, 2006. Published in conference proceedings.

Paper B: Hulthén, E. and Evertsson, M., *Algorithm for dynamic cone crusher control*, Minerals Engineering (Journal), 2009. Volume 22, pp 296-303.

Paper C: Hulthén, E. and Evertsson, M., *On-Line Optimization of Crushing Stage Using Speed Regulation on Cone Crushers,* Proceedings of XXIV International Mineral Processing Congress, 2 pp. 2396-2402. ISBN: 978-7-03-022711-9.

For this paper Erik Hulthén received "Young Author Award" at XXIV International Mineral Processing Congress in Beijing, 2008.

Paper D: Hulthén, E. and Evertsson, M., *Two Variable Real-Time Algorithm for Cone Crusher Control*, *Proceedings of XXV International Mineral Processing Congress*, 1 pp. 813-819. ISBN: 978-1-921522-28-4.

Paper E: Hulthén, E. and Evertsson, M., *Real-Time Algorithm for Cone Crusher Control with Two Variables*, Submitted to Minerals Engineering (Journal), October 2010.

CONTRIBUTIONS TO CO-AUTHORED PAPERS

In all the papers A-E, Hulthén and Evertsson initiated the idea. The implementation was performed by Hulthén. Hulthén wrote the paper with Evertsson as a reviewer.

CONTENTS

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Erik Hulthén

Göteborg, November 2010

1 INTRODUCTION

The aims of this chapter are to:

- *Introduce the concept of crushing plants and their importance in a modern society.*
- *Describe the operation of a crushing plant.*
- *Introduce real-time control of crushing plants.*
- *Describe the main challenges associated with crushing plant control.*

1.1 CRUSHED ROCK MATERIAL

Rock crushers are used in the aggregate, mining, and mineral industries. Cost-effective production, including size reduction and size classification, is the primary challenge in these industries. Size reduction is achieved using crushers, while classification is achieved by screens.

Aggregates are used in homes and office buildings as well as in transportation infrastructure. Due to their low inherent value of about €5-15 per tonne, they are usually manufactured less than 40 km from where they are being used. Aggregates can be composed of gravel, crushed rock material, or both. Aggregate rock materials are processed by both crushers and screens, while sand and gravel sometimes are only screened. In Sweden in year 2008, 78 million tonnes of aggregates were produced from crushed rock materials [1], corresponding to 79% of all manufactured aggregate products. The remaining 21% of aggregates were mainly produced from sand and gravel deposits. However, extraction from natural sand and gravel deposits is steadily decreasing, which motivates finding more cost-efficient processing methodologies for crushed rock aggregates. In Europe, about three billion tonnes of aggregates were produced at about 28000 production sites in year 2007 [4].

Crushing plants are used as a pre-processing stage before milling and other fine particle treatments in the mineral and mining industries. In year 2008, 51 million tonnes of ore and bedrock from iron ore mines and non ferrous mines and 9 million tonnes of limestone were extracted in Sweden [9]. These tonnages were pre-processed by crushing plants.

1.2 CRUSHING PLANTS

Crushing plants consist of single machines or a set of machines that are put together to form a process to gradually reduce the size of the processed material. The machines include the following:

- Size reduction machines, e.g. crushers.
- Separation machines, e.g. screens.
- Transportation equipment, e.g. trucks and conveyor belts.
- Storage, e.g. stockpiles or bins.
- Extra equipment, such as scrubbers and soil mixers (occasionally).

The process is divided into several stages with different size ranges in each. The configuration of the plants can differ, but in general they are as follows. The primary stage consists of a jaw crusher or sometimes a gyratory crusher. The secondary and tertiary stages, on the other hand, use cone crushers as size reduction machines. However, the final shape of the product is sometimes achieved in a vertical shaft impact crusher (VSI). In addition, screens are placed between the crushers in most stages. A single-stage crushing plant using gravel as the raw material is shown in Figure 1.

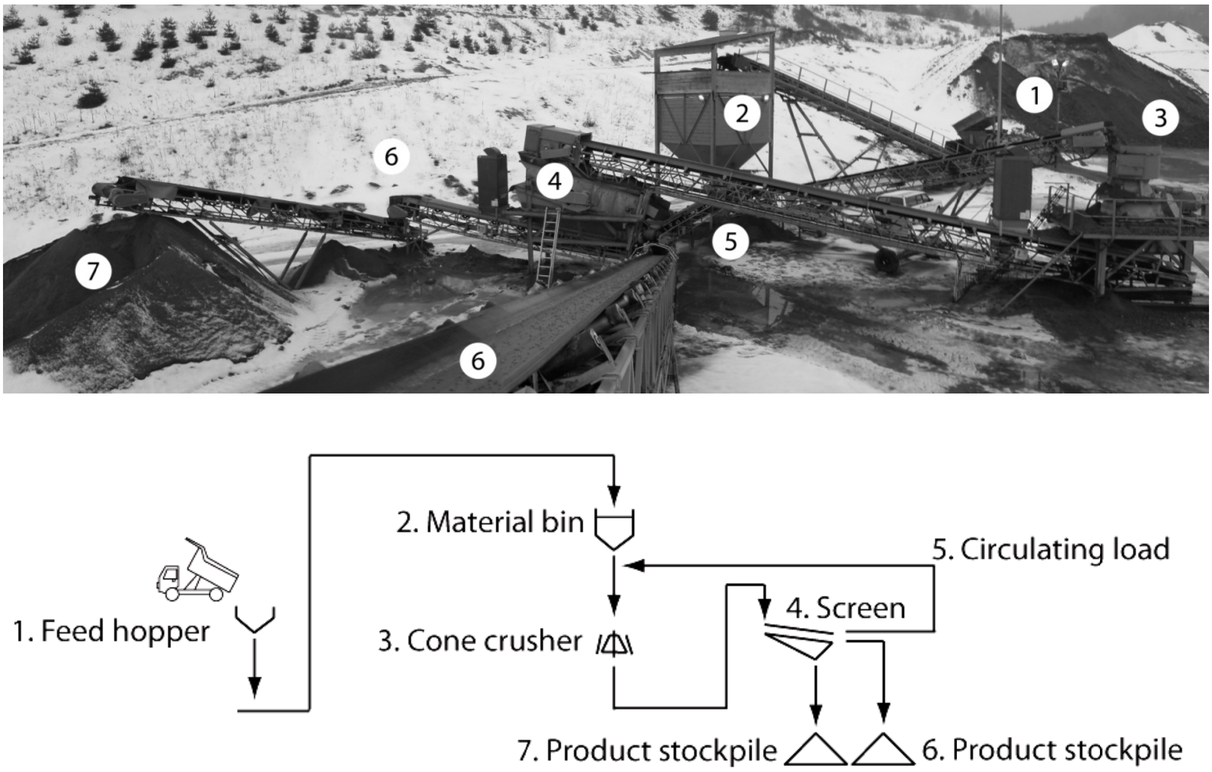

Figure 1. Sand & Grus AB Jehander's crushing plant in Fjärås. A photo (top) and a schematic illustration (bottom) as often depicted in order to see the process more easily. The numbers on the photo correspond to the numbers on the depiction.

1.3 Operation of Crushing Plants

Crushing plants are dusty, dirty, and noisy and therefore harsh environments to work in. The machines are large and heavy because they need to handle large quantities of abrasive rock material and resist high internal loads. Although it is a process industry, the level of automation is often scarce, specifically in the aggregates industry. One reason for the lack of automation is that the low inherent material value of the manufactured products does not appreciably motivated automation development. Another reason is that the required number of personnel is relatively low. For instance, most production units only require maintenance and repair a few times per year. In addition, cone crushers have level indicators that stop raw material feeding when the crushers are full. Most primary jaw crushers, however, are controlled by an operator.

Worn parts are replaced regularly by maintenance personnel. Crusher manganese liners wear quickly in most cone crushers, except when the feed material is a soft material like limestone. A typical wear part change interval for aggregate cone crushers is 100-1000 hours of operation. In highly abrasive quartzite crushing, the wear life can be as low as two weeks. Wear in cone crushers has been thoroughly investigated by Lindqvist [32]. In Figure 2, a cone crusher can be seen during a wear part change.

Figure 2. A Sandvik Hydrocone H6000 at NCC Roads' crushing plant Ramnaslätt during assembly after a wear part change. The cone, main shaft and top bearing can be seen in the center of the crusher.

Screen cloths wear out regularly. The cloth consists of either weaved steel wires, punched rubber or molded polymer. The wear of crusher mantle liners and screen cloths dramatically affects the products and the performance of the crushing process, Svedensten [46]. Changing liners in a crusher too late may cause severe mechanical damage. Changing too early, however, will cost money in the form of both unutilized parts as well as production loss.

Loading and unloading rock material is a common task for personnel. The rock material is loaded from the muckpile into the plant, or mobile unit, with an excavator or a wheel loader, which often, but not always, occurs in combination with a dump truck. After the crushing process, the produced material, i.e. the product, lands in either a stockpile or a material bin. If it lands in a bin, it is possible to load trucks or train hoppers directly from the bin. An example of such an automatic loading system can be seen in Figure 3. More often, however, the material has to be handled by an operator-controlled wheel loader when it is loaded onto trucks or train hoppers. When the plant is situated near the sea, ships are also used as a means of delivery. An example of loading equipment for ships can be seen in Figure 4.

Figure 3. Loading and weigh station at the same place. VMC's Reliance operation, Irwindale, CA, USA.

Depending on the size of the crushing plant, personnel duties can vary greatly. For larger plants, the tasks are more specialized, such as maintenance, loading, and process operation, while for smaller plants, one person may have several or even all of the mentioned tasks.

Figure 4. Loading equipment on the quay that can be used for ships and trucks. Norstone AS' Tau plant, Norway.

1.4 REAL-TIME OPERATION OF CRUSHING PLANTS

Crushing plants today operate in a static mode, which means that the intention when designing the circuits and operating them is to achieve an even and smooth production result, which is also, hopefully, as good as possible. However, no, or at least very little, feedback propagates back to the operator, unlike in many other industries. It is the author's opinion that feedback together with control would improve the process in this industry and is defined here as real-time optimization of crushing plants.

OPEN LOOP CONTROL OF CONE CRUSHERS

Most cone crushers are fed automatically; the material level is kept in a specific range by a programmable logic controller (PLC) or a relay that switches a feeder and/or a belt conveyor on and off according to signals from feed level sensors. Sometimes, if the belt and/or feeder is controlled continuously with a frequency converter, this level is kept in its range with a proportional-integral-derivative (PID) controller. Some cone crushers are automated; an automatic control system prevents the closed side setting (CSS) from deviating from a desired setpoint. This is done by adjusting the cone vertically with hydraulics or by turning the top shell on its threads, thereby adjusting the concave vertically, depending on the machine type as described later. The control systems attempt to keep the CSS at a value determined by the operator or, when size reduction is important, at a constant maximum pressure or power draw. The crusher control system is an open-loop configuration; the control system controls the machine almost fully independently of what happens to the material passing through the crusher. A block diagram for the control system is illustrated in Figure 5.

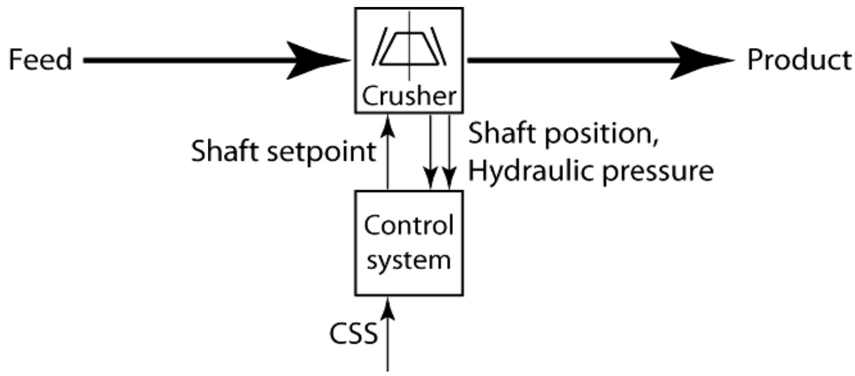

Figure 5. Open-loop control of CSS on a cone crusher.

PROBLEMS WITH REAL-TIME OPTIMIZATION

Aggregate production, including the crushing process, is a complex process because production of a single particle size is not possible using today's technology. Instead, a distribution of differently sized particles is manufactured. The parameters involved in this process and that affect the quantities and qualities therein are also complex.

Raw material varies depending on the excavation site and how the material was blasted. Depending on where the focus is in the process, the feed material can also be affected by earlier crushers and other production units. For example, a crusher earlier in the process flow can generate an excess of fine material, affecting the performance of the following screens and crushers later in the process. Typically, finer material affects the hydraulic pressure, power draw, additional generation of fine material, and capacity. The raw material parameters can vary periodically and stochastically with a long or short time scale.

Manganese liner wear affects crusher performance. A worn crusher chamber has undergone physical changes and has a different profile than that of a new chamber, which affects both the capacity of the crusher and the size and shape of the produced particles. Some crushing chambers are more sensitive to wear than others. Further, crushers with worn liners can behave differently, with some increasing and others losing their capacity as a function of wear.

CSS is the parameter used to adjust many contemporary crushers online. Crushers with a hydraulic CSS adjustment can be controlled online in an open-loop configuration as previously described. Crushers using a threaded top shell design can also be controlled using an open-loop configuration; however, the control is limited by the thread clamping system, which cannot be released when material is present in the crushing chamber. Some crushers using a threaded top shell design can be adjusted when loaded; however, making adjustments when loaded will probably shorten the lifetime of many of the machine parts.

Cone crushers usually run at a fixed eccentric speed. Frequency converters can potentially control the eccentric speed by controlling the frequency of the alternating current to an asynchronous motor. However this has historically been too expensive to implement. Manual speed changes, on the other hand, require changing belt pulleys, which is labor intensive.

Because aggregate crushing is a process industry with a continuous flow of processed rock material, the performance of the process is difficult to obtain online. One way to determine the effect of a change is to take a belt cut before and after the change. Unfortunately, belt cuts stop production and may not accurately represent changes (a typical belt cut only contains rock from 0.5 seconds of production). In addition, they are often divided down to a couple of kilos before being sieved. Thus, substantial manual work is required before anything can be said about the process, and further, by the time the result is ready, the crushing conditions may have already changed several times.

One way to obtain process information is to use mass-flow meters, commonly being a belt scale, on the conveyor belts. Unfortunately, traditional belt scales are relatively expensive, on the order of € 5000-10000, and are therefore sparsely installed. Consequently, the high cost associated with implementing flow meters has hindered the development of process control in this kind of process industry.

Operators are busy and do not have enough time to control an open-loop crusher as effectively as well-configured computer software. Such software coupled with adequate sensors can facilitate closed-loop control, as depicted in Figure 6, which was originally presented by Evertsson [20]. This control configuration also requires models or rules to transform user requests into machine setpoints.

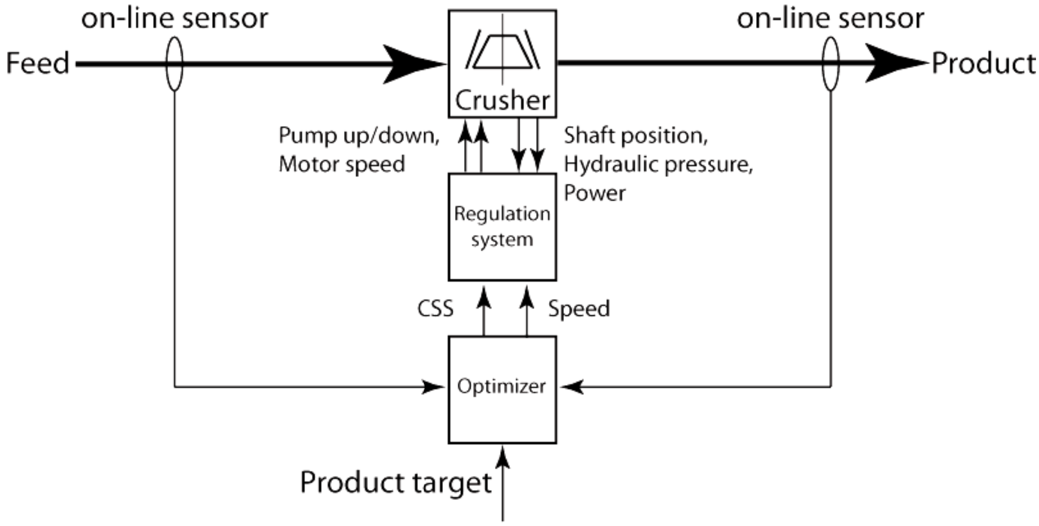

Figure 6. Possible system for closed-loop process control for a single crushing stage.

2 OBJECTIVES

The aims of this chapter are to:

- *Describe the purpose of the research project resulting in this thesis.*
- *Formulate the research questions.*

2.1 RESEARCH OUTLINE

The purpose of this research project is to understand the production process of rock materials in which cone crushers are used and to develop knowledge and methods for optimizing the operation of these machines in real-time to maximize product yield. Real-time is here interpreted as what is possible to adjust during operation with sufficient feedback from the process. Real-time optimization will potentially increase the automation in the aggregates, mineral, and mining industries and will thus assist operator decision making and increase production. Crushing plants are investigated in particular, with the goal of helping producers at crushing plants directly select which products they want to produce, which is accomplished by real-time optimization of the machines.

This thesis focuses on optimizing a single crushing and screening stage, see Figure 7. The reasons for focusing on a single crusher are that there are currently two real-time adjustable parameters and that even by optimizing a single crusher, the output of the crushing plant will be directly affected in terms of final products.

The objective for this thesis is to develop theories, models, software and hardware that enable real-time optimization of a single crushing and screening stage. An important part of this investigation is to find or develop suitable sensors for this type of process.

The main hypothesis is that fixed parameters can never be optimal over time because several other parameters change continuously.

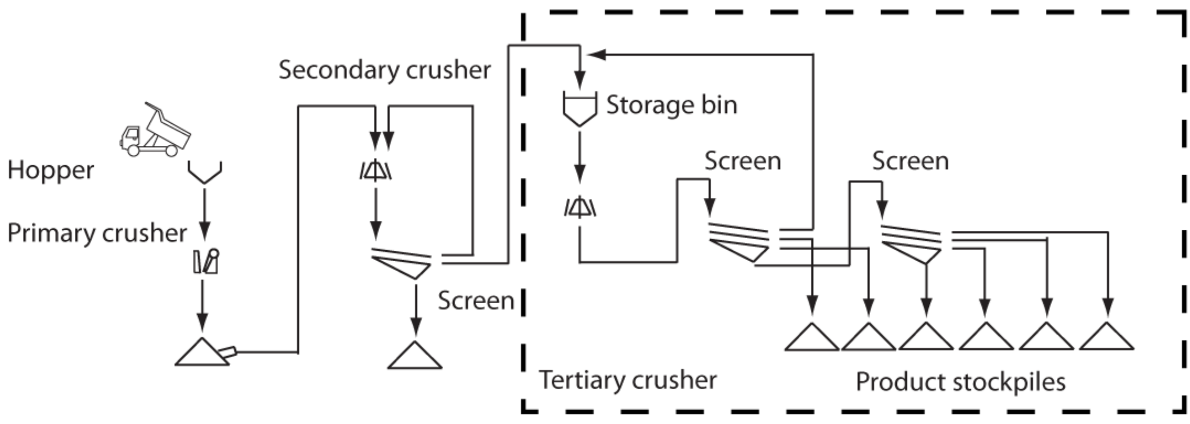

Figure 7. The focus of this thesis is a crusher and screening stage, depicted in the dashed box.

2.2 Research Questions

There are five research questions that have been formulated within the scope of this work:

- Crusher control systems are widely used for wear compensation and machine protection (e.g. over load, fatigue life). Is it possible to improve the production process by complementing these open-loop systems with feedback from the process and product yield and thereby obtain a closed-loop control system?
- In order to control crushers using information about the product yield, it is necessary to monitor the material flows at different positions in the process. Is there a more cost effective alternative to expensive belt scales?
- CSS is the most common control parameter for adjusting the product from cone crushers. Is it possible to use other parameters such as eccentric speed for real-time optimization?
- Is it possible to optimize the process with two real-time adjustable parameters at the same time?
- Is it possible for a real-time algorithm to perform the optimization described above?

3 RESEARCH APPROACH

The aims of this chapter are to:

- *Introduce the research methodology used.*
- *Explain the relevance of the applied research method with respect to the project and the research questions.*

The work in this thesis was carried out at the Chalmers Rock Processing Research (CRPR) which is a part of the Machine Elements group at the Department of Product and Production Development at Chalmers University of Technology. Research on equipment and processes for producing crushed rock material in the aggregate and mining industry has been performed here since 1993. The Machine Elements area has a long history and tradition of problem-oriented research methodology. The core idea focuses on selecting an appropriate method based on the nature of the problem. This problem-oriented research method has been described by Evertsson [20]. However, because of the nature of the current project, which requires early implementation and evaluation of the research ideas, project implementation was carried out and tested in real crushing plants along with ongoing research, i.e. project implementation was introduced earlier than normal, as described by Svedensten [46]. The different steps in the applied research method are shown in Figure 8.

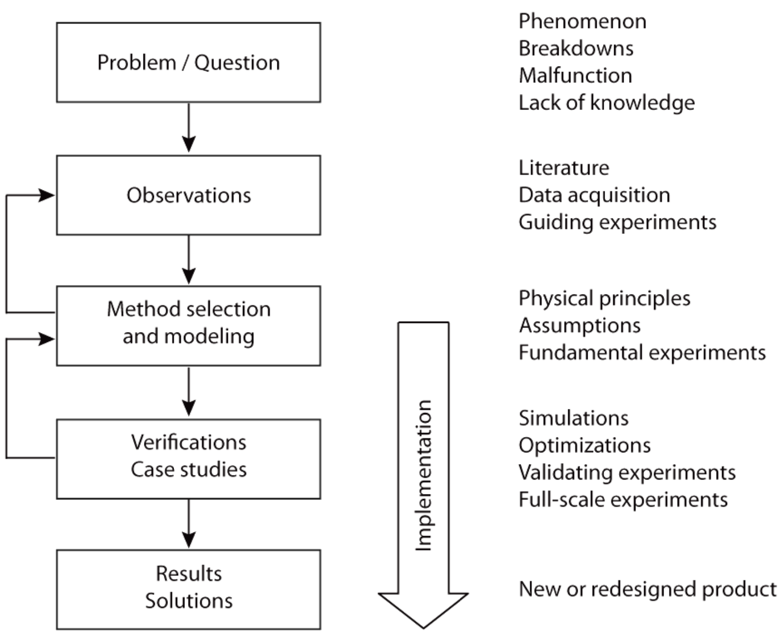

Figure 8. Problem-based research method with early implementation.

Problem-based research begins by identifying a problem or question that needs to be solved to achieve some benefit or improvement. The nature of the problems can, of course, be very different, which is why the method is not selected beforehand. The problem in question does not necessarily originate from a malfunction, but can, as in this research project, start with an assumed potential of increased productivity.

The problem area in question is observed to identify its nature. This can be done with field studies, examining the literature, guiding experiments, or performing interviews, for example.

Subsequently, appropriate methods are selected and models are developed. During this phase, several potential methods and models, in combination with previously reported literature, are studied to select the ones most suitable for the problem. The process is iterative, and a new method is selected if the previous is found to be insufficient.

The result of this work is then tested and verified, preferably together with the industry. This verification phase is also an iterative process, meaning that further potential improvements may lead to a new iteration.

To assist the previously described steps and to ensure that the result is applicable, implementation should begin during the course of research. Implementation leads to product and process development, which is a separate challenge and research field unto itself. However, doing the opposite, i.e. not considering implementing the results, likely leads to unrealistic solutions to the problems and results that are of no practical use.

This project was conducted in collaboration with aggregate producers, which involved regular meetings between project members and industry workers and the utilization of their plants for the discussed case studies. The advantage, and challenge, of this arrangement was to design test equipment to be handled by the producers themselves, both during the studies and afterward.

One of the most important scientific challenges in working in this type of project is interpreting industrial needs. In support of this function, the CRPR group has complemented the problem-based research method with a value-based approach. The Value Model [33], which originates from value management, is a method that aims to improve the value of products and services by focusing on the value created for the customers. The concept of value is based on the relationship between satisfying needs and expectations and the resources required to achieve them [10]. Value engineering was first used at General Electric during World War II with the purpose to use limited resources as effectively as possible. The method was later adopted by many other industries.

In this five years project everything was not set from the beginning. Research is evolutionary itself, also in the short perspective in the meaning that the hypotheses that are confirmed are also the same as the next generation hypotheses are built upon. Furthermore, those that were not confirmed, or perhaps showed to be false, are not the basis for the next step, even though it is only from these anomalies new knowledge can be achieved. The fact that the problem-oriented research method does not accept that a certain method or solution did not work, and instead finds a new way to solve the problem makes it suitable for engineering fields. This evolutionary development of the research presented in this thesis is best reflected in the appended consecutive papers, A-E.

4 LITERATURE REVIEW

The aim of this chapter is to:

- *Provide an overview and introduction to the research performed for optimizing crushing plant control and control in similar process industries.*

The amount of research around real-time optimization of crushing plants is very limited. Even with a wider focus including many crushing plant simulations the amount of work is sparse. Although process control with respect to the produced products is a common practice in many other process industries, it is rarely seen in an aggregates context.

CRUSHING AND CRUSHER PARAMETERS

Since the 1970's models of production units and processes in the comminution industry has been modeled, e.g. by Whiten [49] from the Julius Kruttschnitt Mineral Research Center (JKMRC). Work more specific on cone crusher performance have been published e.g. Briggs [19] from JKMRC and Evertsson [20] from Chalmers. Unfortunately, many of these models requires both crusher geometry and feed input data and the subsequent calculation is time consuming, which make them less useful in a real-time optimization perspective. Sensors capable of providing data for use in these systems are rare. However, these models can still be used for validation and for understanding.

Karra [28] tested several parameters on cone crushers in the 1970's by investigating eccentric speed as a parameter setting and found speed had no significant effect on the particle size distribution or the capacity. These results are difficult to explain, but could possibly be due to effects of other much more significant parameters. The lack of an accurate procedure for long-term evaluation is another explanation. No references or investigations for dynamic speed control have been found. Bearman has investigated how several material parameters affect comminution machines, e.g. in [13]. Bearman and Briggs [14] have investigated how several time dependant parameters affect the crusher output. They state that an active use of these parameters, including a better control system, would help in keeping up performance.

SIMULATION AND OPTIMIZATION

Maximum plant output can be obtained by theoretically optimizing gross profit using simulation software, and then running the plant according to those optimizations. Such simulation software are provided by for example Sandvik (Plant Designer), Metso (Bruno), JK Tech (SimMet) and BedRock Software (Aggflow) [40]. The optimization in this kind of software is described by Svedensten [46]. Many variables impact plant operation: natural variations of rock material properties in the feed, equipment wear, weather, and unscheduled stops. To implement real-time control of a crushing plant, an accurate measurement of the process status with these variables in mind is crucial.

SENSORS

For both the aggregate and the mining industry there are several image analysis systems entering the market during the recent years. Most of them consist of cameras above the conveyor belt. The good thing with this is that almost all of the flow can be investigated, in contrast to batch based systems as PartAn [27]. On the other hand systems like PartAn, where the material is falling and rotating in front of the sensor, are the only way how to get all the fine particles, and at the same time include the shape of the material.

Moshgbar et al. [38] described a product driven control strategy for cone crushers using wear sensors and adaptable control parameters. They used a laser-based aggregate particle size monitoring device.

REAL-TIME OPTIMIZATION

Impact crushers are controlled by adjusting their feed capacity. Reitemeyer [41] described a method by which the feed rate to an impact crusher is controlled by a system using information about the material flows as a control input. The throughput of feldspar was doubled using this control technique. The same principle of determining the capacity through the power draw of lifting conveyor belts was used in this work.

Milling operations have been more extensively investigated in the mining industry with numerous of publications each year due to the high intrinsic economic value of the products. At the PT Freeport copper mine, Mills et al. [36] have developed a real-time, adaptive optimization system based on continuously calibrated models. The system is described as an “optimizer on a higher level”. This system runs on a conventional personal computer and delivers setpoints to the existing control system. Further, it also presents a number of non-measurable variables as estimates to the operator screen. Using this system increased the throughput of the mill circuit by 5.7%.

Moshgbar et al. utilized integrated sensors in the manganese liners for determining wear, thereby enabling the ability for dynamical wear compensation [38] and [39].

ALGORITHMS

An algorithm is an effective method for solving a problem with a finite number of steps [2]. It is simply a set of rules in how to act or calculate in a deterministic way. In a comminution context, it is sometimes seen for solving optimization problems theoretically. For instance Svedensten [46] uses Evolutionary Algorithms (EA) for plant optimization, While et al. [48] use EA for designing machine and process parameters on a crusher and Lee [30] uses EA for theoretical optimization of crushing.

Evolutionary operation (EVOP), as described in Box and Draper [17], is a method wherein the process variations are used for process improvements. The method is not an automated method, rather on the contrary; it is used manually in manufacturing and process industries. Holmes has successfully optimized a cement plant with an automatic EVOP system without any explicit model [25]. The result was that the desired variable increased by 37% at the same time as the mixture of raw materials used was changed to a more profitable one.

5 PROCESS CHARACTERISTICS

The aims of this chapter are to:

- *Describe the production units used in crushing plants. Because the cone crusher is a very common machine and has a significant impact on the result, the focus will be on cone crushers.*
- *Describe the different parameters that are investigated for use in real-time optimization.*

The parameters to adjust, and thus control, the output of a cone crusher machine are the closed side setting (CSS), the eccentric stroke (sometimes called throw), the eccentric speed, and the crushing chamber. Other parameters to investigate are the particle size distributions of the feed material, and parameters on screens installed upstream in the process. Not all of these parameters can currently be adjusted in real-time while the machine is in operation. The two parameters that can be adjusted in real-time until today are CSS and the eccentric speed.

5.1 PRODUCTION UNITS

CONE CRUSHERS

The basic principle of a cone crusher is depicted in Figure 9 and described here. A cone crusher consists of a circular outer concave, wherein a mantle, shaped like a cone, moves eccentrically. The concave and mantle together form the crushing chamber, which is where crushing takes place. When the mantle is performing its eccentric motion, approximately at 6 Hz for a 36” cone crusher, the distance between the mantle and concave increases and decreases harmonically. When the mantle-concave distance increases at an arbitrary vertical cross-section, the rock particles fall down, and when the mantle-concave distance decreases, the rock is compressed and crushed (compression phase). Each piece of rock is crushed approximately 10 times on its way through the crusher. Cone crushers are usually operated at a fixed eccentric speed. Cone crushers have been thoroughly described by Evertsson [20].

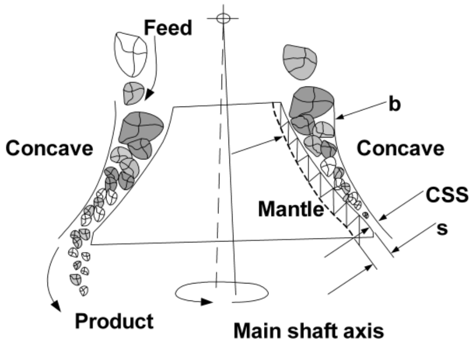

Figure 9. Principle of a cone crusher.

The distance between the concave and mantle, measured at the narrowest is called the closed side setting (CSS). The narrowest distance is normally at the outlet of the crushing chamber. The CSS is adjusted and controlled differently depending on the type of cone crusher. In one cone crusher design, the main shaft assembly with the supporting cone and mantle is adjusted vertically by hydraulics underneath the main shaft, while the concave is fixed. The hydraulic system protects the machine from overloading and potential damage from large non-crushable objects, such as mill balls, bolts and excavator teeth, by evacuating the oil and thereby lowering the mantel rapidly. During normal operation, the hydraulic system keeps the CSS at a given position by controlling the vertical position of the mantle. This type is denoted as Hydrocone from here on. For instance, most of Sandvik's cone crushers, Metso's G-series and Thyssen Krupp's Kubria-series are of this type.

In a different cone crusher design, the crusher head and its mantle are fixed vertically and rotate eccentrically. The concave is fixed in the top shell, which is connected to the crusher through a thread with a large diameter. As the mantle and concave are worn, the top shell rotates and moves down and thus keeps the CSS at a given number. To protect the machine from large non-crushable particles, the top shell also has a hydraulic release system that can open the crusher rapidly if needed. This type is denoted as the HP type from here on. For instance, Metso's HP-series and FL Smidth's Raptor-series are of this type. The two crusher types are depicted in Figure 10.

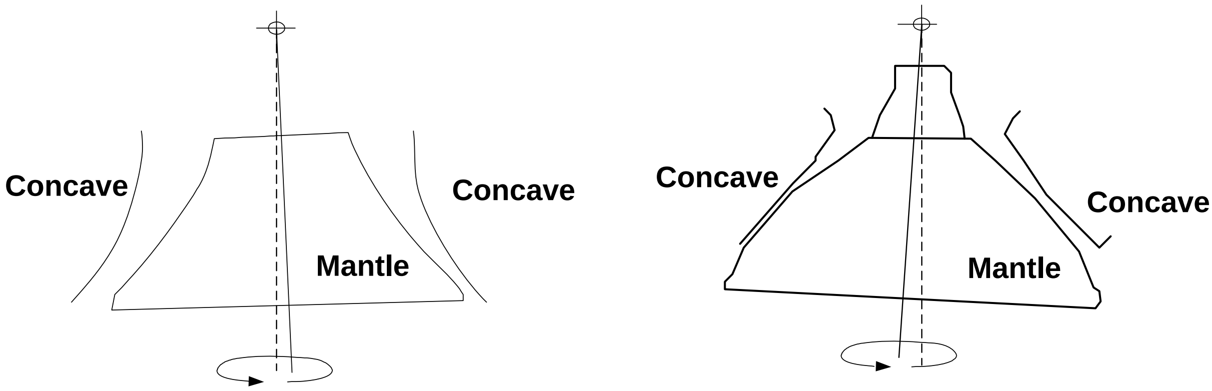

Figure 10. Crusher types. The Hydrocone crusher (left) has a top bearing, and the angle between the horizontal plane and the cone is steeper (~55 degrees), while the angle of the HP type (right) is flatter (~45-50 degrees).

VERTICAL SHAFT IMPACTERS (VSI)

A Vertical Shaft Impact crusher (VSI) is an impact crusher, which works like a centrifugal pump, throwing the particles out from rotor. VSI crushers are used both in aggregate, mineral and mining industries. VSI crushers have been thoroughly described Rychel [42]. Their use for quality reasons in the aggregates industry are described by Bengtsson [15]. Generally, VSI crushers produce a more cubical particle shape, however the production of fine materials increases compared to a cone crusher, which is often non-desirable in the aggregates industry. In mining, on the other hand, fines are often wanted, and VSI crushers can then be more energy effective [31]. The machine itself is lighter than a cone crusher, which also makes it cheaper to buy, however the costs for wear parts may be higher. The parameters to change in this machine are the feed itself, by-pass of a portion of the feed material, the rotor geometry and the speed. The speed is the most obvious parameter to work with in real-time, however it is beyond the scope of this thesis. An alternative impact crusher is Horizontal Shaft Impact crusher (HSI). The HSI crusher is mainly used for softer materials, e.g. Limestone, in the minerals industry. In an HSI crusher, the material is hit by hammers that are fixed to the rotor, and never by the material itself.

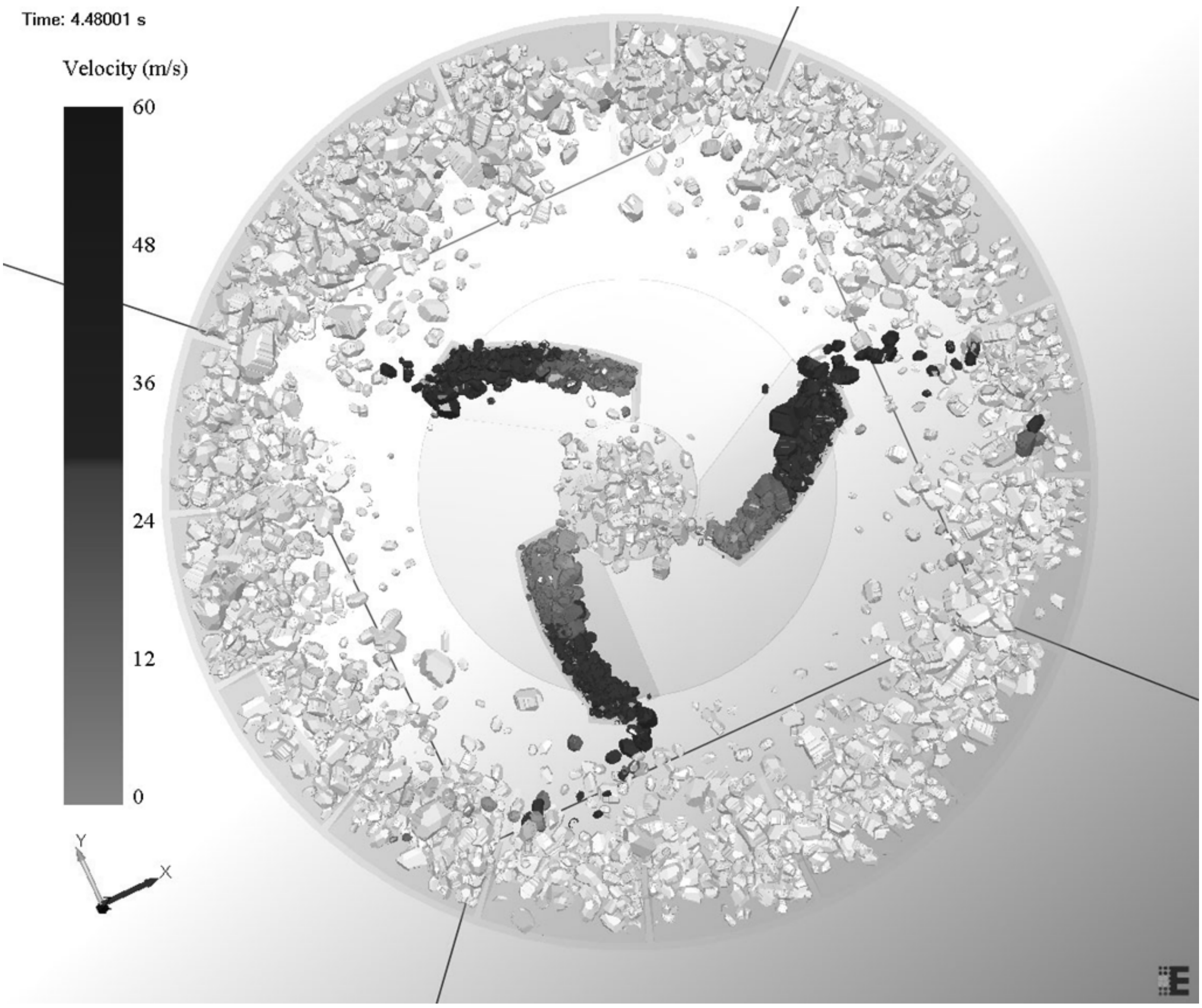

Figure 11. VSI crusher seen from above, modeled with discrete element modeling. Illustration by J. Quist.

SCREENS

Screens are used in aggregate, mining and mineral industries to separate particles of different sizes from each other and thereby form the products. Screens consist of steel wire of punched rubber cloths which oscillates in order to transport the material and to let particles pass through the apertures. The screening process was investigated thoroughly by Soldinger Stafhammar [45]. Screens have, just like crushers, several machine and process parameters, of which some might be on-line adjustable, and would thus be possible to optimize in real-time. However, screens themselves are beyond the scope of this thesis, apart from that they are used for separation of the products, which in their turn will be measured in real-time. Screens cloths wear rapidly (dependent of the abrasiveness of the rock material), and will thus different sizes of particles pass depending of how long the screen cloths have been in operation. An example of a screen in an aggregate plant can be seen in Figure 12. For fine sizes (less than 2 mm) air classifiers can be used to separate the particles by gravity and aerodynamic drag.

Figure 12. This screen is fed from the conveyor on top coming in from the right. The products are conveyed on different conveyor belts away from the screen. NCC's Glimmingen operation, Uddevalla, Sweden

CONVEYORS

Conveyors are frequently used in crushing plants for the transportation of feed material and products. The sizes of the particles are often less than 200 mm. A conveyor belt is much more energy effective than vehicles [26]. However, it is a fixed installation and since quarries changes in form and distance vehicles are often used instead because of flexibility. Both design criteria and examples of conveyor belts can be found in [5]. An example of many conveyors used in the same plant can be seen in Figure 13. A depicted conveyor belt is shown in Figure 20 in Chapter 6.1.

Figure 13. Conveyor belts are frequently used for transportation between different production units in crushing plants. VMC's Reliance operation, Irwindale, CA, USA.

5.2 PARAMETERS

The variable parameters can be divided into design parameters, machine parameters and operating parameters. For cone crushers, these parameters have been described by Evertsson [20] in matrix form, showing what each of the parameters affects. In addition, management parameters also exist, such as selecting the time for changing wear parts.

CLOSED SIDE SETTING

The CSS is the most commonly used parameter to adjust the degree of comminution in the machine and thus the particle size distribution. It is also the parameter that has the largest impact in Karra's experiment [28]. As mentioned previously, it is currently used for open-loop control in numerous crushing plants all over the world. Some crushers have automatic control systems that have a feature that compensates for crushing chamber wear during operation. In many other crushers that do not have a fully automatic control system, on the other hand, the gap between the mantle and concave is controlled manually. This brings the drawback that the process must be stopped while adjusting the CSS, see Process Control below. The effect of varying the CSS parameter is shown in Figure 14 (Hydrocone type) and Figure 15a (HP type).

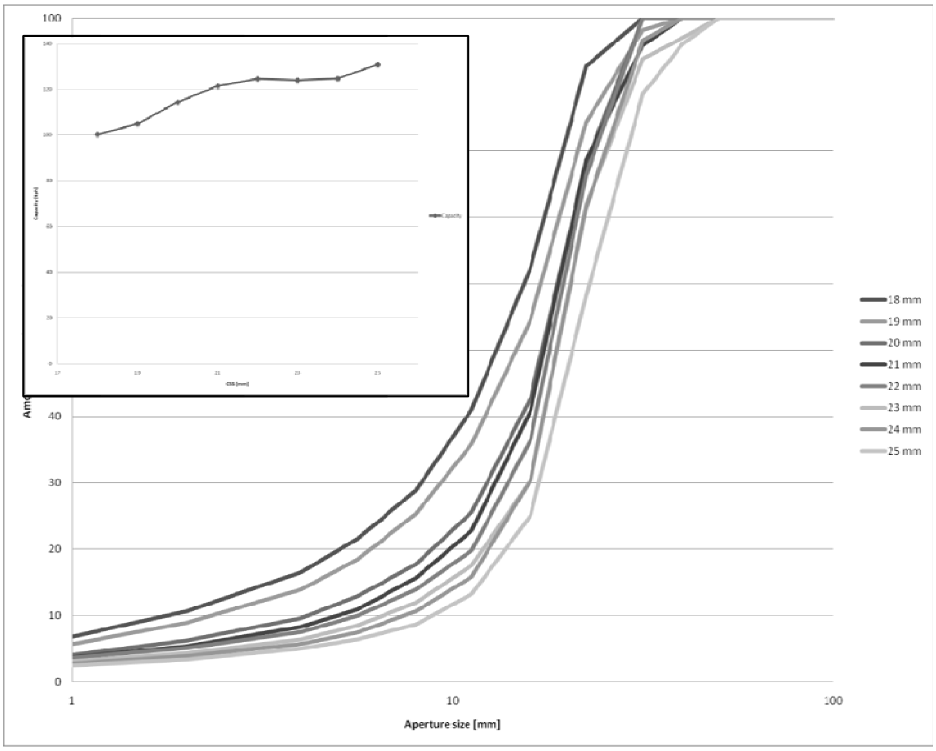

Figure 14. Particle size distribution (main illustration) as a function of CSS in a Hydrocone crusher. The capacity for the same CSS range (embedded illustration).

The CSS affects the particle size distribution because the distance between the mantle and concave changes, and thus, the crushing ratio and the capacity changes, according to Evertsson [20]. The amount of time that a particle stays in the crushing chamber determines the number of compressions it will be exposed to. Note that in both Figure 14 and Figure 15a the curves are basically shifted horizontally in the cumulative particle size distribution diagram, i.e., both the top-size and finest size are affected by the changes in the same direction. In terms of the CSS parameter, there is no major difference between these two crusher types.

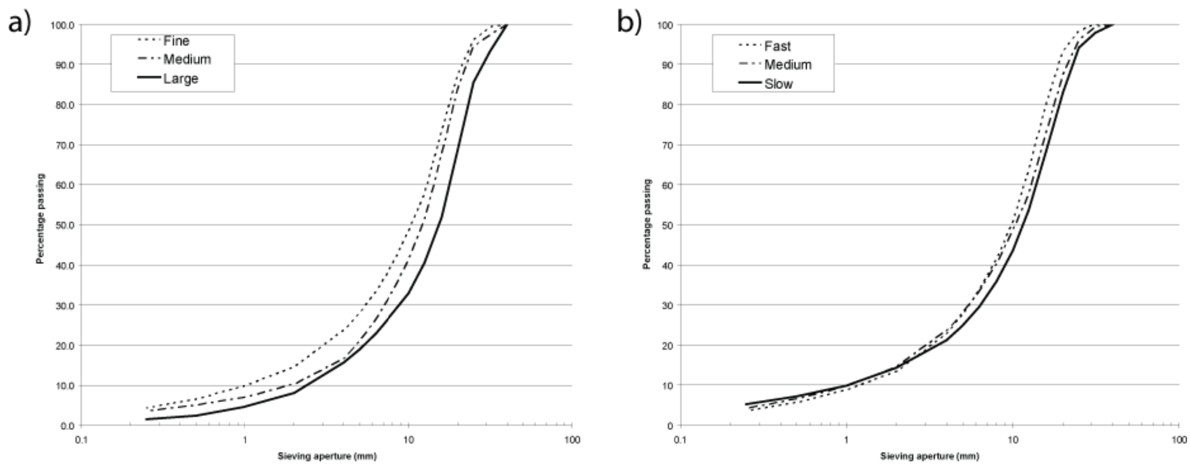

Figure 15. Particle size distribution as a function of the investigated parameter in the HP type: a) the closed side settings (CSS). b) eccentric speed.

ECCENTRIC SPEED

Eccentric speed has a significant impact on the product in a cone crusher. The speed affects the number of material compressions, the effective compression ratio, and thus the particle size distribution of the product. Similarly, speed also determines the shape of the product, but the discussion of this phenomenon is beyond the scope of this thesis. Figure 15 compares the impact of different CSS and eccentric speeds on the produced particles in an HP crusher. While changes in the CSS move the product cumulative particle size distribution curve horizontally, changes in the speed tend to rotate it. The top-size of the particles, i.e., the measurements of the largest particles, is not significantly affected by different speeds. In an HP crusher the share of finer particles increases with a reduced speed. In a Hydrocone crusher, on the other hand, the rotation of the particle size distribution is less prominent, as shown in Figure 16. The direction, at least in the finer particles, is opposite to that of the HP crusher; as the speed increases, the number of finer particles increases.

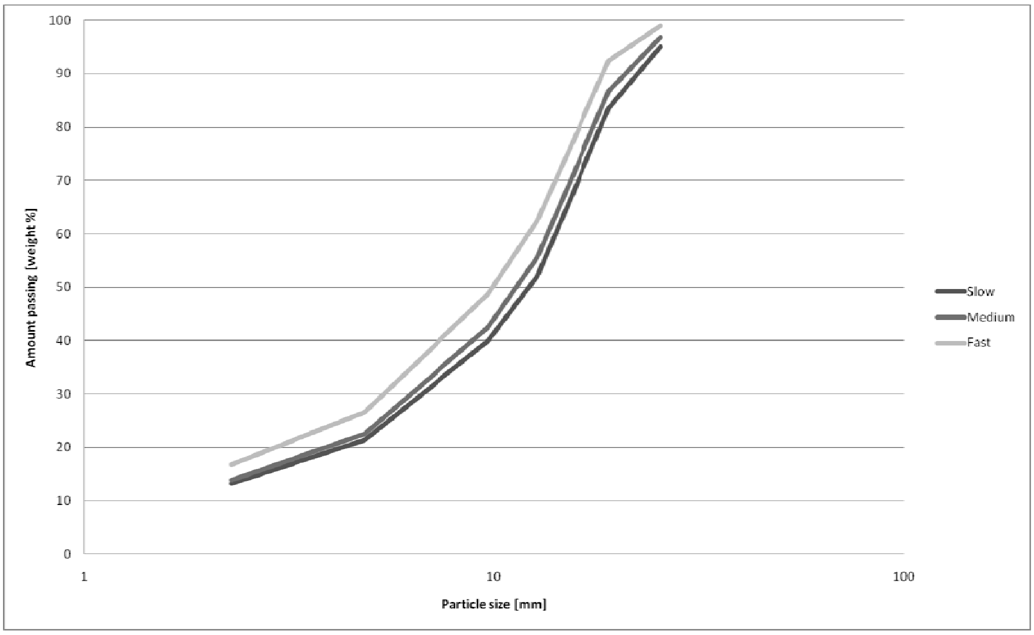

Figure 16. Particle size distribution as a function of eccentric speed in a Hydrocone crusher.

One theory to explain the difference between the types of crushers is that there are two different effects, and one is prominent in one type of crusher, and the other is prominent in the other concept. The first effect is that the eccentric speed affects the amount of time a particle stays in the crushing chamber in the Hydrocone crushers; thus, the number of fine particles increases as the speed increases because the rock gets crushed more times. For the HP crusher, on the other hand, the number of fine particles increases with decreased speed (at least within a range) because the effective stroke is larger and thus the particles get crushed more. The reason why the effective stroke is larger is because the particles have time to fall longer since the eccentric speed is slower.

How the crusher capacity is affected by the eccentric speed has been investigated by Evertsson [21]. These principles can be seen in Figure 17. Both crusher types, Hydrocone and HP, are operating to the right of the maximum capacity, i.e. the crushers' capacity is affected in the same direction by speed, regardless of crusher type.

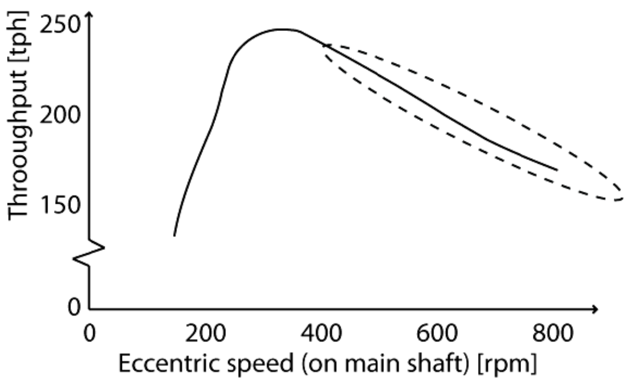

Figure 17. Total capacity in a Hydrone H3000. Original illustration from Evertsson [21]. The dashed ellipse marks the operational area for modern cone crushers.

In most cases, the speed of a cone crusher can be adjusted by changing belt drive pulleys, which is labor-intensive and time-consuming, and is therefore not done unnecessarily. In some cases, where so-called direct drive is applied, it is not possible. In addition, most crushing plants have no accurate or reliable way of monitoring the changes in production that the speed change implies. Taking belt cuts is one measurement strategy. However, this is very time-consuming, it requires additional sieving, and in the end it is still just a single sample that must be combined with further samples for accurate assessment. Therefore, cone crushers are operated at a constant speed. A selected speed is usually used for long periods of time before a new speed is selected. Frequency converters are rare, and if they exist, they are usually only used as soft-starters. Until a few years ago, they were considered too expensive, at least for the aggregates industry. However, they have become increasingly common as production plants see how much the speed parameter affects the output.

STROKE

The stroke is the eccentric distance the cone moves during half a round. This is considered today to be a machine parameter that cannot be adjusted or controlled during operation. It is measured in the lower end of the cone, see Figure 9. For the material that is being crushed, the relationship of the distance between the liners at the point when the crusher is open and the point when it is closed determines the reduction ratio. This ratio varies during a particles path down the chamber, as has been shown by Evertsson [20]. A detailed theoretical work on optimizing the repeated compression steps in a cone crusher has been done by Lee [30].

Practically, the stroke on a machine affects the capacity linearly around a given operating point. It also has some effect on the number of fine particles. If the rock is very brittle one way of producing fewer fine particles is to decrease the stroke. To change the stroke on most crushers, a change or an adjustment of the eccentric bushing must be done, which is practical when changing liners but is seldom done. On Metso’s GP300 and 300S, the stroke can be adjusted from the outside of the crusher and only requires a few minutes [6]. To the author’s knowledge, there is no crusher available with a stroke adjustable in real-time.

FEED

The feed strongly affects the performance of a cone crusher. Bengtsson [15] describes how an increased feed size may result in a poorly choked crusher, even though there is plenty of material in the bin on top of it. This situation will cause increased single particle breakage and thus flakier particles. When the feed contains many fine particles, the forces, and thus the pressure, become too large, which causes the crusher to open to protect the machine. Size (top size), the number of fine particles, and the amount of feed has a large impact on the product and the crusher. The top size affects how deep in the chamber a rock falls and how many times it remains in the chamber.

Change of Wear Parts

Changing worn parts will affect the performance on all of the production units in a crushing plant, but here the focus is on the liners (mantle and concave). With knowledge about how well a production unit can perform with changed liners, an alarm signal can be set off to indicate that it is time for a replacement, if enough data about the current performance is collected. This long term degradation in performance during the lifetime of the liners for flat angled crushers is well known and described e.g. for a Symons 7'-crusher by Andersen and Napier-Munn [11] and for a base supported crusher with 900 mm head diameter by Bearman and Briggs [14]. An example can be seen in Figure 7 in Paper E.

5.3 Process Control

From a process control point of view, the most obvious area of improvement at most crushing plants is the sparse number of measurement points and thus the lack of process data. The measurement points that do exist consist of mass flow meters (belt scales), load sensors (ampere meters), level indicators (light beams, radar, ultrasonic sensors), and machine type specific parameters. On cone crushers, the latter consists of CSS, hydraulic pressure, and the load (power draw or amps).

Hydrocone crushers, equipped with a crusher control unit which controls the hydraulic pump, are operated in one of two possible modes where either the CSS or the hydraulic pressure is kept constant. Since this crusher type adjusts for wear automatically the control question is limited to selection of control method and its setpoint. Crushers in a mining application, i.e. where the purpose is to get as fine product as possible are often operated in the pressure, or power, limited mode. This implies that the crusher is operating as hard as the manufacturer allows, of strength or fatigue reasons. This mode can also be used in the aggregates industry, but there CSS-constant mode is also used. Running the crusher at a constant CSS helps to keep the quality of the produced material high. The particle shape is best for sizes around the CSS [15].

Since HP crushers are seldom adjusted when filled with material, they are adjusted, or controlled, after a specific period of time or when the power draw drops below a certain limit. This results in two disadvantages, which are illustrated in Figure 18. First, while the liners are worn they gradually decline in performance, which is the triangle of lost production in the illustration. Second, when the liners are to be adjusted the production cost can be significant. Even after the feed is running again, it can take several minutes to fill the crushing chamber again. Monitoring during the course of this thesis shows that a typical production loss period is more than five minutes. How often such adjustment is carried out varies from plant to plant, everything between once a week and four times a day is common. If an adjustment is done four times a day and takes six minutes on a plant with one shift this is equal to five percent of the total available time. If not time, e.g. four times a day, an ampere meter is often used as an indicator for liner adjustment.

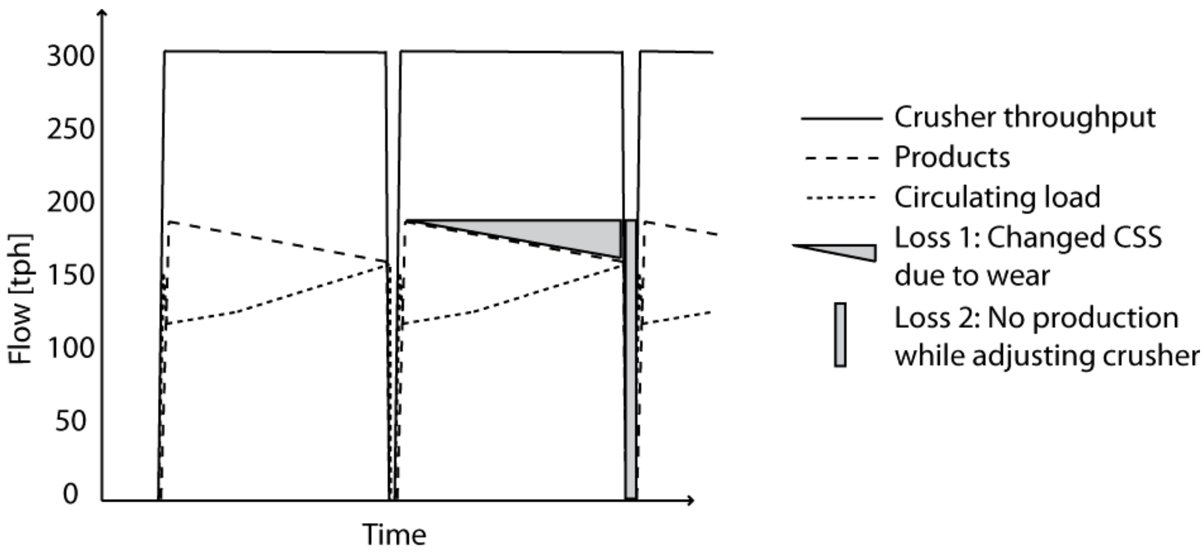

Figure 18. The losses in an HP crusher. The two major losses are depicted with the filled areas.

The selection of setpoints for the process is difficult. One reason for this is the lack of measurement points in the process. Selecting setpoint, i.e. configuring the process is done during the design of the plant or is a heritage if the plant is old. Sometimes steady state simulations are performed with software, for instance Plant Designer (Sandvik), Bruno (Metso), SimMet (JK Tech), Aggflow (BedRock Software). Tests during the commissioning on some parameters are usually performed. The stroke is often used to adjust the capacity. Once these setpoints are selected, sometimes a couple of setpoints in so called *recipes*, they are seldom modified or even questioned.

6 SENSORS

The aim of this chapter is to:

- *Describe sensors suitable for monitoring mass-flows in crushing plants.*
- *Introduce the theory of an alternative, cost-effective mass-flow meter.*

To measure is to know. It is hard to measure the output from crushers and other production units at crushing plants in real-time. Measuring properties of the machines themselves is rather easy; amperes, power, pressure, speed and temperature are commonly measured. Flows are more difficult to measure. One might be interested in the flow, the particle size distributions, particle shape and material properties, such as strength. Since the focus of this thesis is to close the loop from the settings of the machines to the material being produced and back to the optimization system, to measure the material in real-time is crucial. In the past this has not been possible. Typically, particle size distribution is measured by sieving in a laboratory. This is far from real-time. One way to measure particle size distributions in real-time is to use optical belt sensors, which are described briefly below. In this thesis, the measuring method uses material flows from production screens.

6.1 MASS-FLOW METERS

The most common way to measure mass-flows in comminution plants is to use conveyor belt scales. Conveyor belt scales are typically used at one or several conveyor belts due to payment or state regulations. In many production plants, these scales are only installed in a few locations due to cost. As previously stated, there is an increasing need for process flow information in comminution circuits. Real-time process knowledge drastically increases the possibility of process control. In aggregate production, mobile units are becoming more common, and consequently, the economic burden of expensive conveyor belt scales is also increasing. Developing a cheaper belt scale would be of significant economic value.

CONVENTIONAL CONVEYOR BELT SCALES

A classic conveyor belt scale consists of load cells mounted on a scale frame, as depicted in Figure 19. One of the idler frames of the conveyor is mounted on the scale frame, which, in turn, is mounted on the conveyor frame. In addition, a speed sensor is installed on the conveyor. By combining the signals from the load cells, which measure the mass on a given part of the belt, with the speed of the conveyor belt, a measure of the mass-flow is obtained. Conveyor belt scales are described in detail by Soederholm [44].

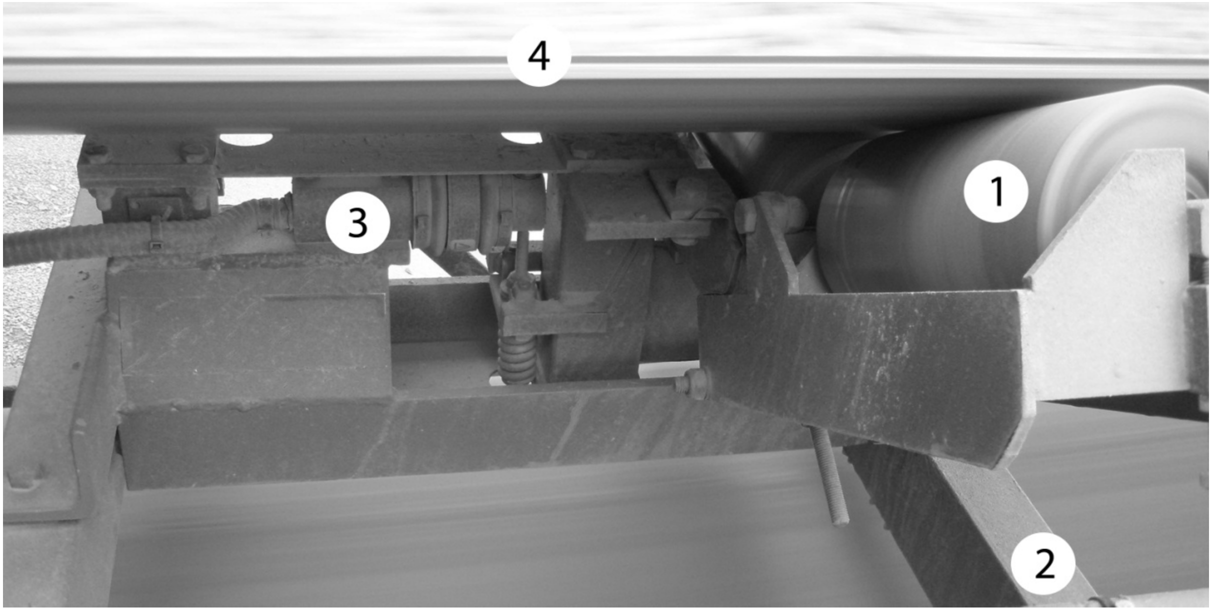

Figure 19. A conveyor belt scale. A set of rollers (1) are unmounted from the frame (2).The vertical force is measured by a load sensor (4), which enables measures of mass-flows on the belt (4). (Photo M. Evertsson)

Load cell-based scales are accurate when the belt is fully loaded and well maintained. However, the accuracy is poor when the conveyor belt is not fully loaded due to the poor linear behavior. In addition, the belt scale requires time-consuming scale calibration and precise roller alignment. For aggregate production plants, the typical calibration error is 0.5-1% when the belt runs with 70 to 90% of its nominal capacity and is 2 to 3% when the range of the load is 20 to 100%. The accuracy of a belt scale is also related to the investment as well as the maintenance costs [43]. Therefore, plants processing more valuable materials or large volumes can invest in more accurate systems, e.g. two scale frames in series.

MASS-FLOW METERS BASED ON ELECTRICAL POWER

Many comminution plants have conveyor belts that lift materials from one level to a higher level. The energy needed to lift a mass a certain height is equal to the mass multiplied by the height and the gravitational constant. Theoretically, the load-dependant part of the conveyor energy consumption is equal to this energy. Thus, it is possible to calculate the mass-flow on the belt by measuring the power draw of the electrical motors of the conveyor. A belt scale that determines the mass-flow by measuring the electric power of the conveyor belt is discussed in paper A. The electric power partly originates from adding height, i.e., potential energy, to the material on the belt. This, of course, only applies when the conveyor is inclined, i.e., does lifting work.

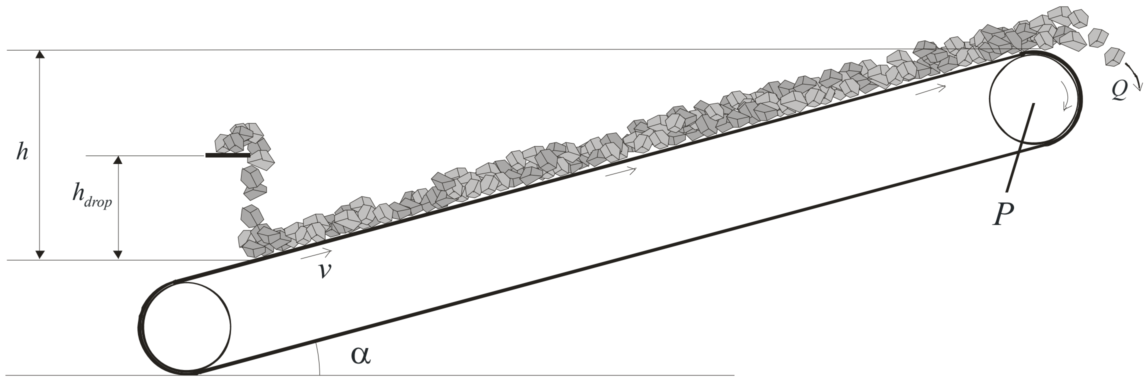

Figure 20. The principles of a conveyor belt lifting material a height h. The particles are dropped on the belt from a height h_{drop}, accelerated to speed v, and lifted to a height h.

The potential energy work for lifting a mass *m* the height *h* is given by:

$$W_{potential} = mgh \tag{1}$$

where *g* is the acceleration of gravity. The parameters for the conveyor belt are shown in Figure 20. When a conveyor belt is lifting material, it converts electrical energy into potential energy of the material. In addition, the acceleration of the material and the loading of the belt also consume energy, as discussed in Paper A. The power can be computed as:

$$P_{material} = \frac{dW_{material}}{dt} = \dot{m}(gh + v^2 + v\sqrt{2gh_{drop}}\sin\alpha) \tag{2}$$

where $\dot{m}$ is the mass-flow, h_{drop} is the height from which the material is dropped onto the belt, α is the angle of inclination of the conveyor, and v is the speed of the conveyor belt. Morin [37] has explained this classic example, but in the formula above the material is being dropped from a non negligible height. If the losses, e.g. due to friction, are neglected, this is the minimum amount of energy required to lift the material.

Apart from this power, other losses occur when electrical energy is converted to material potential energy. A model comprising the electrical motor, the belt transmission, the gear stage, and the belt pulley has been developed for the efficiency, which can be computed as:

$$\eta_{tot} = \prod \eta_i \tag{3}$$

where η_i is the efficiency for the i[th] drive. Using the efficiencies derived from Gerbert [22], the total efficiency of a typical belt conveyor is in the range 0.702 to 0.826. If poorly maintained, this average range can adjusts downwards. In Paper A, the efficiency of a well-conditioned belt, determined by averaging 15 efficiency tests, was found to be 0.758, which is in the published range.

The power that remains after these losses can be expressed as

$$P_{material} = P_{load} \cdot \eta_{tot} \tag{4}$$

where P_{load} is the load dependant electric power. The total electric power is

$$P_{electrical} = P_{idle} + P_{load} \tag{5}$$

where P_{idle} is the idle power. The mass-flow can now be computed as

$$\dot{m} = \frac{\left(P_{electrical} - P_{idle}\right)\eta_{tot}}{gh + v^2 + v\sqrt{2gh_{drop}}\sin\alpha} \quad (6)$$

The causes of idle power are not fully understood and need to be investigated further. The most likely explanations for idle power are mechanical friction losses, e.g. in rollers and bearings, and the dissipative component of the rubber in the belt. For each revolution, the belt is bent two to five times (depending on the belt tensioning system). This causes energy loss. The dissipation of mechanical power depends on the shear modulus, frequency, and the strain rate of the material [29]. The shear modulus for rubber is strongly temperature dependant. Gerbert [23] shows examples of the strong relationship between loss module (E'') and temperature for a typical V-belt rubber. Martins and Mattoso [34] tested used tire rubber and found that the loss factor (tan δ) varied from 0 to 0.54 at -100°C and -30°C, respectively, and back to 0.08 at 190°C. Thus, if the temperature range for conveyor belts is maintained between -30°C to +30°C, conveyor belt power loss decreases with increasing temperature. This is also shown in Paper A, where the idle draw of a conveyor belt at the startup was evaluated as a function of the outdoor temperature; the correlation was 0.874, and the temperature was measured at a distance of 18 km from the belt.

Carlo Gavazzi WM-12 and 14 power transducers were used to monitor conveyer belt power. It is important to use a measurement device that calculates the power as

$$P = U \cdot I \cdot \cos\varphi \quad (7)$$

where U is the voltage, I the current, and cos φ is the power factor. The power factor, often labeled on the electrical motor in the range of 0.85 to 0.9, can be as small as 0.35 for low power draws.

LIGHT BEAM SENSOR

Another sensor used for monitoring the current material flow on a conveyor belt is a light beam sensor, which is mounted on a frame positioned around the material. The frame holds a laser beam that measures the contour of materials that pass through it. This process requires the density of the material to be known, or at least be constant. Such a system is sold by Hartle Sensortechnik GmbH [7]. The price is not significantly lower than that of a traditional belt scale and thus is not further investigated here. The advantage of a beam sensor system is that it can be mounted without affecting the conveyor frame or idling rollers, and it is not sensitive to misalignment.

6.2 IMAGE ANALYSIS

There are a number of measurement systems that claim to directly monitor particle size distributions. Most of these systems use optical sensors. Some systems ([16], [24]) take still images of the material, e.g. in a pile, on the ground or on a conveyor belt (it does not matter if the belt is moving), as shown in Figure 21. As soon as a material is placed in a static pile, the finer particles stratify downward and are hidden by larger, overlaying particles. Therefore, this measurement system struggles to accurately monitor fine particle concentrations due to this fine particle stratification effect. However, this problem can be avoided. Sometimes it is important to identify the top-size of a material flow, and sometimes it is possible to get enough information about the particle size distribution by looking at the coarser end.

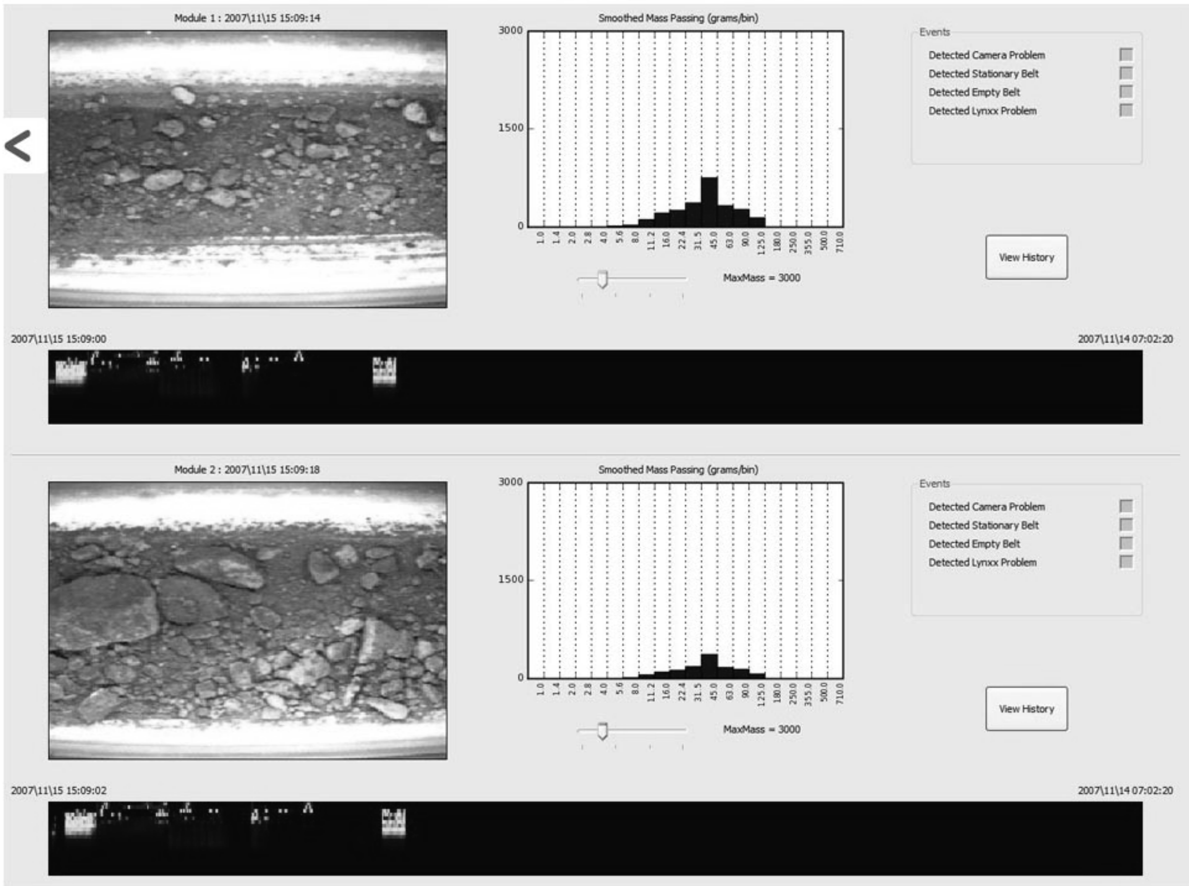

Figure 21. Output from an image analysis system by Stone Three (illustration by Stone Three, published with permission from Stone Three).

Another type of imaging method analyzes images of falling particles. This type of sensor is suitable for laboratories. It was described in detail by Jørgensen in 1990 [27] and has since been developed further [3]. The advantage is that all sizes of particles within the distribution, as well as their shapes, can be measured. Unfortunately systems like these are expensive, on the order of €50,000-100,000. To get a system like this to work for real-time optimization of crushing plants it has to be combined with an automatic sampling system. These samplers are also expensive, but it would probably be a viable solution if the value of the produced product is high.

7 MONITORING AND CONTROL SYSTEM

The aim of this chapter is to:

- *Explain the support system needed to perform real-time optimization of a cone crusher.*
- *Describe the systems developed in this project.*

7.1 OVERVIEW

Real-time optimization at the industrial scale requires a computer or PLC system capable of communicating with measurement devices and actuators. This can be done via several different communication protocols or, in some cases, directly from an analog IO-card to the computer. The collected data and the calculated control signals need to be organized and stored in a database. There must be a processing unit that can calculate the data and interpret it after preset rules. Finally, there must be a user interface to communicate with the operator. This system is illustrated in Figure 22.

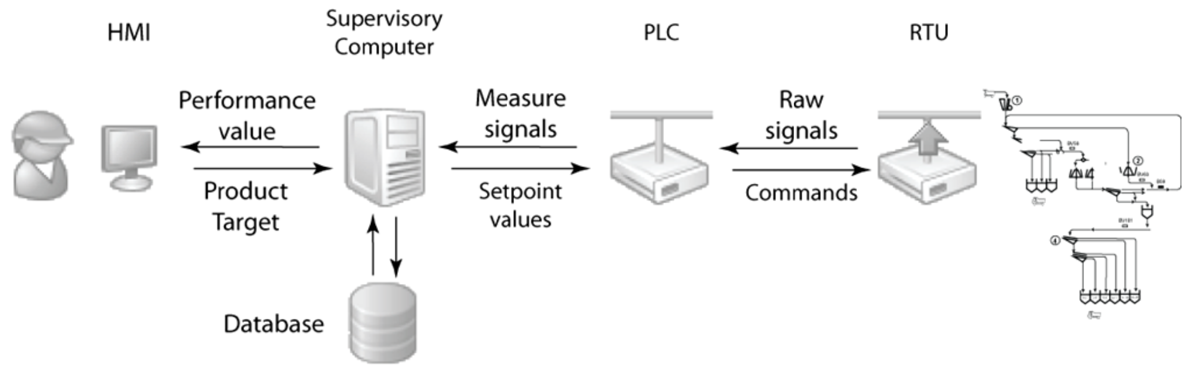

Figure 22. A monitoring and control system needs to be able to communicate with sensors, a database, controllable units, and the operator.

7.2 SCADA-SYSTEM

A Supervisory Control And Data Acquisition (Scada) system is used for controlling industrial processes and for communicating with users. It is divided into five parts [8]:

1. Human machine interface (HMI)
2. Supervisory computer
3. Remote terminal units (RTU)
4. Programming logic controller (PLC)
5. Communication (infrastructure)

Implementation is an important part of this thesis, and Scada systems on different levels have been used as tools. Scada systems are not direct parts of the research questions, but they are crucial parts of real-time optimization. Each part is explained briefly below.

The systems (HMI and the supervisory computer) used in this thesis can be divided into two generations. The first generation was built on a Linux platform with a simple homemade web-HMI (Papers A-C), whereas the second generation is built on a Windows platform with a full industrial HMI package from Iconics (Papers D and E).

HUMAN MACHINE INTERFACE

A human machine interface (HMI) is the interface through which the operators control a process. On old pulpet systems, the switchboard with its buttons was the HMI, whereas on modern computer-based systems, the HMI is made graphically to give a good overview and at the same time be intuitive. Graphical software HMIs are flexible, intuitive, easier to copy, and can be remotely controlled.

A web interface was developed by the author for the first generation of SCADA, see Figure 23. It was developed to facilitate remote control of the system. A remote-controlled Scada helps during both the development and the usage of a system. Using this interface, operators can see material flows, the status of machines as text and graphs, and changes to the operating mode, and they can set limits for the algorithm. The same information can be accessed via the Internet by the author from Chalmers in Göteborg. Successful installation of this kind of system requires that the onsite operators trust the system. If they are not comfortable with the algorithm, they should be able to change limits or manually control the system if necessary.

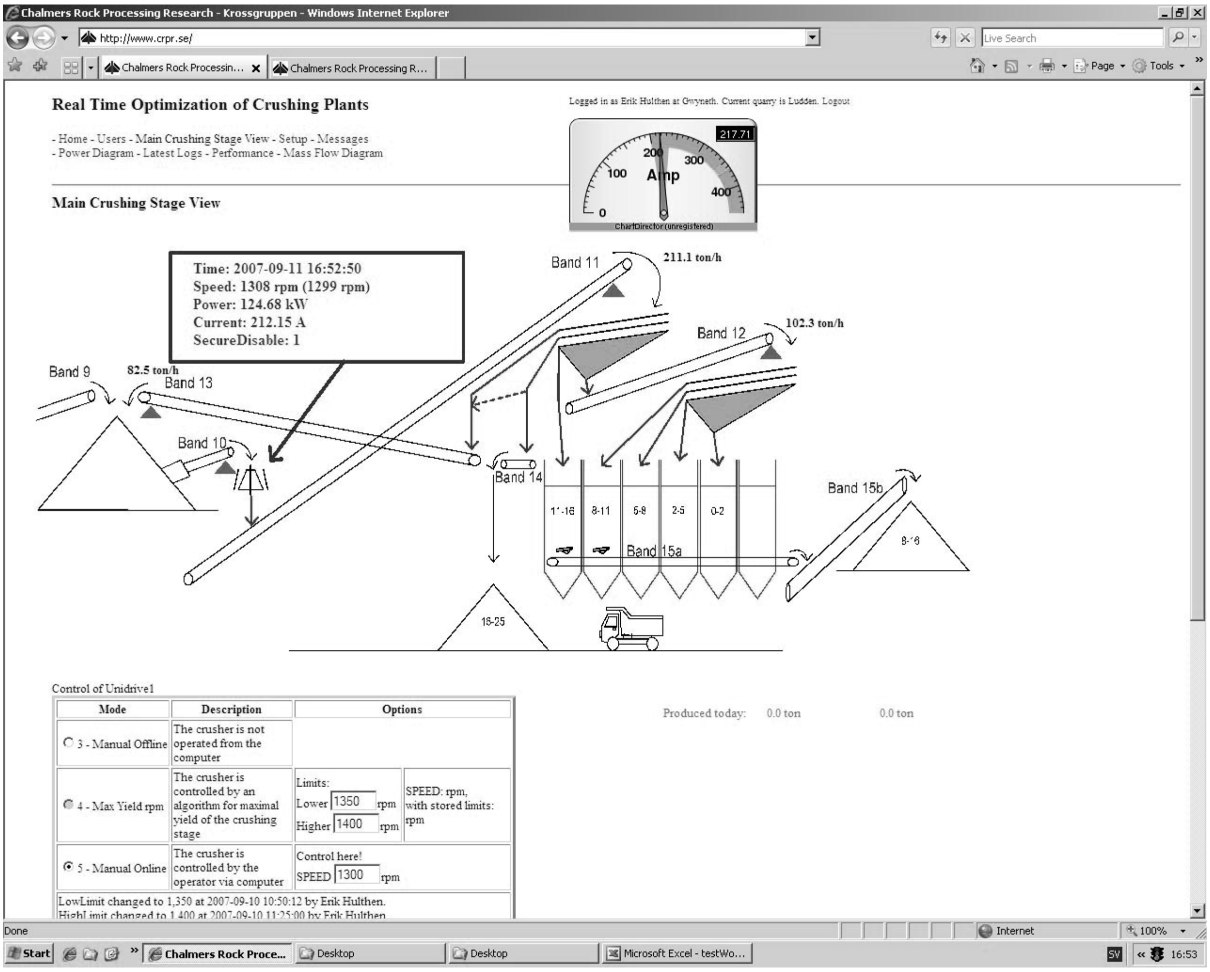

Figure 23. Human machine interface via a web browser. The crushing plant shown is Jehander Ludden's, wherein the eccentric speed optimization tests were first performed (Paper C).

The second generation of HMIs were built on a platform called Genesis from Iconics, see Figure 24. Using this interface, operators can see material flows, the status of machines as text and graphs, and changes to the operating mode, and they can set limits for the algorithm. The system uses a Windows-PC and is widely used the industry. Other manufacturers of HMI platforms include Citect, Siemens, and Wonderware. Some of the benefits of an HMI platform include:

- Standard of graphical illustration of production
- Adaptability
- Connectivity to other devices
- *Plug & play* graphical modules
- Fully supported

These upsides come with the drawback of less flexibility.

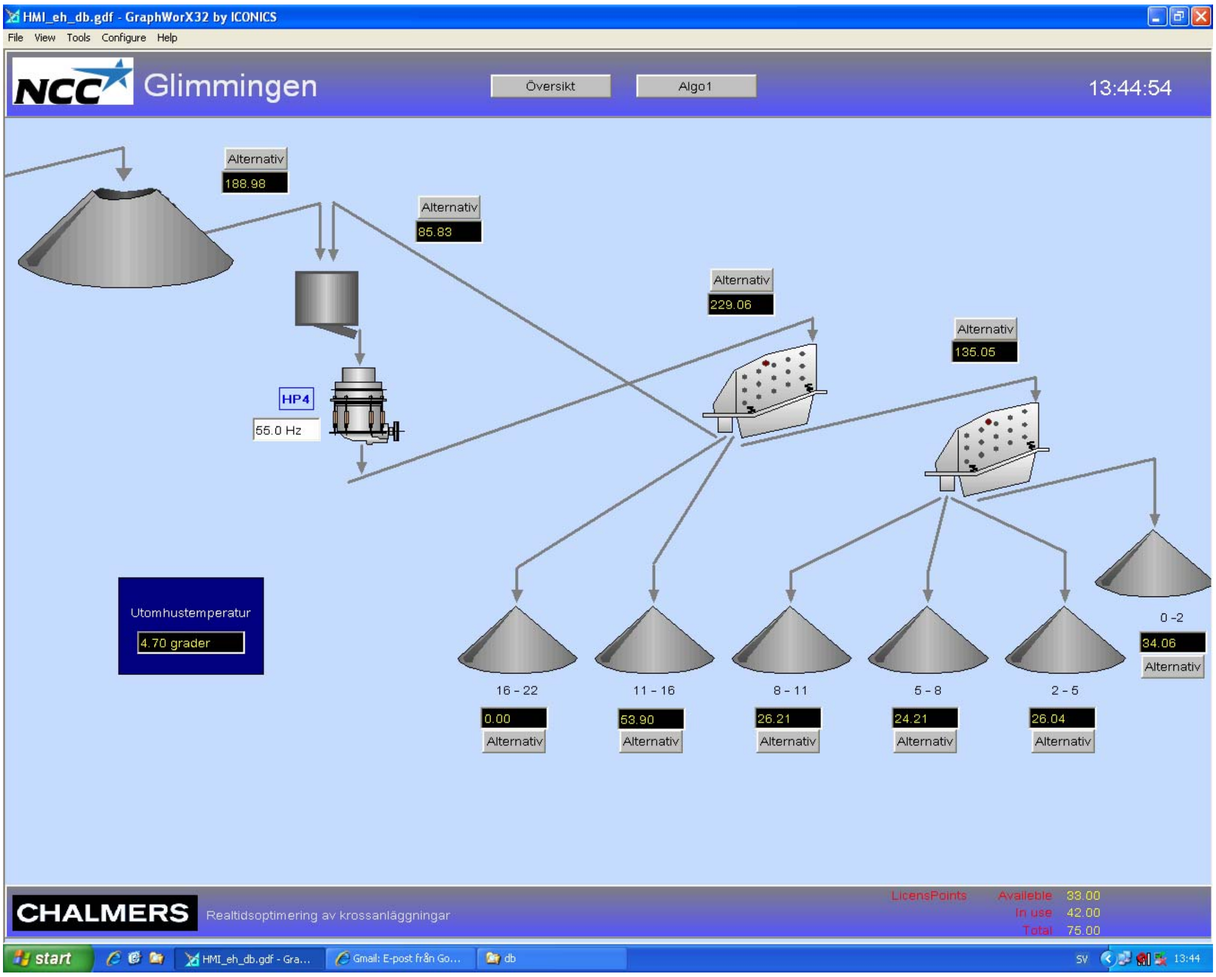

Figure 24. Human machine interface for the research implementation at NCC's aggregates plant, Glimmingen (Papers D and E).

SUPERVISORY COMPUTER

In a Scada system, a supervisory computer is used to display the HMI, to send control signals to the process and to collect data in a database. The process is often controlled and supervised by a PLC (see below). However, the PLC often gets its commands from the supervisory computer.

In this thesis, the supervisory computer is also used for executing algorithms. In the first generation, the supervisory computer was an industrial PC with Linux. The advantage with this was that Linux is very stable and cost effective. This computer had no graphical user interface (GUI), but hosted a webpage with which the operator could monitor the process from another PC.

In the second generation of the system, which was developed in this project, a server with a Microsoft Windows operating system (OS) was used. In this case, the process was monitored from the host computer. The advantage with Windows is that it was easier to maintain.

All measured data and changes are logged and stored into databases. For example, if the set-point limit is changed by a user, then this event is stored in the database and is later used to determine if a process change was caused by the user or by some phenomena in the machines or raw material. In the first generation, the data were loaded into a database using software developed in the programming language C. This software also analyzes the data and provides new set-points based on an algorithm that will be discussed later. In the second generation, an

OPC server (by Kepware) handled the communication to the RTUs, and the scripts were written in Visual Basic, which is included in the Genesis software.

REMOTE TERMINAL UNITS

Remote terminal units (RTUs) can be sensors and or machines in a process. The communication is often digital, i.e., electrical levels that are either on (e.g. +5V) or off (0 V), or performed with a communication protocol, e.g. Modbus or Profibus. Reading values from sensors can either be digital, a communication protocol or analogue, e.g. 0-10 V or 4-20 mA.

In this project, Carlo Gavazzi WM-12 and 14 power transducers were used to monitor conveyer belt power. They were mounted in an electrical cabinet and were retrievable via a Modbus protocol over a serial connection, see Figure 25.

Figure 25. Inside an electrical cabinet on one of the test plants. In the top of this figure, ten power meters can be seen.

Experiments investigating the CSS parameter used a 36” Hydrocone cone crusher with an ASR-C control system. ASR-C stands for automatic setting regulation – computer. The ASR-C regulates crushers toward either a constant CSS or a constant maximum pressure in the hydraulic system. Crusher parameters can be monitored by operators at the ASR-C, which is mounted in a cabinet close to the crusher. Communication with the ASR-C is achieved using a ComLi protocol via a serial connection. All set-points can be modified through this communication methodology, permitting process control.

Cone crusher speeds are changed using frequency converters, SP-series, from Control Techniques. This unit has a number of connection alternatives, e.g. TCP-IP, Can-Bus, and serial connection with a Modbus protocol. Other settings on the frequency converter can be similarly adjusted.

PROGRAMMING LOGIC CONTROLLER

In a Scada system, the PLC is the brain that controls starts and stops, interlocks and collects measurement data from the measurement units (RTUs). A PLC is often more or less distributed, meaning that an analog signal (e.g. 4-20 mA) is connected by a node to the PLC that is distributed. In the node, the signal is converted to a digital signal, which can then be transferred over a long distance to the central processing unit (CPU). PLCs are programmed in special languages to a deterministic behavior. This means that they must be more stable than commonly believed a PC does. An example of a PLC can be seen in Figure 26.

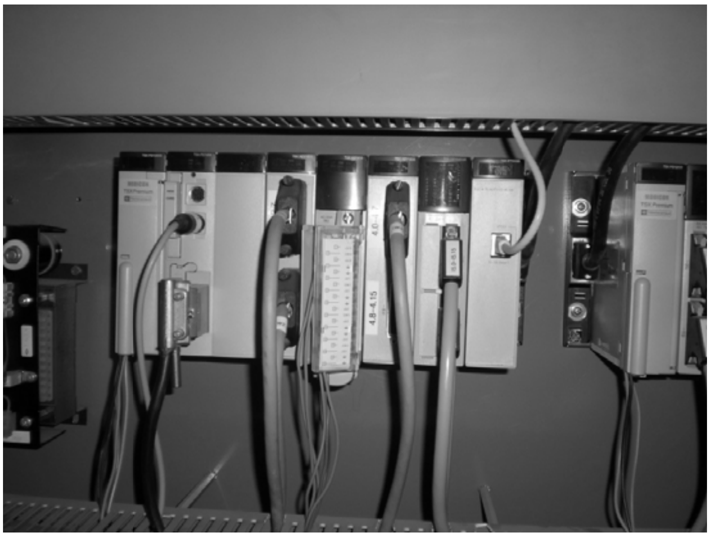

Figure 26. A rack-based PLC from Schneider. The PLC is divided into a CPU, analog and digital IO-modules, and communication modules.

In this thesis, some of the test plants had PLCs, some did not. Anyhow, the measurement and, in existent cases, control was bypassed the PLCs of safety reasons. Thus, the supervisory research computer was connected separately to the RTUs.

COMMUNICATION AND INFRASTRUCTURE

Communication between different units and computers in a SCADA is done via serial connections or Ethernet. Typical protocols are Modbus and Profibus.

In the systems developed here, communication with the measurement devices and controllable production units are performed using the Modbus protocol via serial connections or TCP/IP. In the first generation, the supervisory computer was networked via TCP-IP permitting remote connectivity via intranets and the Internet. This made it possible for the researchers to reach the systems via the Internet as well as by the operators via their local networks. Remote connection has been an advantage during the development of the system. In the second generation the SCADA was stand alone.

8 ALGORITHMS FOR REAL-TIME OPTIMIZATION OF CRUSHING PLANTS

The aim of this chapter is to:

- *Introduce the hypothesis behind real-time optimization.*
- *Explain why normal control theory in practice can be difficult to apply.*
- *Introduce algorithms for selecting set-points of CSS and eccentric speed on cone crushers.*
- *Explain the differences between the finite state machine and model based algorithms.*

The purpose of this thesis is to give set-points to crushing plants to let them perform optimally given the rock material and machine equipment. The rock material varies all the time. The hypothesis is that it is possible to use this variation and control the plant in a suitable way. Earlier chapters have described how the crushing process works, which parameters can be used to manipulate them, how to collect data from the process and how to handle this data and control the plant with a SCADA system. With this information, a skilled operator would definitely increase the yield or performance of the plant. However, in several ways a computer can be more effective than an operator:

- It is hard for an operator to determine what is significant in a signal if it is noisy.
- An operator cannot get an overview of the entire business, including sales, stocks, maintenance, spare part cost, and other factors.
- Their decisions regarding the process will affect many factors and thus the gross profit of the company.
- It is likely that an operator will increase the deviation of the process, which is not desirable from a quality management perspective [12].
- The retention time is longer for the operators than a computer, i.e. the time between a change is introduced until enough information is collected for an operator to draw conclusions and act from it.

For these reasons the author’s wish and aim is to organize many of these decisions and to make set-point selections automatically using a computer system. This is defined as real-time optimization. A computer is also better than humans at handling large numbers of data because a computer is deterministic and can calculate deviations.

Many contemporary cone crushers are equipped with automatic systems to control the CSS and to protect the equipment from over-loading. The settings are determined by the operator most of the time. The quality and the size distributions of feed materials normally change with time. In addition, wear occurs on both the crusher manganese liners and screen cloths. What is the objective of the crushing stage? The answer is to produce the largest possible amount of one or several desired products. The quality of the material, e.g. the particle shape, must be sufficiently high.

8.1 CONTROL SITUATION CHARACTERISTICS

In many processes, the important control issue is to keep a parameter on a certain value or move the process to a certain position when a set-point makes a step change. However, in this situation, there is no target set-point as the best possible production yield will be dependant on the varying feed and wear situation. The goal for the crushing plant is to maximally produce a certain product or to keep the product yield as high as possible. However, the rock material is constantly varying, so the product yield also varies. Thus, there is no obvious set-point. Due to the fact that the set-points are unknown, classic control theory cannot be used. This is a special situation, and it is hard to copy control theories from other engineering areas. Therefore, an algorithm is introduced. An algorithm is an effective method for solving a problem [2]. The output from the algorithm can be a set-point to the controllable parameters on the production units in the process, e.g. CSS or eccentric speed on crushers. In this thesis, two types of algorithms have been tested; Finite state machines (FSM) and Evolutionary operation (EVOP) with an empirical model.

8.2 FINITE STATE MACHINE ALGORITHM

Flowcharts are often used to represent algorithms graphically. An FSM algorithm from Paper B is shown in Figure 27. It is assumed that there exists an optimal setting for each parameter at every point in time, as depicted by Figure 28. However, it may exist constraints, e.g. limited power draw, which make the optimal operating point on the border of the constraint. Several factors can vary over time, so a fair comparison between two different settings at different times is difficult. When determining the best choice of parameter values, usually CSS, several manual, repeated step changes are performed. The performance of the crushing plant before and after the change can then be compared under equal conditions. If there is an overlying trend, it is important to alter the order of the trials, for instance with so called split-plot designs, e.g. by Box et al. [18].

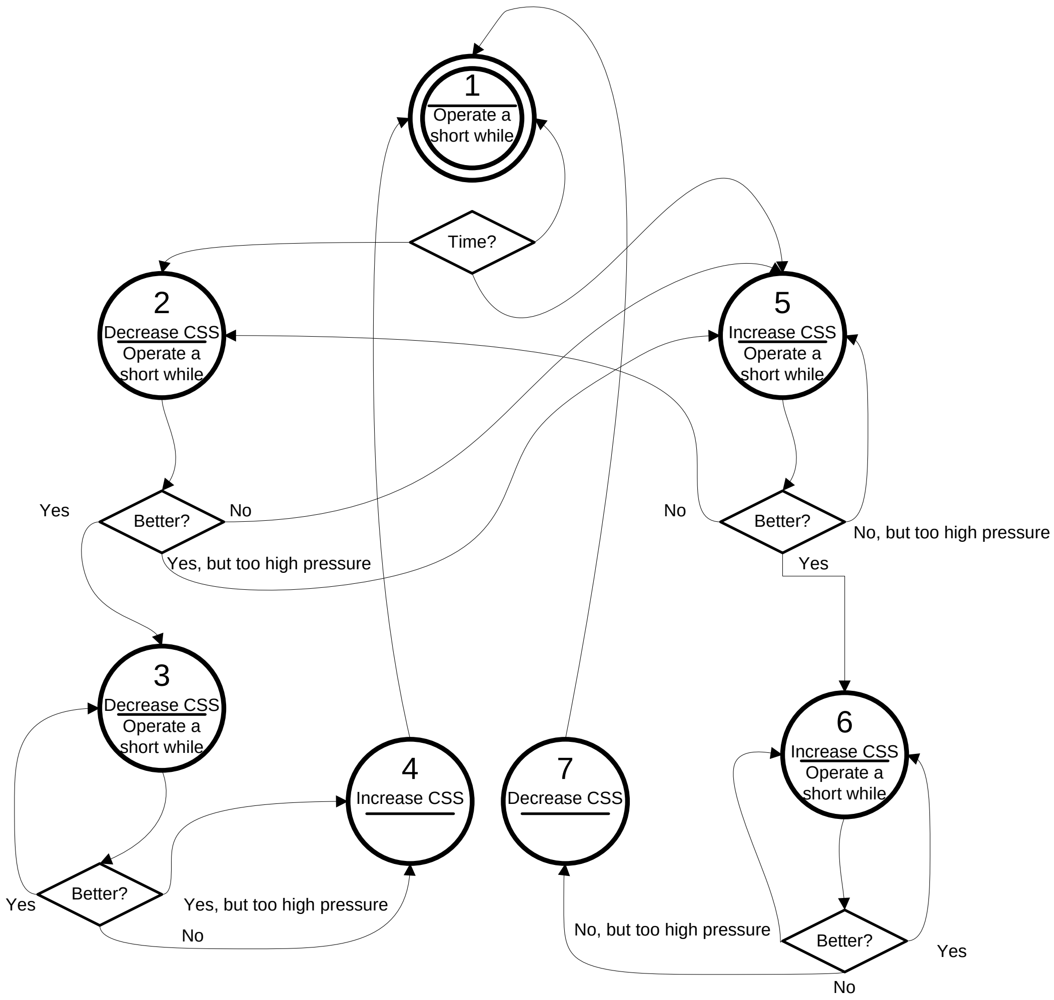

Figure 27. A flowchart can be used for explaining the algorithm more pedagogically. A finite state machine is used in some algorithms in this thesis.

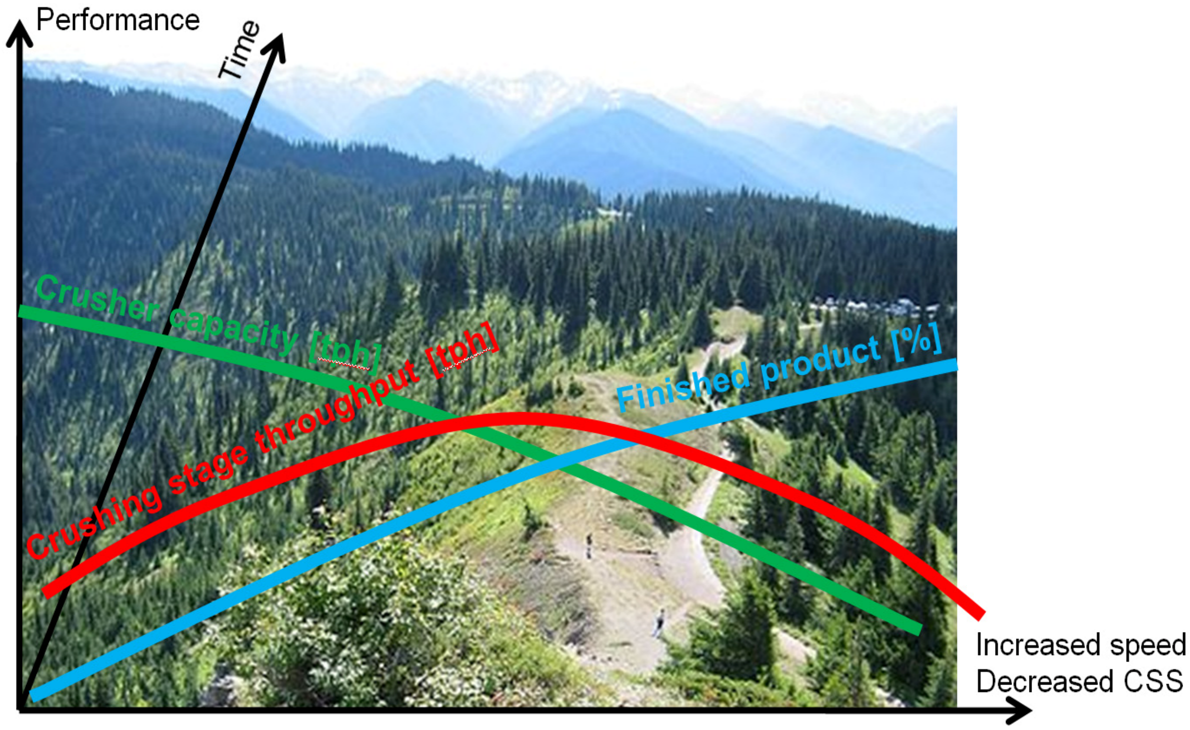

Figure 28. The fitness landscape is compared with a ridge, where time is pushing in the direction of the ridge. At each moment it is assumed that there is an optimal setting of the studied parameter.

ALGORITHM FOR CLOSED SIDE SETTING

Paper B describes the development of the first algorithm. The first algorithm, which was designed as a naïve pathfinder, found an assumed maximum; however, it was oscillatory around a value, which degraded the performance. This can be compared to a PID control system with too much gain, i.e. too high P-factor. A finite state machine (FSM) based on a Mealy machine [35] was subsequently used as an improved algorithm.

The FSM was developed manually (in contrast to a computer generated algorithm) to find an optimal CSS and stay there for a period of time. The structure of the developed FSM is summarized in Figure 27. The developed FSM has seven states, of which two are directly transient, i.e. the action connected to the state is performed thereafter a new state is entered.

The introduction of the FSM also permitted the use of crusher load (hydraulic pressure) when computing the next set-point. The pressure was controlled after each state with an exit condition. If the pressure was too high, then a state that opens the crusher to reduce the pressure is selected. The pressure protection is still performed by the crusher control system, but with this feature, a set-point generating too high of a pressure can be avoided before the crusher automatically stops operation due to a long time period with too much load.

The developed algorithm was tested in a 36” Hydrocone crusher equipped with an ASR-C control system. The algorithm was written in a script and executed in a computer and evaluated the process continuously via belt scales. The goal for the algorithm was to maximize a selected product. The output from the algorithm was delivered as a set-point value to the crusher.

ALGORITHM FOR ECCENTRIC SPEED

The algorithm for the eccentric speed is a development built upon the previously described CSS algorithm. Instead of the crusher control system executing the set-point CSS, the frequency converter executes the frequency of speed change of the asynchronous motor turning the eccenter. The states for avoiding high pressure were removed. The eccentric speed algorithm is thoroughly described in Paper C.

The developed speed algorithm was implemented and tested on a Metso Nordberg HP300 (Paper C) and confirmed on a Metso Nordberg HP4 (Paper D). The algorithm was written in a script and executed in a computer. It evaluated the process continuously via belt scales. The goal for the algorithm was to maximize the yield of a certain product. The output from the algorithm was delivered as a set-point value to the frequency converter.

There is a significant difference between a CSS-controlled and speed-controlled crusher in terms of the electrical current behavior (measured in amperes). At the test plant, operators use a current meter to determine when they have an acceptable CSS. When they turn the top shell part of the crusher with the hydraulic motor to decrease the CSS, the current increases. The crusher responds to an increased speed by pulling less current. It is important to inform the operator of this fact.

8.3 MODEL-BASED ALGORITHM

The idea behind a model-based algorithm is to actively use several parameters to control the process. The FSM algorithm above also uses a model, see Figure 28. While working with the FSM algorithm in the NCC Glimmingen aggregate plant, a large quantity of data was collected and subsequently used for fitting the model.

The data from the first trials in Glimmingen were used to build a simple model for the crushing-stage performance during one stint. A run is the operating time, e.g. between two CSS adjustments on a crusher of the HP type. On a Hydrocone crusher, runs are short and occur often if operated intermittently. In the best case, a run can last the entire shift (or more, if operated over several shifts). The model, which was described in Paper D, resembles a hill or a mountain ridge, see Figure 29. It has the mathematical form:

$$\hat{y} = a + bx_1 + cx_2 + dx_1{}^2 + ex_2{}^2 + fx_1x_2 \tag{8}$$

where $\hat{y}$ is the crushing-stage output, x_1 is the eccentric speed, x_2 is the time since the last CSS adjustment, and $a - f$ are constants. During later tests, the constant e was shown to be very close to zero. This means that the quadratic term in the time since the last liner adjustment is almost negligible.

When the model is tuned and accepted, the algorithm simply follows the top of the ridge. As the time since calibration increases, there is always an optimal speed adjustment, which, according to Equation 8, is linear. This linear change of eccentric speed was tested in Paper D.

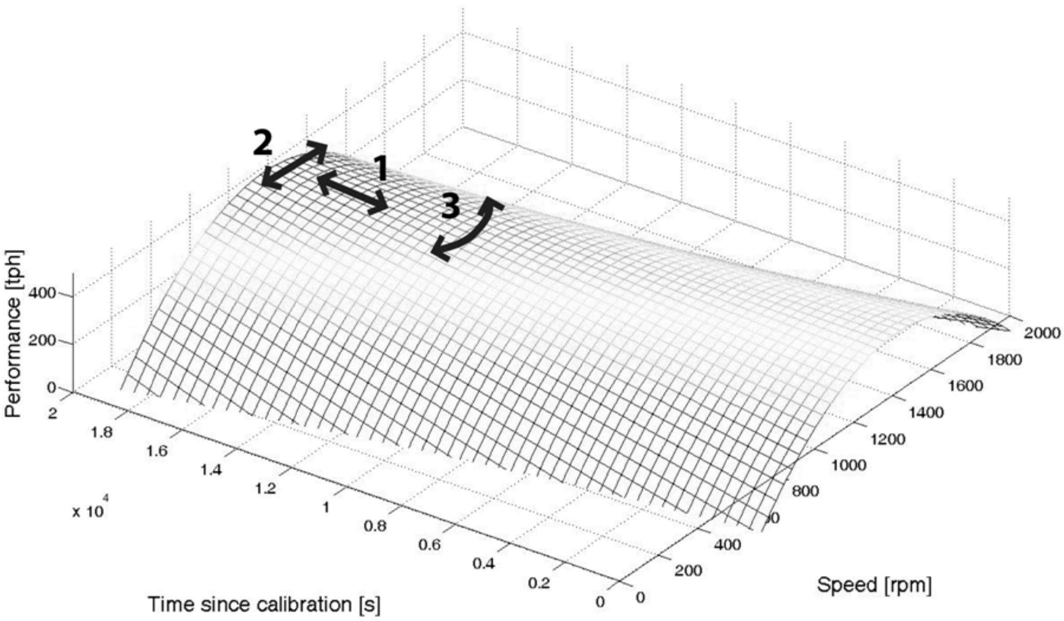

Figure 29. The suggested and fitted model for the crushing stage performance looks like a ridge. The parameters are speed and time since the last CSS adjustment. In the EVOP test, parameters 1-3 correspond to CSS, start speed and speed change rate, respectively.

Considering a Continuously Changing Closed-Side Setting

In Paper E, the model in Equation 8 is applied, but the issue here is how to use it to improve a process automatically. Therefore, an Evolutionary Operation (EVOP) approach was implemented on the same Metso crusher from the Nordberg HP range. The CSS was adjusted regularly, but not dynamically, typically every two or three hours of operation (this depends, of course, on the application). When the liners become worn the crusher must be empty of material before the CSS can be adjusted, because of the design of the crusher. The CSS is adjusted by stopping the feed, unclamping the thread, turning the top shell, clamping, and restarting the feed. This takes six to ten minutes before the process is up and running in steady-state mode again. Therefore, this adjustment can only be performed, at most, a couple of times during each shift. Every operating time period between adjustments can therefore be defined as a *run* in an EVOP context. Taking the model and the crusher-type limitations into consideration, three parameters are resolved:

1. Power draw when adjusted. If the power draw is high, the CSS is small. This implies high reduction but decreased capacity. A small CSS will also lead to a longer runtime before a new adjustment is needed.
2. Eccentric speed when the run is started, n_0.
3. Speed change, i.e. how much the eccentric speed should be changed, e.g. every ten minutes.

These three parameters are illustrated in Figure 29 and correspond to positioning of the model in x and y direction and rotation in the x-y-plane. Because Parameter 1 (Power Draw) is dependent on how much the gap is tightened, this was excluded as a controlling parameter in the EVOP algorithm.

The main reason why fixed settings are not optimal is that several factors in crushing plants vary with time. In addition to the short-term wear period of the crushing chamber discussed above, the factors that are beyond operator control are raw-material variation, screen-cloth wear, and total crushing-chamber wear over its useful lifetime.

The developed EVOP algorithm was implemented and tested (Paper E). The algorithm was written as a script and executed on a computer. It delivered set-point values to the frequency converters based on the different runs in the EVOP. The process was monitored and logged continuously via belt scales. After a set of runs, when entering a new phase, new directions for the EVOP were taken by the author based on the information from the previous phase and a knowledge of the process and its constraints. As stated previously, EVOP is a manual method.

9 RESULTS AND DISCUSSION

The aim of this chapter is to:

- *Present and discuss the results from previous chapters.*
- *Discuss the work in more general terms.*

POWER DRAW BASED MASS-FLOW METERS

The power draw based mass-flow meter, described in Chapter 6.1, was tested on an inclined conveyor belt with a belt scale mounted on another belt in series. The worst error during a test day was 2.33%, with an average error of 1.12%. The coefficient of correlation between the power draw based mass-flow meters and the belt scale was 0.998.

Power-based mass-flow meters have been used in this project since 2006 for measuring flows for process control in Fjärås (3 units), Ludden (4 units) and Glimmingen (10 units), 17 units altogether. The companies involved in this project have installed these sensors on additional belts, a total installation of 62 belts.

Both the validation of the belt scales in Kållered (Paper A) and the fact that it was possible to use them for process monitoring at all other plants in this work, i.e., Fjärås (Paper B), Ludden (Paper C) and Glimmingen (Paper D and E), demonstrate that the belt scales do work for this purpose. The most common doubt about them is usually related to what might happen if an idler gets stuck, i.e., the increased friction between the rubber belt and the idler might increase the idle power draw and, because the belt scale cannot differentiate between idle power and material power, it might show an increased mass flow on the display. However, for the purposes of the belt scales used in this work, such a stuck roller would increase the measured flow if this occurred but would then continue to show a too-high mass flow. Thus, the next time this flow is used for monitoring a step change of a parameter it will give the correct direction again. This works as long as the comparisons are made within a short period of time. This also raises the possibility that if the idle power draw is carefully monitored, it could be beneficially used for preventive, or even predictive, maintenance. Although classical belt scales are negatively affected by the tough environment in a crushing plant, they are usually only calibrated once a year, however, many things can happen during this time. Two further reflections can be made on the performance of power-based belt scales: they work better on a belt with more inclination and they work better on newer or well maintained conveyors.

REAL-TIME OPTIMIZATION WITH CSS

The CSS control algorithm was tested on an Allis Chalmers 36” Hydrocone crusher. The crusher was operated by alternating between a fixed CSS and an algorithm-controlled CSS to determine the effectiveness of the algorithm. Due to large variations, the evaluation took place over the entire period of the fall of 2007. The crusher was often limited by pressure rather than the CSS setpoints. The reason for this was that the target product was a very fine product (2-5 mm) and thus required a large reduction ratio which leads to a high hydroset pressure. In the cases where the desired CSS was achieved (by the algorithm or a constant value), the algorithm was 3.5% better on average than the constant CSS. A *t*-test was performed, showing that the algorithm was better under a 3% significance level, meaning that the algorithm was better than the constant CSS with 97 % certainty.

The work on adjusting the CSS on a crusher with a control unit demonstrates that the focus must be shifted from the crusher itself to the process as a whole. The fact that the crusher was often limited by the pressure means that it did not matter what algorithm was used to set the CSS, as it could not be maintained. Therefore, a shift from CSS control to load control should be considered, i.e., with the crusher tightening the CSS until the pressure or motor power becomes too high. However, this is actually a decision that an algorithm could possibly make.

REAL-TIME OPTIMIZATION WITH SPEED

The speed control algorithm was tested on a Metso Nordberg HP300 cone crusher, which was operated in a closed-loop configuration during the late fall of 2007. The crushers were operated in three different modes: a fixed standard speed of 1500 rpm, a speed corresponding to the operator’s choice, and a speed determined by the algorithm. The operators chose which mode was used. The algorithm was tested during a full mantle lifetime. Every time the mode was switched, a comparison between the prior and the new operating modes was performed. The crushing-stage total throughput, which increasing was the plant management’s highest-priority goal, was increased by 4.2%. A *t*-test showed the superiority of the crushing operation with either the operators’ choice of speed or the algorithm speed over crusher operation at a standard speed at a significance level of 0.05%. This means that with 99.95% certainty, the operator/algorithm together was better than the standard speed. The same algorithm was also tested on a Metso Norberg HP4 cone crusher operated in a closed-loop configuration during the fall of 2009. Here, the results, shown in Table 1, were confirmed with the algorithm showing a superiority of 5.3% compared to running at the best fixed speed. Compared to the OEM-specified speed, the superiority was even higher, at 16.7%. However, the tests with the HP4 were not performed on the same statistical grounds as those with the HP300.

Table 1. Results with different modes in Glimmingen.

	Method:	**Ridge-model**	**FSM**	**1380 rpm**	**1500 rpm**
	Results at 7200 seconds operation in one stint	262.5 tph	258.4 tph	245.5 tph	221.5 tph
Comparison:	Ridge-model	-	1.6%	6.9%	18.5%
	FSM		-	5.3%	16.7%
	1380 rpm			-	10.8%

The results from the two plants with speed control on the HP crusher types demonstrate a huge potential. It is strange that frequency converters have not been implemented on a wider scale. The reason is probably a combination of several factors, and a lack of process monitoring and the cost of frequency converter the two most important. As a conservative business, the aggregates industry has not accelerated this development. Some people consider frequency converters unreliable. It is understandable, however, that if you cannot measure things and the environment is tough, it is probably a good idea to keep things simple.

An unexpected result was that the mantle lifetime increased by 27% during the HP300 trials in Paper C. Since these trials and because of the achieved improvement, the plant management has not allowed any running at a constant speed. The explanation to this result is beyond the scope of this thesis but is believed to depend of changed internal dynamics in the crushing chamber or a difference in work hardening of the crusher manganese liners.

REAL-TIME OPTIMIZATION WITH TWO VARIABLES

The model-based algorithm, described in Paper D, follows the top of the modeled “ridge” linearly. The operators normally adjust the crushers every two hours. Therefore, a time of 7200 seconds was chosen as the period for which performances were compared. The results, shown in Table 1, were an improvement of 6.9% compared to the best fixed speed. Compared to the OEM speed, the improvement was 18.5%. Note that there is no statistical confidence associated with these numbers as in Paper C, although the trend was repeatable.

The EVOP approach, which is tested in Paper E, is intended to change the parameters of the linear dynamic algorithm. An economical optimum for the time between CSS adjustments is probably between one and two hours. Therefore, a time of 5000 seconds was chosen as the period for which performances were compared, regardless of whether or not a run was continued for a much longer time; runs of less than 5000 seconds were neglected. The reason why 7200 seconds was not chosen, as in Paper D, was that too few of the runs would then be taken into account, and EVOP requires several runs with each configuration in a phase. Note that these several runs were not performed in consecutive order.

The EVOP was run in four phases. The results can be seen in detail in Paper E, Table 1. The most important to note are that in every phase there was a difference of between 20 and 30% between the best and worst runs. After Phase I and II, an increase in performance was observed when moving to a slower speed and a lower speed increase. After Phase III, the direction was the same, but the best performance was the same as the center point. Then, after a change of liners, in Phase IV the speed and speed increase continued to point downwards. The actual speeds with the different algorithms are shown in Figure 30. During an entire liner lifetime, the difference in performance was more than 100 tph, or 50%.

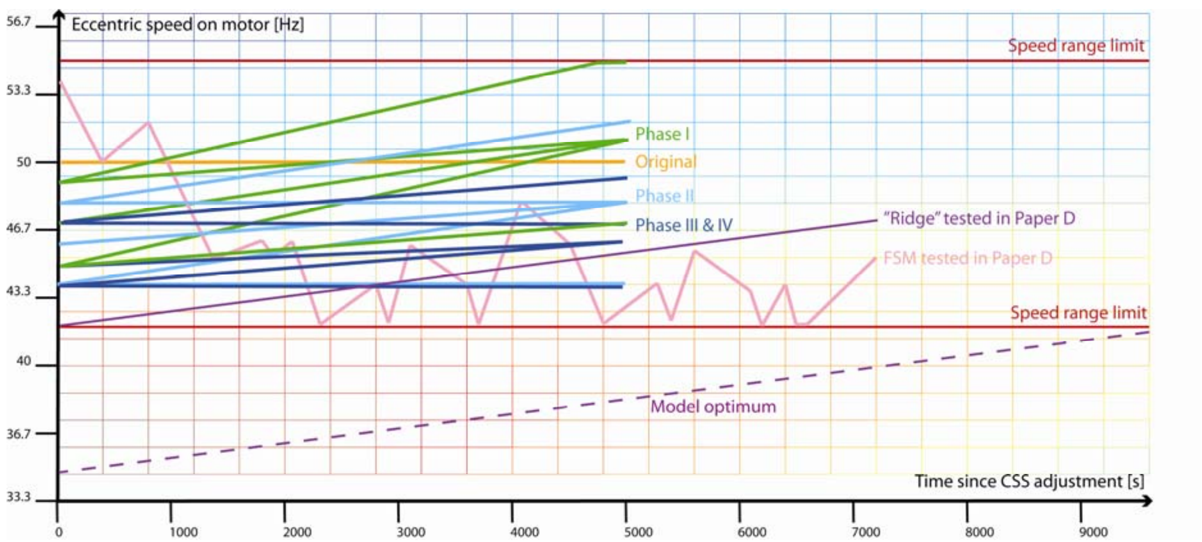

Figure 30. A comparison of the actual speeds in the different phases of the EVOP, the "Ridge" and the FSM.

When combining several parameters, it is important to change the parameters in controlled combinations. In this work, the level of two parameters was controlled, however, only one (speed) was actively and continuously variable. It was not possible to control the other (CSS) because of the limitations of the crusher type. The introduction of a model with two variables increased the improvement from 5.3% to 6.9%. Because speed and CSS are two different parameters that affect the crusher differently, the combination of the two is important.

ALGORITHMS

An algorithm is an effective method for solving a problem. In this work, two different kinds of algorithms were used. First, the FSM was chosen to optimize one parameter on single crushing stages operated in closed circuit. The reason for selecting an FSM was that it is both possible to configure manually, as in this thesis with appended papers, but also automatically by for instance an evolutionary algorithm (EA), described e.g. by Wahde [47].

While the FSM successfully optimized one parameter at the time, the EVOP, in contrast, could find the correct directions for optimizing the combination of two parameters. The EVOP-algorithm clearly pointed towards lower speeds and smaller speed changes. To understand this, new adaptations of the models were made from data collected during the EVOP tests. The result, as shown in Figure 30, was that all runs were performed at higher speeds than the model optimum. Thus, the correct direction for any algorithm was downwards. The EVOP algorithm successfully gave the direction for the dynamic optimal speed. In comparison with the earlier algorithm, FSM, the EVOP algorithm is less sensitive to noise and more stable. However, it cannot react to short-term variations, e.g. changes in raw-material properties. EVOP is therefore more likely to be suitable for a crusher where the CSS can be kept constant. EVOP can be useful for evaluation and parameter testing when building new models (incorporating new understanding) of the process.

GENERALITY

The models used in this thesis (Papers B, C and D) are created with the general knowledge of the process behavior, for instance knowing that a decreased CSS will also decrease the capacity, and that the wear of an HP crusher will decrease its performance. However, the process models do not include a mechanistic model of the crusher. At this stage, the models have been created in order to repeat the most significant behaviors of the process, rather than to include too many parameters and thereby risking difficulties in explaining inconsistencies from data or the risk of fitting noise to the model.

Real-time optimization as implemented here is so general that it can probably be applied to a VSI crusher so that its rotor speed becomes optimal. The speed of the rotor will in turn affect both the reduction and the capacity [42]. Since the crusher, the screen cloths and the feed material also change in this crusher type, a similar situation as with the cone crusher will arise.

In this thesis, a single crushing stage at the time has been optimized. From a plant perspective this is probably a sub-optimization if no other actions are taken. For example, if the demand for material is larger than the possible supply and a real-time optimization algorithm increases the production with X percent, then X percent more material can be sold. But if the plant already produces what it can sell, real-time optimization will instead result in the possibility of the maintenance being planned differently and thus stop hours to be saved. Different parts of the plant can have different goals, but they will affect one another. There is thus a risk for sub-optimization and therefore a general plant optimization which also takes plant economics into consideration is recommended, described e.g. by Svedensten [46]. Also with a real-time perspective there are examples where coordination of the local crushing stages is needed.

Generally, the operators on the test sites were very positive in their feedback. There is always the risk that they might feel watched when introducing more sensors and on-line connections as in some of the tests here. However, the overall feeling was nevertheless positive as the operators felt that someone actually cared about their work.

10 CONCLUSIONS

The aims of this chapter are to:

- *Present the most important conclusions drawn in this thesis.*
- *Answer the research questions stated in Chapter 2.*
- *Discuss what has been found important for future work but not researched.*

The purpose of this work was to monitor the material mass flows in crushing plants and to tune crusher control parameters to improve process performance. During the course of this work, two generations of monitoring and control systems were designed and implemented. These systems can communicate with sensors and actuators (for crushers), store data, process data, and communicate with users via graphical user interfaces.

Crushing plants can be very different in their layouts, and thus there is a need for a general system that can be adopted to many crushing plants. This work therefore focused on developing a new theory and methods to be used as a toolbox for solving different crushing plant problems.

10.1 GENERAL

The intention of this work was to find methods for the real-time optimization of crushing plants, rather than maximizing the output of a single plant. To be able to truly optimize a crushing plant, several things are required:

- An understanding of the customers and the market situation to know exactly what would be the most beneficial to produce.
- Models of the equipment and the process.
- Sensors able to monitor everything important in the process but nothing else.
- Computers fast enough and equipped with an algorithm to calculate the perfect settings in real-time, including all the factors mentioned above.

It cannot be stated that everything mentioned above is in perfect order. However, the author does not doubt that that is the direction we are heading. This work does contain some elements of each point above, in particular, models of the process as a basis (Papers B, C and D), but here the models are not too detailed. At this stage, there might be a risk of fitting the models to noise and odd phenomena at singe-crushing plants instead of understanding the models. Optimize a plant in steady state either manually or with one of the software programs mentioned above would be a good start, and adding the time dynamics as a factor in the future will make these simulations even better. However, this does not contradict the practice of adjusting the plant in real-time while depending on un-modeled phenomena. Today, these phenomena are mainly machine wear and raw material properties. In the future, it may be other factors. The FSM algorithm described above can handle unpredictable things on a short time scale (hours), while the EVOP approach, as tested here, is better for optimization when the parameters do not change quickly. Additionally, the EVOP approach can be very good for evaluation and parameter testing when building new models (incorporating new understanding) of the process.

A recommendation from the author is to run a HP type crusher with a frequency converter and an FSM algorithm. For the Hydrocone crushers, the EVOP is probably a good way of continuously trying to find the best combination of speed and CSS.

10.2 Answers to the Research Questions

Here the answers to the research questions stated in chapter 2.2 are given.

Is it possible to improve the production process by complementing these open-loop systems with feedback from the process and product yield and thereby obtain a closed-loop control system?

Yes, it is definitely possible. These results obtained from testing both algorithms show that using a system in addition to the machine-specific system can control the crushing process with respect to the amount of products produced. In practice, an improvement of 4.2% has been demonstrated on an HP crusher with a frequency converter. On a Hydrocone, a ~3.5% performance increase has been demonstrated on a crusher equipped with an automatic setting regulation system using a closed-loop feedback data input from the process. The control of a crushing process with a varying feed is an unusual control problem as there is not a known setpoint. The absence of a setpoint value can be solved by using an algorithm that continuously improves the process.

In order to control crushers using information about the product yield, it is necessary to monitor the material flows at many different positions in the process. Is there a more cost effective alternative to expensive belt scales?

The algorithm tests and the belt scale tests demonstrate that materials flow monitoring can be performed with sufficient accuracy by measuring the power draw of the conveyor belt. It is possible to accurately monitor materials flows and product yields in the process by measuring the electrical power on inclined conveyor belts. This has been demonstrated by comparing tests conducted with traditional belt scales as well as in two full-scale process control cases. Changes in the process are difficult to observe due to noise, spread, and natural variations. Repeated or continuous measurements with statistical analysis are required to accurately measure changes in the process.

CSS is the most common control parameter for adjusting the product from cone crushers. Is it possible to use other parameters such as eccentric speed for real-time optimization?

The results from the tests investigating the effect of speed control on a cone crusher clearly show that the eccentric speed parameter can be used to control and improve the process. Speed is an important machine parameter that, up to now, has not been used for active control of cone crushers. It has been demonstrated to have a great impact on the efficiency of cone crushers. It can also be used to compensate for both slow changes in the crushing chamber geometry and wear and input material variation and to tune the product particle size distribution.

Is it possible to optimize the process with two real-time adjustable parameters at the same time?

Yes, on an HP crusher, the speed can constantly be used to compensate for the lack of CSS compensation. The results obtained from tests in which both CSS and speed were taken into account show that the total performance space that can be accessed by tuning the parameters is about 20% on an HP crusher. Not all crushers are operated in the worst-case scenario, making roughly half of this increase possible in practice. Typically, a performance increment of 6.9% has been demonstrated.

Is it possible for a real-time algorithm to perform the optimization described above?

Natural stochastic and systematic variations in the crushing process can definitely be taken advantage of and be compensated for in order to improve the production yield in a crushing process. A finite state machine (FSM) has proved to be a successful way of creating an algorithm capable of selecting setpoints for the CSS and the speed, respectively. An algorithm inspired from EVOP can be used for tuning long term optimization with feed-back from the process on a continuous basis.

10.3 Future work

Several things have been investigated and put together to achieve real-time optimization in this thesis, and subsequently improvements can be done in several areas:

- The development of improved sensors, e.g. image analysis equipment directly after the crusher, would make it easier to optimize crushers with respect to the products, because more measurement points on the cumulative particle size distribution will be accessible. As an alternative to image analysis, the use of mass-flow meters after screens would be much more applicable if they could be placed on horizontal belts to a reasonable cost.
- To improve the models of the process behavior and have a simulation environment where the algorithms could be improved automatically would probably be fruitful. Especially the FSM algorithm is suitable for such training.
- Real-time optimization for only one crushing stage (a crusher with consecutive screens) has been investigated. A crushing plant often has several consecutive crushing stages. In order to avoid a sub-optimization, the entire plant must be optimized simultaneously. This applies also when the optimization is performed in real-time. To optimize the entire plant also economics, stocks, maintenance and scheduling would be necessary to include.
- The phenomenon with the extended lifetime of the liners in Paper C can have several explanations (less long term changes on crushing chamber, changed wear hardening) and an investigation why this phenomenon occurs would be interesting.

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