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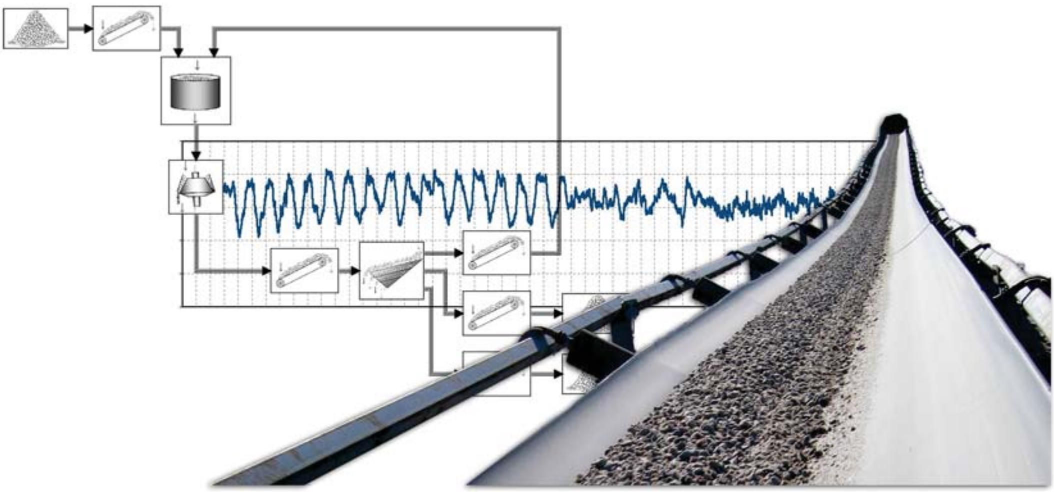

Modelling and Simulation of Dynamic Behaviour in Crushing Plants

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Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2013

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

IN

PRODUCT AND PRODUCTION DEVELOPMENT

MODELLING AND SIMULATION OF DYNAMIC BEHAVIOUR IN CRUSHING PLANTS

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"When You Come to a Fork in the Road, Take It!"

Yogi Berra

ABSTRACT

Crushing plants are a vital part in the production of aggregates and metals. Plants are traditionally simulated with a steady-state simulation. With steady-state simulation the plant is simulated until equilibrium is achieved. However, crushing is a continuous process and as such it is subjected to variations and changes in performance depending on the dynamics of the system. A different technique is therefore necessary to estimate the real behaviour of the plant.

The main hypothesis in this research is that crushing plants are affected by both gradual and discrete changes in the process which alter the performance of the entire system, making it dynamic. A dynamic simulation is defined here as continuous simulations with sets of differential equations to reproduce the dynamic behaviour of a system. Crushing plants experience different operating performance depending on the configuration of each individual process unit, the configuration of the plant, the design of the control system, events occurring in the process and additional disturbances. Three different application areas for dynamic simulation have been demonstrated in this thesis: plant performance, process optimization and operator training. Each of these areas put different constraints on the modelling and simulation of crushing plants.

Traditional steady-state plant simulations are able to provide an overall estimation of the ideal performance. Plants can however experience changes in performance during operation. Plant simulation for an unstable plant has been performed in order to increase the level of stability of the operation. Simulations and experiments of different operational strategies revealed that a higher level of stability was possible with different configuration on specific production units.

Development of control systems is important for the operating conditions in a crushing plant. Real-time optimization is a relatively new field in aggregate production which aims to optimize the production in real-time with the help of advanced process control algorithms. One way of achieving this is with a Finite State Machine. By connecting a Finite State Machine algorithm to a dynamic simulator, tuning of the control parameters becomes possible. Even though only a marginal improvement was estimated with optimized parameters, located with a genetic algorithm, it is an important step in control system development.

The system structure required to enable operator training was built in the Chalmers Rock Processing System laboratory. The fundamental framework around the system is built on the dynamic simulator. The process is simulated in real-time and information from the simulated process is communicated to a Human Machine Interface and a Programmable Logic Controller. With this system, different scenarios can be simulated to assist the operator in gaining knowledge and experience.

In conclusion, dynamic simulation of production processes has the ability to provide the user with deeper understanding about the simulated process, details that are usually not available with traditional steady-state simulations. Multiple factors can affect the performance of a crushing plant, factors that need to be included in the simulation to be able to estimate the actual plant performance. The dynamic response of a system is determined by the characteristics of the system involved and the changes in the process.

Key words: Modelling, Dynamic Simulation, Crushing, Screening

ACKNOWLEDGEMENTS

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Gauti Asbjörnsson

Göteborg, February 2013

PUBLICATIONS

This thesis contains the following papers.

Paper A: Asbjörnsson, G., Hulthén, E. and Evertsson, C. M., *Modelling and Dynamic Simulation of Gradual Performance Deterioration of a Crushing Circuit - Including Time Dependence and Wear*, Minerals Engineering (Journal), 2012, Volume 33, pp 13-19.

Paper B: Asbjörnsson, G., Hulthén, E. and Evertsson, C. M., *Modelling and Simulation of Dynamic Crushing Plant Behaviour with MATLAB/Simulink*, In press at Minerals Engineering (Journal), 2012.

Paper C: Hulthén, E., Asbjörnsson, G. and Evertsson, C. M., *Tuning of Real-Time Algorithm for Crushing Plants Using a Dynamic Crushing Plant Simulator*, Published in the proceedings of the 8th International Comminution Symposium, Cape Town, South Africa, 17-20 April 2012.

Paper D: Hulthén, E., Asbjörnsson, G. and Evertsson, C. M., *A Training Simulator for Crushing Plant Operators*, Published in the proceedings of the XXVI International Mineral Processing Congress, New Delhi, India, 24-28 September 2012.

Paper E: Asbjörnsson, G., Hulthén, E. and Evertsson, C. M., *Modelling Dynamic Behaviour of Storage Bins for Material Handling in Dynamic Simulations*, Published in the proceedings of the XXVI International Mineral Processing Congress, New Delhi, India, 24-28 September 2012.

CONTRIBUTIONS TO CO-AUTHORED PAPERS

In all the papers A-E, Asbjörnsson, Evertsson and Hulthén initiated the idea.

Papers A-B & D: Implementation was conducted by Asbjörnsson. Asbjörnsson wrote the paper with Evertsson and Hulthén as reviewers.

Papers C: Implementation was conducted by Hulthén. Asbjörnsson provided the simulator. Hulthén and Asbjörnsson wrote the paper with Evertsson as a reviewer.

Paper E: Implementation was conducted by Ankarbranth and Mårtenson. Asbjörnsson provided the simulator. Hulthén and Asbjörnsson wrote the paper with Evertsson as a reviewer.

CONTENT

1 INTRODUCTION

The aim of this chapter is to:

- *Introduce the principles of crushing and screening.*
- *Provide an overview of crushing plants in general, the process, the control and their operators.*
- *Give an introduction into the simulation technique.*
- *Define the problems with plant simulations today.*

Modern society is literally built on rock. Construction such as buildings, roads, bridges and railways are almost entirely built out of excavated rock material which has been processed into a usable product, such as aggregates and metals. Aggregates are processed rock materials such as sand and gravel, commonly used in roads and construction. Structural frames and rails are constructed from steel material which is a product of mining, a process in which the metals in the ore are extracted from the raw material and then used to create other products, for example steel.

In Sweden, aggregate production is an industry with approximately 920 active quarries spread throughout the country. In 2008 they produced 101 million tonnes. Most quarries are however relatively small, with 78 % of the plants producing less than 10.000 tonnes annually [1]. Aggregate production in Sweden is increasing again after the global economic crisis in late 2008 which affected the quantity of infrastructure and construction projects in Sweden in 2009 and in 2010.

Sweden is one of the major mining nations in Europe. In total, nearly 68 million tonnes of ore were mined in Sweden in 2011 from only 13 mines. Out of these 68 million tonnes, 30.8 million tonnes was from iron ore. The rest consisted of zinc, copper, lead, silver and other metals [2]. Over the last decade the price of base and precious metals has steadily increased. In the case for gold for example, the price in 2001 was roughly 280 USD/oz. and in 2011 the price reached 1896 USD/oz., which is a 677 % increase over 10 years [3]. This growth has caused an increased focus on process development in the mining industry and several research groups are collaborating to react to this research demand.

1.1 CRUSHING & SCREENING

Comminution is the process of size reduction of particles until the liberation of valuable minerals can be achieved [4]. In mining and aggregate production, the size reduction of rock material can be achieved by blasting, crushing and grinding. The material is processed in a number of different stages until a desirable particle size distribution is achieved. In Figure 1, a layout of a crushing plant in an aggregate production process can be seen. The material is crushed in crushers and classified in screens.

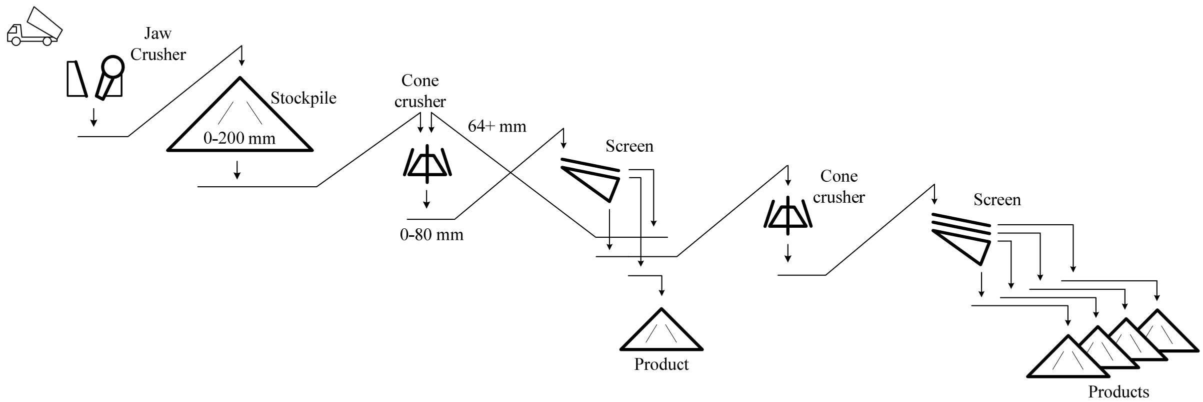


Figure 1. A crushing plant in an aggregate application.

Comminution of rock material in mining and aggregate production is usually categorised with three different crushing principles: compression, impact and attrition. These principles are described in detail by Evertsson [5] and Lee [6], who denote a more general name instead, form conditioned and energy conditioned crushing.

In form conditioned crushing, the size reduction is performed by a controlled compression of a particle or particles to a certain degree or displacement. Form conditioned crushing can be found in jaw- gyratory- and cone crushers (see Figure 2a). In the case of form conditioned crushing, the amount of size reduction is determined by the displacement of the surfaces while the force and energy required for the size reduction are functions of the displacement. In cone crushers, the crushing is enabled with an eccentrically nutating cone within a concave. The amount of surface displacement is determined by the amount of eccentric motion of the cone.

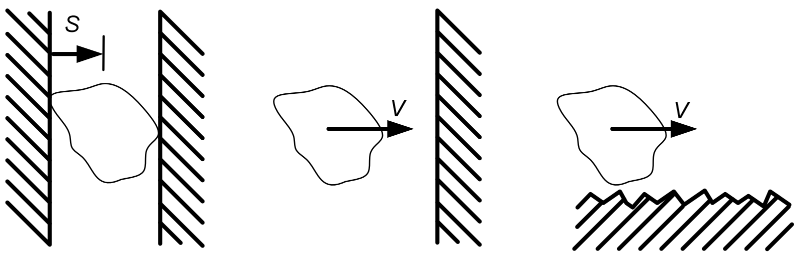


Figure 2. Schematic principles of form conditioned crushing (a), energy conditioned crushing (b) and attrition (c), as presented by Evertsson [5].

In energy conditioned crushing, size reduction is determined by the amount of kinetic energy applied to the particles (see Figure 2b). The more kinetic energy applied to the particles, the harder the particles are thrown against a solid steel wall or a bed of particles which subsequently determines the amount of breakage of the particles. This form of breakage is typical for Vertical Shaft Impact (VSI) crushers and Mills. In VSIs the material is fed onto a rotating plate which changes the trajectory of the particles and throws them against a steel wall or a bed of particles. The faster the plate rotates, the harder the particles are thrown, thereby generating more breakage.

Attrition is breakage caused by shear failure [5], usually as a result of friction between particles, such as in interparticle breakage [6] (Figure 2c). This friction is caused by the difference in relative motion between the particles which occurs in both form conditioned and energy conditioned crushing. This type of breakage usually generates more fines as small corners on the particle are chipped off in the process.

Classification is the process of separating objects according to specific grades. In the crushing phase the flow of material is separated with respect to specific particle size. Different techniques can be used to separate the material flow into separate fractions. Usually the technique used is determined by the particle size distribution of the feed. For a coarse material, vibrating screening decks or grizzlies are most commonly used. There, the material is transported over the screening deck due to the inclination and the oscillating motion of the deck. This enables the particles to move in the particle bed and eventually fall through apertures on the deck if the particle is smaller than the size of the aperture, see Figure 3a. Particles larger than the aperture on the screen will however not fall through and are therefore transported over the deck [7].

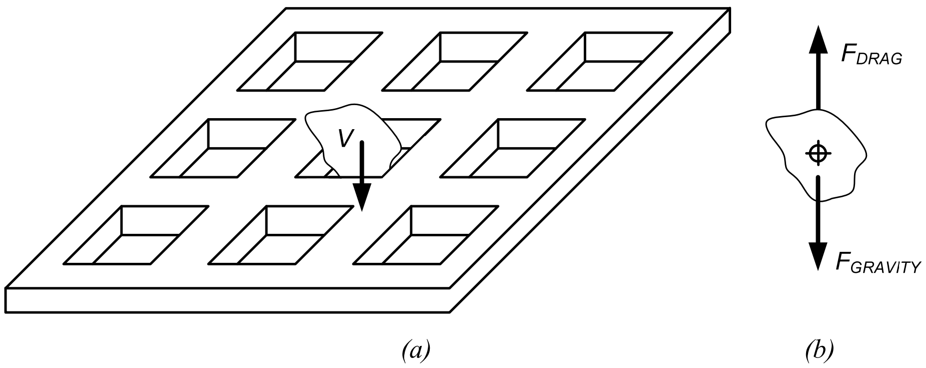


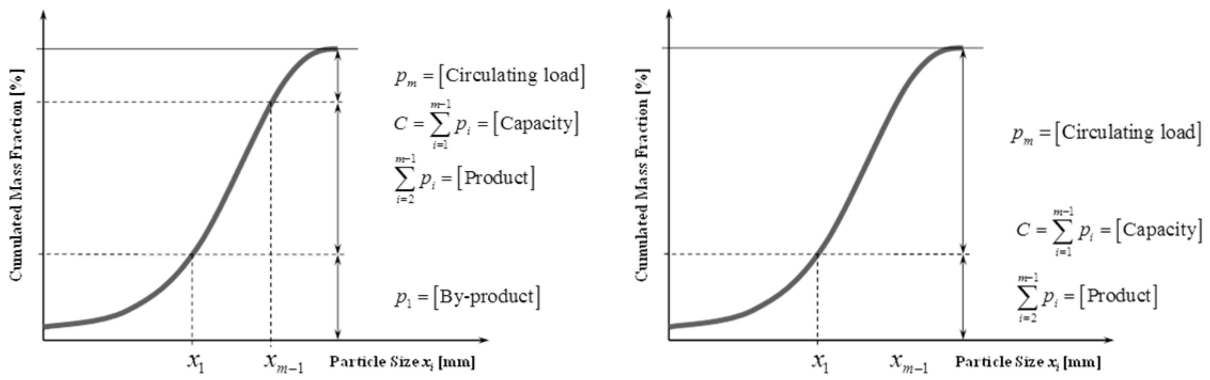
Figure 3. Two methods of separating the material with respect to certain particle size. With a fixed aperture (a) and with relative drag force (b).

For fractions smaller than 2 mm, vibrating screens become insufficient due to pegging and blinding. In cases where it is beneficial to separate the sub 2 mm material, such as for the production of manufactured sand [8] and in the mining industry, air classifiers or hydrocyclones can be used. The same principle applies in both cases but with different media used; air or water. If the drag force on the particle, which is generated by the flow of the medium, is larger than the gravitational force the particle will follow the flow. If, on the other hand, the gravitational force is larger than the drag force, the particle will fall down, as illustrated in Figure 3b. The cut point can therefore be controlled by manipulating the flow of the medium [8].

1.2 Crushing Plants in Mining and Aggregate Production

A crushing plant is a configuration of different production units, such as crushers, screens, conveyors, bins, stockpiles and feeders. The number and configuration of units is dependent on the preferred performance for which the plant and equipment are designed. The configuration of each plant depends on the feed from the quarry and the desired purpose of the material. This can range from a single crusher with a couple of conveyors to multiple reduction stages in combination with a complex system of bins, screens and conveyors.

The setup and the configuration between crushing plants for mining and aggregate applications differ as they have different purposes. In aggregate production, the purpose of the process is to create a narrow, particular particle size fraction (the product in Figure 4a), while minimizing the circulating load and the finer by-product (see Figure 1 and Figure 4a). The size fraction that is desirable is usually determined by the market demand and the available material at the plant.



(a) *(b)*

Figure 4. Schematic illustration of capacity, product, circulating load and by-product identified on a particle size distribution for aggregate (a) respectively mining application (b), as presented by Lee [6].

In mining applications, the purpose is to generate fine particles as depicted in Figure 4b. The particles should be fine enough so that the valuable minerals in the ore can be liberated and purified [4]. After the dry crushing section, the fine material (–40 mm) is fed to mills for further size reduction before it is sent to flotation.

1.3 Plant Control

Any modern industrial process that involves mass production with continuous processes, such as aggregates and mining, uses a high level of automation and process control. The larger and more complex the production system the higher the demand is on the level of automation. In crushing, the level of automation is relatively low compared to other process industries, especially for aggregate production.

Control system architecture of a typical crushing plant consists of local regulatory controls on actuators, which operate under a supervisory controller. How the controllers operate will depend on the control objectives and the response of the system. Process units such as feeders, the most commonly controlled actuators in a crushing circuit, are controlled by altering the frequency of the actuator with an On-Off controller or a PID controller which in turn changes the flow rate from the feeder to supply the subsequent part of the circuit with material. More advanced control algorithms are required when controlling crushers. Asbjörnsson and Åberg [9] and Hulthén [10] have described different methods for controlling a cone crusher. In Figure 5, a closed control loop for controlling the Close Side Settings (CSS) and the eccentric speed on a cone crusher is illustrated [10].

If the focus on the control system is neglected during the design phase of the plant, a number of problems can occur during the start-up of the plant, such as lower plant performance or unexpected fluctuation as a consequence of process instability.

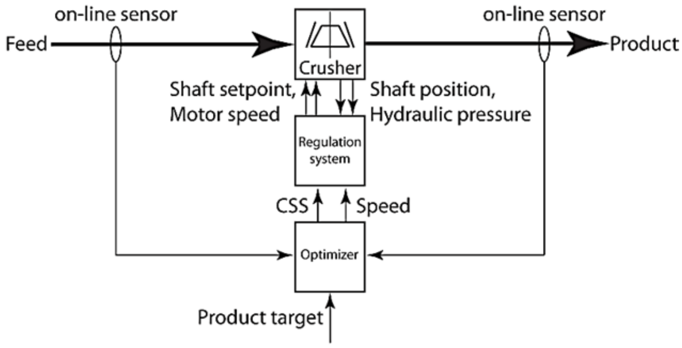


Figure 5. A closed loop process control for controlling the CSS and the eccentric speed of a cone crusher, as presented by Hulthén [10].

1.4 Operators

Operators are responsible for keeping the process running. The level and the type of interaction an operator has with the process is determined by a number of factors such as: the level of automation integrated into the process, the size of the plant, the complexity of the process and the operational management. In a larger plant, with a high number of personnel, an operator's tasks become more specific, such as maintenance, material hauling or process monitoring, whereas in a smaller plant, the operator can be involved in all of the previously mentioned tasks.

Even with an increased automation in general, the level of automation is usually considered to be quite scarce in the aggregate and mining industry. Many decisions are made by the operators, decisions that rely on the operator's previous experience. Multiple operating decisions, which in many cases could be controlled by the supervisory control system, are left up to manual control. For instance, the crusher operating set points for cone crushers, e.g. the CSS and eccentric speed, are often selected by operators, resulting in crusher performance being dependent on the operator's ability to select appropriate operating set points for that particular condition.

A common reason for operators to shut down the process is due to maintenance. The process and equipment are designed to withstand high load, abrasive material and high vibration. Because of this the process does not require frequent maintenance, except for changing wear parts. Wear on critical components usually affects the process by causing loss of potential production [10, 11]. Regular maintenance of such components is therefore necessary, but too frequent maintenance is not advantageous either, since the cost of new components and downtime has to be less than the potential gain in production profit.

1.5 Plant Simulations

Equipment manufacturers as well as plant designers use software packages for predicting the plant performance. There are a number of software packages available that are able to predict plant performance. The most widely used type of simulations technique is steady-state simulations, meaning that the system is considered to be at equilibrium with all derivatives equal to zero. Another common simulation technique is dynamic simulation, sometimes called time-dependent simulation. Dynamic simulation calculates the performance of the system under different operating conditions as the system experiences changes and accumulation of mass.

Eq. 1.1 illustrates how an output (differentiation of x_i with respect to t) is linked to multiple input variables ($u_1(t),...,u_m(t)$) and internal state variables ($x_1(t),...,x_n(t)$) which are time-dependent (t) [12].

$$\frac{dx_i(t)}{dt} = f_i(x_1(t),...,x_n(t),u_1(t),...,u_m(t)) \tag{1.1}$$

Examples of steady-state simulation packages include: PlantDesigner (Sandvik), Bruno (Metso Minerals), JKSimMet (JKMRC), Aggflow (BedRock Solution) & UsimPac (Caspeo). Examples of available software that can perform dynamic simulations includes: SysCAD (Kenwalt), MetProSim (Metso Minerals), MATLAB/Simulink (Mathworks), Aspen Dynamics (Aspentech) and Dymola (Dassault Systémes), With SysCAD and MetProSim currently being the only feasible software with a built-in equipment library for comminution.

Plant simulations are usually used for evaluating plant performance or for optimizing a current design. For these simulations, the steady-state simulation technique is an industry standard with multiple available software that can perform the task. Steady-state simulations are easy to set up and can offer results within a few seconds. Dynamic simulation however, requires more configurations and more calculation time but in return it can give more detailed information about the plant performance under different conditions. The increased configuration time is a consequence of the additional effort required in constructing the plant controllers and discrete events. The necessary calculation time increases as well since the accumulation of mass, the response of the system and changes within the system have to be calculated during a predetermined time period.

1.6 Problems Associated with Plant Simulations

Every process is subjected to changes in performance and efficiency over time. Traditional plant simulations are performed with steady-state simulation and are therefore limited to showing only the performance in an ideal situation. However, actual plant performance usually tends to deviate away from the predicted plant performance. These dynamics are usually consequences of an altered state of the plant due to factors such as natural variations, unmatched, inappropriate or degrading equipment performance and stochastic events.

Simulations are usually considered to be a cost effective tool. It is easier and cheaper to simulate the process behaviour rather than building the actual process and running experiments to find its optimal settings. Process simulations for aggregate production and mining are limited when it comes to the plant startup phase. With steady-state simulations, no consideration is taken with regards to control, startup and shutdown operation. This results in a trial-and-error phase, where operators adjust equipment and control settings in order to achieve maximum performance of the system.

Operators usually rely on their own previous experience, as mentioned in Section 1.4. However, this entails that the operator needs to have experienced from that particular situation before and remembers which reaction was taken and how that reaction affected the process and the production. There are multiple scenarios that can be performed and maybe only a handful of these will result in improved process performance. Operator training is one way of reducing the risk of operators making the wrong decision to changes in the process. With operator training, multiple cases can be created in which the operator can test different strategies to deal with the problem.

2 OBJECTIVES

The aim of this chapter is to:

- *Describe the aim and objective of the research.*
- *Formulate the research questions.*
- *Clarify the delimitations of the research undertaken.*

2.1 RESEARCH OUTLINE

The aim of this research is to understand how crushing plants which are used for production of aggregates and metals operate under different conditions over time and to develop knowledge and methods for improving plant operation. The main objective of this research is thus to develop models and a simulation platform for the analysis of time-dependent plant behaviour in crushing plants.

The hypothesis of this research is that crushing plants, as a continuous process, are affected by gradual and discrete changes in the process, which in turn alters the performance of the entire system. In order to simulate the effects that the changes have on the process, a dynamic simulator has been developed. A dynamic simulation is defined here as continuous simulation with sets of differential equations used to reproduce the dynamic behaviour of a system.

This thesis focuses on the plant operation and the performance of crushing plants for both aggregate plants and the dry comminution in mining applications. The area of focus for a mineral processing plant is depicted in Figure 6.

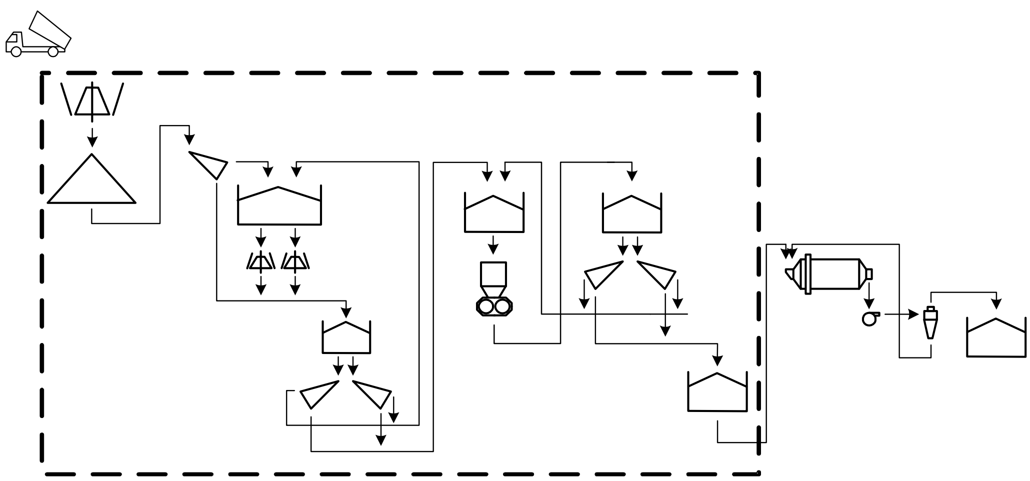


Figure 6. The focus of this is the crushing and screening stage in aggregate and mineral plants alike, depicted in the dashed box.

2.2 RESEARCH QUESTIONS

The scope of this thesis can be described by the following research questions:

- RQ1. What factors can cause dynamic behaviour in crushing plants?
- RQ2. What methods and techniques exist, and should be used to represent dynamic crushing plant behaviour?
- RQ3. How can dynamic simulations assist in evaluation of effects of step changes and other variations on crushing plant response and production?
- RQ4. How can dynamic simulation be used for industrial purposes?

2.3 DELIMITATIONS

In this work the focus on the plant operation and performance has been from a holistic perspective. Plant simulations include multiple equipment models with different characteristics and complexity. A majority of models used during the plant simulations are industry and academic standards but often with some modification in order to account for the dynamic behaviour.

Drilling and blasting is left outside the scope of this thesis. The product from the blasting is entered as a feed input for the plant simulation, which includes the particle size distribution and material properties. In a similar way milling and flotation are also left outside the scope of this work. The material is in turn defined as a product as it leaves the last crushing stage. At this stage of the work no consideration is taken into the quality aspects of the rock material, e.g. the ore grade and the flakiness of the rock.

3 RESEARCH APPROACH

The aim of this chapter is to:

- *Introduce the research methodology used.*

This research was carried out at the Chalmers Rock Processing Systems (CRPS), which is a part of the Machine Element Group at the Department of Product and Production Development at Chalmers University of Technology. The group has been active in research within the field of equipment [5-8, 11, 13] and process performance [10, 14] for two decades.

3.1 RESEARCH METHODOLOGY

The research approach which has been adopted by the Machine Elements Group is characterised as a problem-based approach. The process of problem-based research has been described by Evertsson [5] and Lee [6] and is depicted in Figure 7. In problem-oriented research the choice of methods for solving the problem or question of interest is based on the nature of the problem itself. In other words the problem itself is in the focus rather than the method or tools required to solve it.

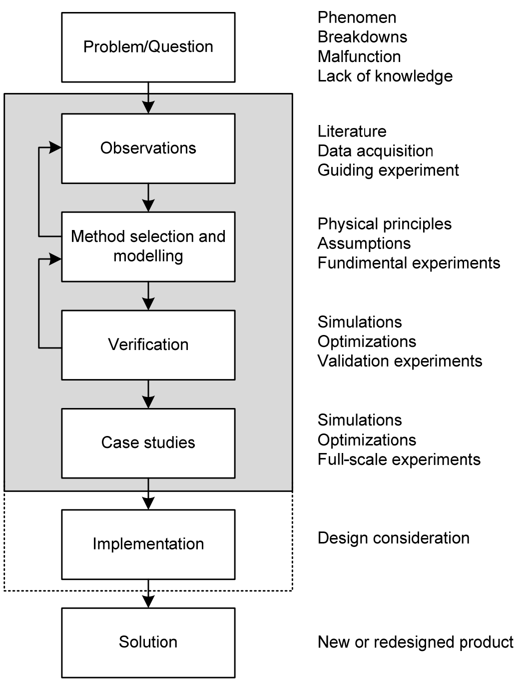


Figure 7. The applied problem-oriented research model as illustrated by Evertsson [5].

Svedensten [14] and Hulthén [10] adopted a different view to the problem-oriented research approach due to the nature of their respective problems. In their opinion, the importance of early implementation was essential for the reliability of the results, making it an integrated part of the entire problem-oriented process. According to Crotty [15], each piece of research is unique and calls for a unique methodology. Therefore a general view of problem-based research is described here in detail in order to further show the holistic perspective of the approach.

This work, like other projects at CRPS, was initiated and objectives formulated with regards to an identified problem or a research gap with an industrial relevance. The problem or question in hand is usually a single entity in the system which for some reason causes undesirable changes in the process or can be improved to increase the performance of the process or an object.

The first step after the initial problem formulation is to identify the most significant aspect of the problem through observations using both quantitative and qualitative methods such as literature studies, initial experiments, interviews and on-site data acquisition.

When the most significant aspect of the problem has been identified the task of method selection and modelling can start. As mentioned earlier, in problem-oriented research the choice of methods for solving the problem or question of interest is based on the nature of the problem itself and therefore is an in-depth knowledge of the problem is essential before this phase can be appropriately carried out.

The models are run through a series of simulations and validation experiments to determine the fidelity of the results. This is an iterative process. If models or methods are not adequate enough the process is repeated with new sets of experiments or possibly new modelling or method selection which improves the representation of the studied object or process. If the models are adequate, larger case studies are performed to further evaluate the models and methods.

How the implementation is conducted is different depending on the characteristics of the problem. Generally the implementation is performed after the iteration process, often as an integrated part of the results from the research as depicted in Figure 7. However, as pointed out by Svedensten [14] and Hulthén [10], an early implementation, during the research phase, is quite important as it will add an additional dimension to the validation process and ensure that the research results are applicable when implemented in reality.

The CRPS works in conjunction with the Swedish aggregate and mining industries. By working closely with the industry, problem identification and research implementation becomes more qualitative as challenges that are faced by the industry are studied.

4 LITERATURE REVIEW

The aim of this chapter is to:

- *Provide an overview and introduction to the research on aggregate and mining production.*
- *Describe research that has focused on dynamic simulation of crushing plants.*
- *Describe related research areas that have studied factors that influence plant performance.*

The research done on crushing plant simulation is diverse. The focus is mainly concentrated on single production units, while less focus is given to the interaction between different units, the operation of the plant and controls. This seems to be the case in both the mining and the aggregate industries.

4.1 COMMINUTION

The essential parts of any crushing plant are the size reduction and size separation processes. The classical comminution theories, which were derived by Rittinger [16], Kick [17] and Bond [18] respectively, aim to describe the relation between energy and size reduction for a given feed size. The three theories, which are usually referred to as the first, second and third theory of comminution, are formulated in Eq. 2.1 – 2.3.

$$E_{Rittninger} = C_{Ritt}\left(\frac{1}{p_{80}} - \frac{1}{f_{80}}\right) \tag{2.1}$$

$$E_{Kick} = -C_{Kick}\ln\left(\frac{p_{80}}{f_{80}}\right) \tag{2.2}$$

$$E_{Bond} = C_{Bond}\left(\frac{1}{\sqrt{p_{80}}} - \frac{1}{\sqrt{f_{80}}}\right) = W_I\left(\frac{10}{\sqrt{p_{80}}} - \frac{10}{\sqrt{f_{80}}}\right) \tag{2.3}$$

Where E is the energy input, C is a material constant, p_{80} is the size which 80 % of the product passes, and f_{80} is the size which 80 % of the feed passes. W_I is the Bond´s *work index* which expresses the resistance of a material to crushing or grinding. This constant is a function of material properties and the efficiency of the crusher. A lower efficiency in a crusher will give a higher work index.

These theories, especially Bond´s and Rittinger´s, aim to provide an estimation of product particle size from empirical testing for crushing and grinding. A significant drawback of these theories is however that they only rely on a single point of the particle size distribution curve as pointed out by Lindqvist [19], namely f_{80} and p_{80}. This is not enough to characterize the whole particle size distribution curve and can only provide a rough estimation of the breakage behaviour in comminution equipment. Walker et al. [20] and later Hukki [21] were able to create a more general form of the relation between energy and size reduction. Today the energy-size relation in the comminution process is usually presented in the form of the differential equation proposed by Walker [20] and revised by Hukki (see Eq. 2.4) which is proportional to the surface area of the particle in relation to specific volume.

$$dE = -C\frac{dx}{x^{f(x)}} \tag{2.4}$$

Crushers are an essential part of the process as the size reduction occurs in the crusher. The most common mathematical model used today for expressing the crusher performance is the empirical Selection-Breakage model proposed by Whiten [22]. This model is however empirically fitted to data from drop weight tests, which is more suitable for mills than compressive crushers and does not predict capacity. More detailed analytical models based on the mechanical properties of the crusher have been proposed by Evertsson [5] and Briggs [23]. These models can provide more accurate information from the process but require detailed information about crusher geometry, breakage behaviour and require considerable simulation time.

Screens are traditionally simulated with quite simple mathematical models. The most commonly used model is the one proposed by Karra [24], where the screen efficiency is determined by a number of independent factors. A more detailed model has been proposed by Soldinger [7] where stratification between particles is estimated in order to calculate screening efficiency.

4.2 CRUSHING PLANT SIMULATION

Research on numerical crushing plant simulations has been conducted since the 1970´s, by researchers such as Lynch [25] and Whiten [22] (JKSimMet at JKMRC), King [26] (MODSIM at University of Utah) and Svedensten [14] (PlantDesigner at Chalmers University of Technology). These software, as well as Bruno (Metso Minerals) and Aggflow (BedRock Software LLC), are all steady-state simulations packages which are industrial standards for evaluating plant performance in both the aggregate and the mining industries.

Steady-state simulations have been used with great success for plant analyses and optimizations [14, 27]. However, these simulators lack a certain perspective of the operation, namely, changes in the system over time and performance at non-ideal operating conditions. The development and the use of continuous-time simulation (or dynamic simulation) has been increasing worldwide in aggregate and mineral processing.

The most commonly used platform for dynamic modelling is the MATLAB/Simulink software. However, other commercial software packages are available such as SysCad and MetProSim as previously mentioned.

In Sbarbaro [28], semi empirical models are used and modified to give the plant a dynamic response. This is done by including accumulation of mass, time delay and simple mixing models to enable model-based control system design. Sbarabro states that even though mechanicals models are used to describe the factors affecting the unit, the empirical models are more feasible since they provide a reasonable compromise between representability and simplicity. However, no consideration is given to dynamic response of the actuators, gradual changes due to wear or discrete events.

Similar to Sbarbaro, Liu et al [29], adds accumulation of mass, time delay and mixing models to empirical models. The focus is only on a simple grinding circuit to visualize the possibilities of using dynamic simulation, where the mill is equipped with a constant residence time. The equipment used in this study only includes a mill and a hydrocyclone where even the model for the hydrocyclone does not include any dynamics, thus limiting the general purpose use of dynamic simulation.

In Itävuo´s work [30] the base for the dynamic modelling is the mechanistic crusher model developed by Evertsson [5], with the addition of the effects from material properties studied by Ruuskanen [31]. Itävuo estimates the response of the actuators under different condition to be able to estimate the actual response of the crusher when discrete changes are initiated such as changing the CSS. These simulations are computational heavy making the simulation time long and not suitable for all purposes, however these simulations are able to supply qualitative information about the process response and are therefore well suited to the development of control system.

Evaluating long-term availability of production units in comminution has been done by Herbst et al [32]. In their work a continuous-time simulation was run together with a Discrete Event Simulation (DES) in MetProSim to include the impact of discrete events such as scheduled and unscheduled maintenance. The unscheduled maintenance was random stochastic events generated from the specific mean time between failures and a probability distribution for the time between failures, while scheduled events occur at a predetermined instance. This data is usually gathered from historical data from the plant such as from equipment logs and plant data, but estimating this information for a non-existing plant is difficult since no data is available. Also, since the events are randomly generated the results will differ in each individual simulation.

The use of dynamic simulators is still not generally common in aggregates and mineral processing. The use of dynamic simulators within other industries is usually tied to control system development. By using a dynamic simulator, the control system can be designed and tuned without access to a physical plant as illustrated by Sbarbaro [28], Itävuo [30] and Herbst [28, 30, 33].

The operators are an essential part of the process but are often overlooked [34]. Even though a major part of the process is controlled by automation the operators are still interacting with the process on different levels. Very few cases have been documented where a dynamic simulator has been connected to Human-Machine Interface (HMI) to train operators to control the simulated process [35, 36]. This procedure is standard within other industries such as in power plants and aviation [37, 38].

4.3 FACTORS INFLUENCING PLANT PRODUCTION

Every production process experiences dynamic behavior as a result of internal and external disturbances. The process can be sensitive to wear, segregation, natural variations and more.

Wear on equipment and machine parts in comminution is extensive due to the characteristics of the crushing process and will have different effects on the process depending on the machinery and rock material. Studies on wear in comminution is a reoccurring subject both due to the fact that it affects the production [10, 11, 39] and because of the environmental impact [40]. The wear in compressive crushers, such as cone crushers, is typically categorized as only abrasive [11], this causes changes in the liner profiles and in turn affects the crusher´s performance. The amount of wear in a cone crusher depends on a number of factors such as material properties, particle size distribution [41] and moisture [42].

Research on wear on screening media is not as comprehensive as the wear in crushers and mills but as pointed out by Svedensten [43], wear on screens does cause larger aperture on the cloth and therefore alters the particle size distribution of the screened product. This is a large problem when considering quality of the aggregate production where production of a particular particle size is important because of quality requirements.

Segregation and inadequate material handling can reduce plant performance and product quality. In Powell et al. [44], several problems are identified that are considered to be a direct consequence of segregation and inadequate material handling in a dry crushing section in a mining application. If not attended to, these problems can cause reduced plant performance and could even cause premature equipment failure. Even though segregation is often possible to observe with the naked eye it is usually studied with a Discrete Element Method (DEM) and in Quist and Evertsson [45] segregation in cone crushers is studied. Factors such as lower product quality, uneven wear, high stress amplitudes and premature equipment failure are considered as consequences of segregation and misalignment of crusher feed.

One of the challenges in plant simulation is the estimation of natural variations and variations are everywhere, both in the production units and in the rock material itself [46]. Continuous monitoring, such as mass-flow meters [10] and image analyses of particle size distribution [47] can provide helpful information about the process variations but certain information can still only by gathered by manual sampling from the process (material properties and often particle size distribution). This is not ideal as the samples are small compared to the amount of processed material and only reflect a momentary state at a certain part of the process.

Several factors that affect equipment performance with specific focus on cone crushers have been discussed from a holistic perspective by Evertsson [5] and from a time-dependent perspective by Bearman & Briggs [48]. The effect of varying feed by, for example, feed grading, crushability, moisture content and more has been described in detail by Ruuskanen [31] but most of the data has been gathered when studying one factor at a time, therefore not taking into consideration the possible effects of interaction.

5 MODELLING OF CRUSHING PLANTS

The aim of this chapter is to:

- *Introduce the characteristics of dynamic modelling.*
- *Explain the modelling approach adopted in this thesis.*
- *Present the different elements needed for dynamic modelling of crushing plants.*

Modelling and simulation of industrial processes, such as crushing plants, provides an insight in the process which would be difficult to obtain otherwise. However, the modelling process is a complex task involving different systems that requires different modelling techniques depending on the characteristics of the problem. In general, dynamic plant simulations include a number of different factors that needs to be included which affect the dynamic performance of the system. The process can be sensitive to startups, discrete events, wear, segregation, natural variations and other factors that common during operation. All depending on interaction between single production units, plant configuration, plant control and diverse events and disturbances that can influence the process, see Figure 8.

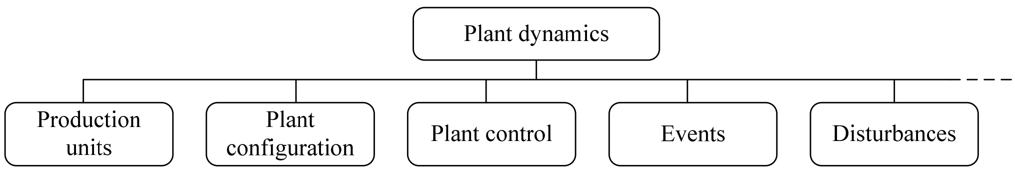


Figure 8. Plant dynamics can originate from different sections in the process operation.

Changes and variations occur everywhere in the process and can be both discrete and gradual. Figure 9 illustrates factors that can affect the total performance of the plant in one way or another, ranging from different settings of production units to unavoidable consequences of the process such as wear and segregation. How these elements affect the process is dependent on multiple factors involving both the rock material itself and the utilized production units.

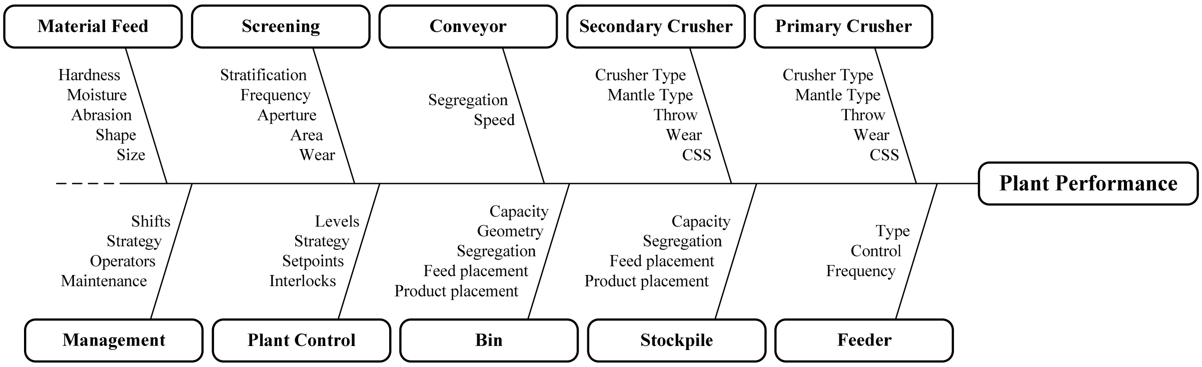


Figure 9. Cause-and-effect diagram over factors that can influence plant performance.

5.1 Modelling Approach

A crushing plant is a system of different production units and components connected together. The modelled system is built up in a similar manner as with multiple principal subsystems connected together to build a plant model. With a well-defined system the performance of the plant can be predicted. The accuracy will be dependent on how well the model is able to replicate the real conditions of the plant.

For the modelling of the system a modular approach has been adopted. With a modular approach the modelling is done with a top down design perspective. In other words, the system is divided into smaller subsystems or models, denoted the equipment level. Each subsystem can be further divided into smaller modules to represents the functional level of that particular subsystem. Each subsystem is built as an individual model and can therefore be handled separately. Figure 10 illustrates the hierarchal structure of the modelled system.

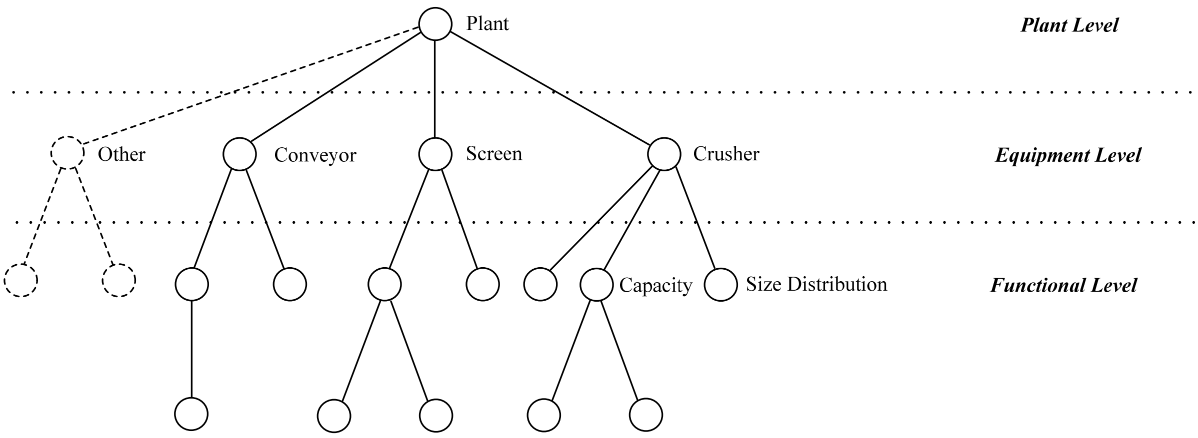


Figure 10. Illustration of the system hierarchy.

Since each equipment model is an independent entity, the communication between models needs to be standardized. The data flows from one model to another and is transformed as it moves through the plant model. This data contains important information about the material which determines the performance of the system. This includes information about the particle size distribution ($PSD(t)$), the mass-flow ($\dot{m}(t)$) and properties of the material ($\gamma(t)$) as illustrated in Eq. 5.1. Each model's output is bundled together into a vector which is the communicated as an input signal to the next model which in turn extracts the necessary information.

$$Material\ signal = \begin{bmatrix} PSD(t) \\ \dot{m}(t) \\ \gamma(t) \end{bmatrix} \qquad (5.1)$$

Each module is expressed as a set of mathematical equations which are used to predict the performance of the system. The mathematical equations can be derived from fundamental principles of the physical behaviour of the system or empirically from experiments which aim to explain the correlation between different parameters. Simplifications and qualified assumptions are often needed in order to assure the level of fidelity of the simulation results in respect to the required computational time.

MODELLING THE PLANT

The plant model is constructed as a flowsheet, as depicted in Figure 11. In comparison with traditional steady-state flowsheet models more units are included representing the conveyors, bins and other time-dependent units. Each involved subsystem is placed accordingly in the process and connected to sequential models. Once the process has been defined, the process settings are configured according to user preference. Appropriate material properties are specified and operating conditions are defined. Finally, control loops of the material flow are created. These factors will determine the predicted performance of the system.

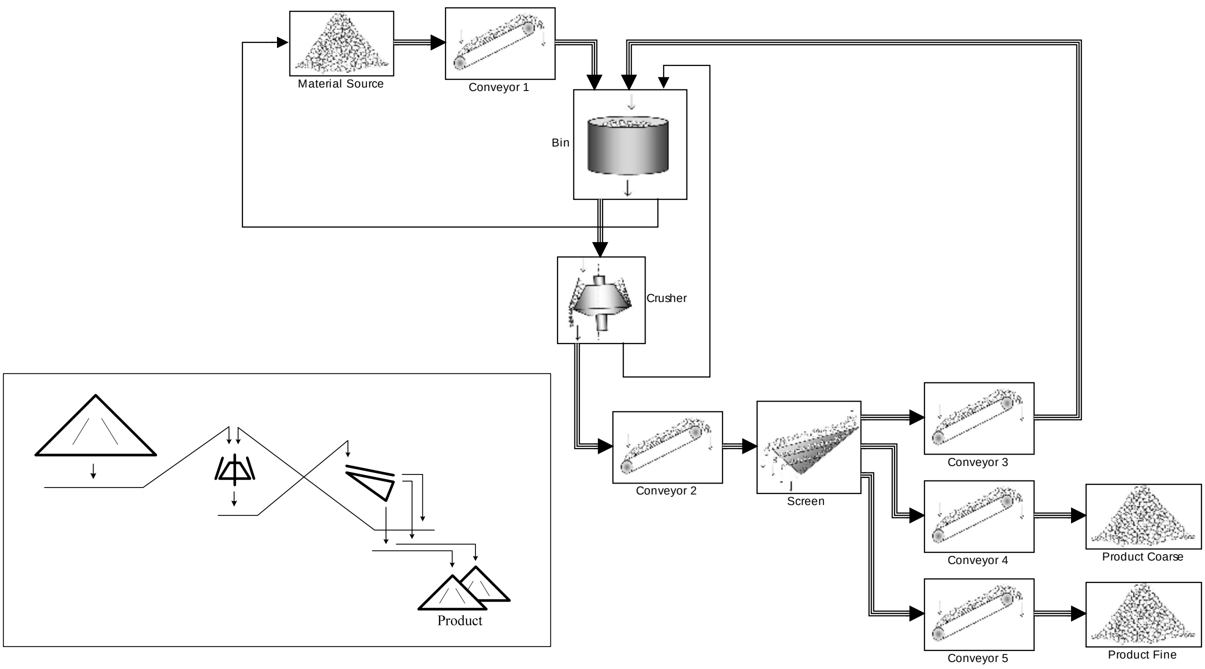


Figure 11. Flowsheet of a single crushing state in MATLAB/Simulink with a simplified layout of the plant in the embedded picture. The broad signal lines between the production units represent the material signal presented in Eq. 5.1 while the thin signal lines are process values ($y_{pv}(t)$) explained in Eq. 5.11.

The modelling work has been performed with two different simulation platforms. The work was initiated with the simulation software SysCAD which is a commercial simulator with a built-in equipment library. The modelling work continued with MATLAB/Simulink in order to enable a more detailed level and flexibility of the models. MATLAB/Simulink is a commercial simulation software developed for simulating and analysing dynamic and discrete systems. It is widely used within the industry as well as within academia for representing process behaviour and control systems. MATLAB/Simulink provides a graphical programming user interface with block-oriented modelling.

5.2 Modelling System Dynamics

The essential modelling principle in traditional steady-state simulation is that the system is simulated until equilibrium is achieved as stated in Eq. 5.2, with all derivatives equal to zero. This means that mass-balance needs to be in all points. In Eq. 5.3 a general mass-balance equation for a three stream connection point is illustrated where a_{SR} is the split ratio of the incoming mass-flow, m_{in}, to the two outgoing mass-flows, $m_{1,out}$ and $m_{2,out}$.

$$\frac{dx_i(t)}{dt} = f_i(x_1(t),...,x_n(t),u_1(t),...,u_m(t)) = 0 \tag{5.2}$$

$$\left.\begin{aligned} m_{1,out} &= (1-a_{SR})m_{in} \\ m_{2,out} &= a_{SR}m_{in} \end{aligned}\right\} \Rightarrow m_{in} = m_{1,out} + m_{2,out} \tag{5.3}$$

In a dynamic system, the system experiences different operating conditions when changes occur in the system. This results in the time-derivative not being equal to zero as defined in Eq. 5.2. These dynamics are usually consequences of an altered state of the plant over time due to factors such as natural variations, unmatched, inappropriate or degrading equipment performance and stochastic events. It is the authors' opinion and experience that crushing plants seldom operate under steady conditions during longer time periods. The production should therefore be considered to be a time-dependent instead of being constant.

In Figure 12 a general representation of a dynamic system is illustrated. The input u is an input parameter into the model which includes information about the material characteristic and the design parameters. The material characteristic information fed into the model is the cumulated particle size distribution, mass-flow and material properties as illustrated in Eq. 5.1. While the design parameters are the settings of the production unit involved, these can be constants, such as throw in a crusher, or variables which can change over time, such as CSS. The disturbance, denoted with w, illustrates the external changes in the process causing both gradual and discrete changes in the performance. The output y is the performance of the model. The output signals are constructed in the same way as the input signals as they are often further communicated to a sequential model. The internal state variable x and the differentiation of variable x describe the state of the system such as the accumulation of mass.

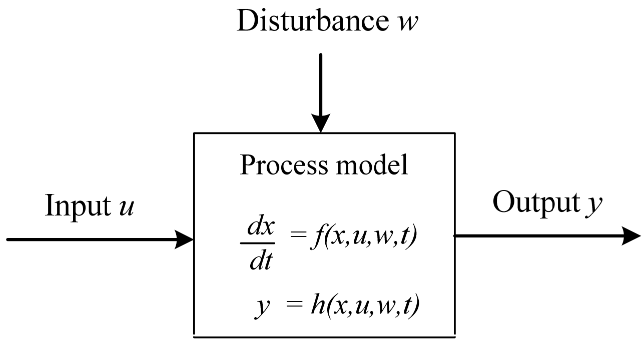


Figure 12. General representation of a dynamic system. The output y and dx/dt are functions of the input u, the disturbance w and the internal variable x, with respect to time t.

Conservation of Mass

One of the fundamental principles of simulating dynamic systems is the conservation of mass. In the mass-balance equation previously presented (Eq. 5.3) it was presumed that the total mass-flow into the system was equal to the mass-flow out of the system. In a dynamic simulation these constrains do not need to be fulfilled to have a system in mass-balance. Instead the material can accumulate according to Eq. 5.4.

$$m(t) = \int_{t_0}^{t} (m_{i,in}(t) - m_{j,out}(t))dt + m(t_0) \tag{5.4}$$

The mass in the system, $m(t)$, is therefore a result of the mass-flow into the system ($m_{i,in}(t)$), the mass-flow out of the system ($m_{j,out}(t)$) and the mass that was in the system at the start of the simulation ($m(t_0)$). Mass cannot disappear nor be created, except in the source material block. The properties of the material ($\gamma(t)$ in Eq. 5.5.), such as density, moisture and work index, are retained within the bulk material with a perfect mix model that is dependent on the accumulation of material and the mass-flow into the system ($m_{i,in}(t)$) as illustrated in Eq. 5.6.

$$\gamma(t) = \begin{bmatrix} \gamma_1(t) \\ \gamma_2(t) \\ \vdots \\ \gamma_n(t) \end{bmatrix} \tag{5.5}$$

$$\frac{d\gamma_i(t)}{dt} = \frac{m_{i,in}(t)}{m(t)}(\gamma_{i,in}(t) - \gamma_i(t)) \tag{5.6}$$

As an example of material handling in Paper E, a bin model was developed which was able to represent the actual process more closely and to approximate the natural behaviour which occurs within a bin. This bin model was needed to increase the fidelity of the simulation due to process disturbance from uneven material flow. The developed model is depicted in two-dimension in Figure 13 where the bin is divided into several segments n in order to simulate the flow within the bin. A third-dimension can be included with additional modelling and constraints to further increase the fidelity of the flow.

The model is defined by the number of segments ($y_1(t)$, $y_2(t)$, ... $y_n(t)$) within the system and the feed (i_f) and product (i_p) placement are positioned in an appropriate section according to the reference. The basic measurements for the bin are entered: length, width and height (l, w and h) in order to estimate the available space within the system. Looking closer into a single segment, the volumetric flow ($q_{in}(t)$, $q_{in,Left}(t)$, $q_{in,Right}(t)$, $q_{out}(t)$, $q_{out,Left}(t)$ and $q_{out,Right}(t)$) within that particular segment can be described by Eq. 5.7.

$$\frac{dy_i(t)}{dt} = \frac{n}{wl}(q_{in}(t) + q_{in,Left}(t) + q_{in,Right}(t) - q_{out}(t) - q_{out,Left}(t) - q_{out,Right}(t)) + y_i(t_0) \qquad (5.7)$$

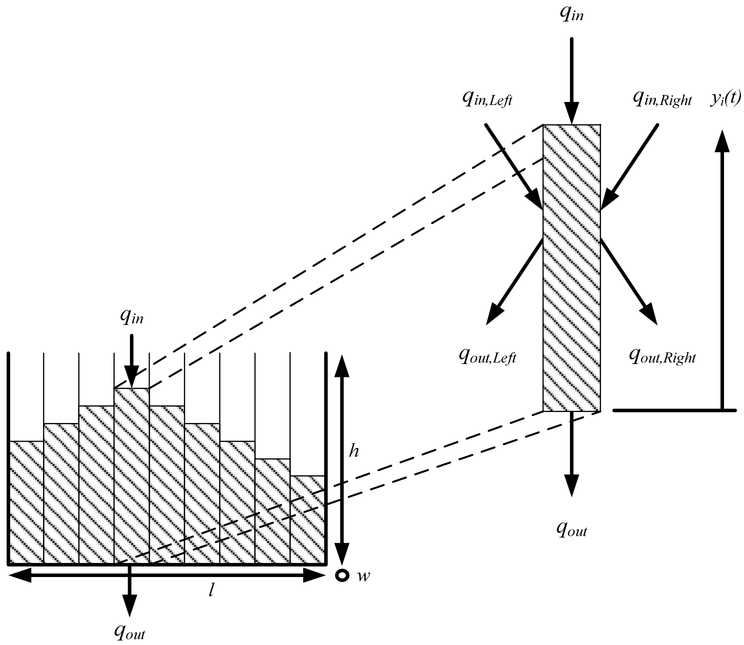


Figure 13. Principle idea with the developed bin model.

During operation, as well as in simulations, the material focus is always on the total mass of the transported material. This is easily measured during operation with belt scales but this has to be changed into volumetric flow to be able to calculate the amount of space that a specific mass occupies. Volumetric flow rate ($q(t)$) is defined in Eq. 5.8, where $\Delta V(t)$ equals the change in volume, $\Delta m(t)$ equals the change in mass, Δt is the time interval for the mass and ρ_{Bulk} is the density of the bulk material.

$$q(t) = \frac{\Delta V(t)}{\Delta t} = \frac{\Delta m(t)}{\Delta t \cdot \rho_{Bulk}} \qquad (5.8)$$

The flow of material within the bin will determine the material flow from the bin. Since the material is segmented into n number of segments, the flow between segments is constrained by conditions that dependent on the volume available in neighbouring segments, the angle of repose (α) and the section placement of the feed inlet (i_f) and product outlet (i_p) respectively. In Eq. 5.9 the fundamental constraints of the flow are given and in Figure 14 a representation of flow during different conditions is illustrated.

$$q_{in}(i)=\begin{cases} q_{in}(t) & if \rightarrow y(i_p)-y(i)<\frac{l}{n}\tan(\alpha)\left|i_p-i\right| \\ q_{in}(t)/\sum(y(i_p)-y(i)<\frac{l}{n}\tan(\alpha)\left|i_p-i\right|) & if \rightarrow y(i_p)-y(i)>\frac{l}{n}\tan(\alpha)\left|i_p-i\right| \end{cases}$$

$$q_{out}(i)=\begin{cases} q_{out}(t) & if \rightarrow y(i_f)-y(i)>\frac{l}{n}\tan(\alpha)\left|i_f-i\right| \\ q_{out}(t)/\sum(y(i_f)-y(i)>\frac{l}{n}\tan(\alpha)\left|i_f-i\right|) & if \rightarrow y(i_f)-y(i)<\frac{l}{n}\tan(\alpha)\left|i_f-i\right| \end{cases}$$ (5.9)

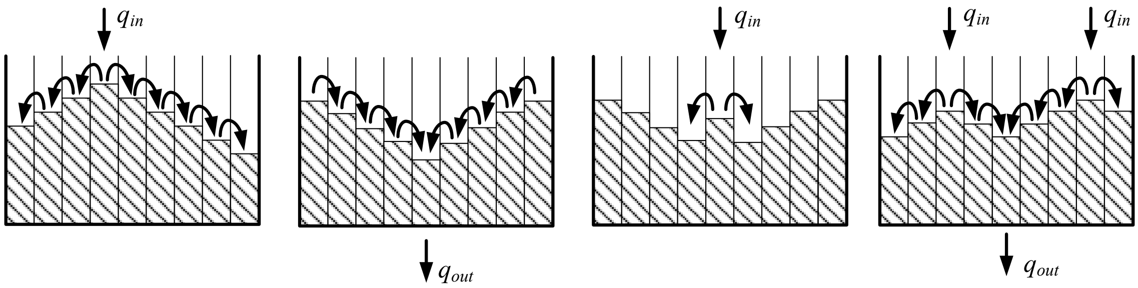


Figure 14. Representation of the flow under different conditions.

VARIATIONS

One of the many factors that affect the plant performance is variation. Since the material is blasted from the bedrock the size distribution and mechanical properties of the rock is dependent on the blast formation pattern and the geological formation of the bedrock.

In Papers A and B disturbances were included in the simulations in the form of variations in the incoming feed material. For Paper A only a variation in the incoming particle size distribution was included while for Paper B both mass-flow and particle size distribution was varied. The particle size distribution is generally presented as a cumulative percentage passing a specific size (see the generated feed curves in Figure 15) and can be estimated using a so called Swebrec function [49]. In this function (Eq. 5.10) the $x_{\max}$ represents the top size of the material, i.e. the size of the largest particle, x_{50} the size of the 50 % passing, x the defined rock size intervals and b defines the shape of the curve.

$$f(x)=\left(\frac{\ln\left(x_{\max}/x\right)}{\ln\left(x_{\max}/x_{50}\right)}\right)^{b} \qquad (5.10)$$

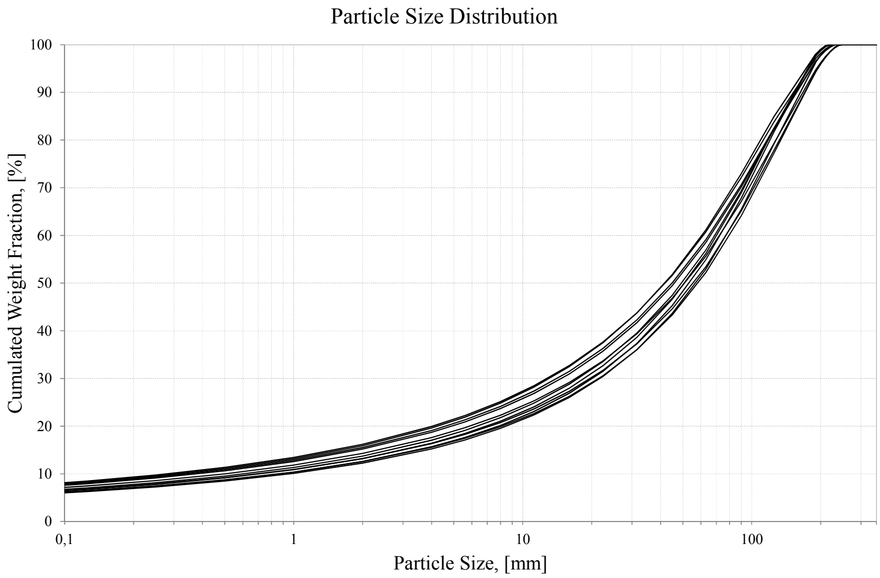


Figure 15. Variations of the particle size distribution for the incoming feed in a crushing plant simulation using the Swebrec function. The generated curves vary between 40-60 mm for x_{50} and 210-250 mm for x_{max}.

EVENTS

During operation, plants usually operate at or near full capacity. But due to different unit's reliability and maintenance strategy there are always disturbances in the process due to starts and stops of individual units which will affect the process. In worst case scenario the disturbance may cause a considerable down time (*DT*) for the entire plant. The reasons for stopping the process can be anything from scheduled maintenance to sustain product quality to a total machine breakdown as depicted in the two scenarios in Figure 16.

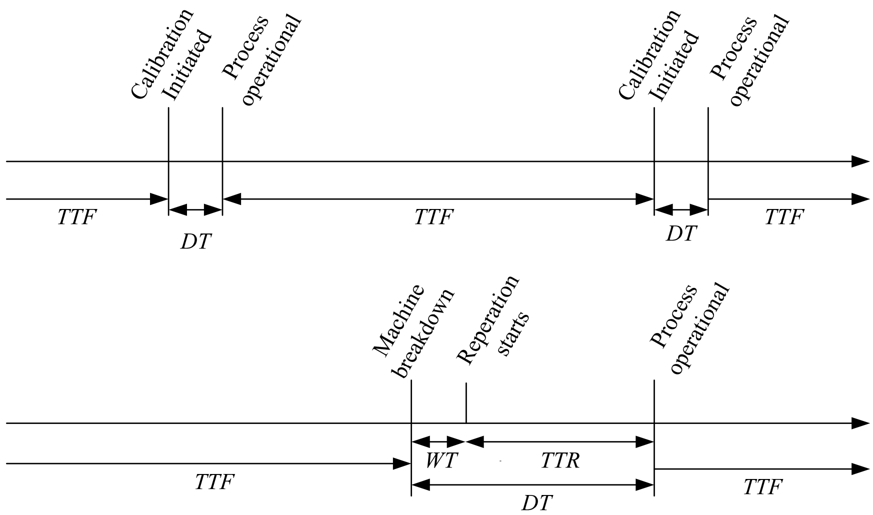


Figure 16. Two different example scenarios for discrete events. The scenario above illustrates the calibration process as an event while the scenario below illustrates the consequence of machine breakdown.

The length of each downtime is determined by how well the plant is prepared to handle particular events. Events can be entered manually into the simulation as a single event or for deeper analyses, a DES can be performed creating a hybrid simulation with discrete and continuous simulation running simultaneously. The DES is used to represent batches and events which can in turn be used to automatically generate events that can disturb the process. The output from a DES would therefore be the time-to-failure (*TTF*), waiting time (*WT*) and time-to-repair (*TTR*), all being dependent on the probability of the event occurring and the severity of the problem [50].

DES can be roughly classified in two categories, deterministic and probabilistic. With deterministic events the time and length of events are determined in advance which will give the same results every time, given that the initial conditions are the same. With probabilistic events however, the time and length of each event is not predetermined, instead the events occur depending on the selected probability distribution [12]. A discrete event model for simulating mechanical breakdown, modelled in SimEvents, is illustrated in Figure 17. SimEvent is a toolbox of MATLAB/Simulink for performing DES.

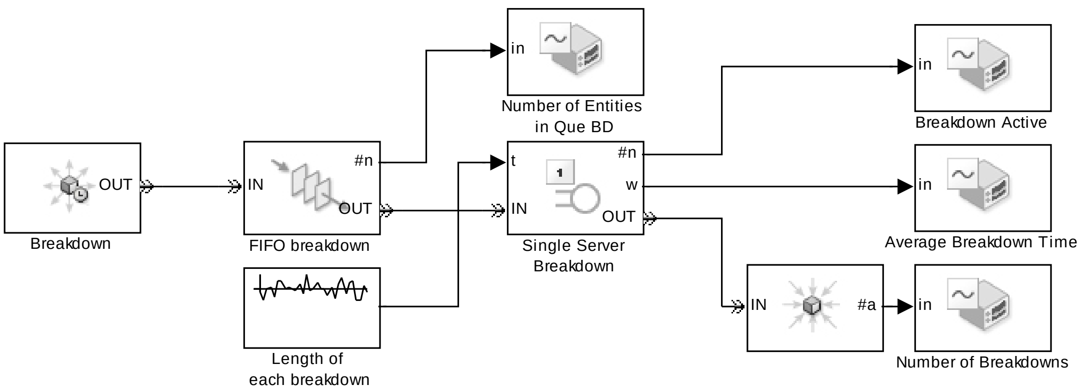


Figure 17. Event generated with SimEvents for representing a mechanical breakdown.

CONTROL

Due to the characteristics of dynamic simulation the material stockpiles, bins and flows need to be controlled. In crushing plants, different types of control systems are used to ensure safe operation while striving for high product quality and high production throughput. The most common form of control is the feedback control loop as illustrated in Figure 18.

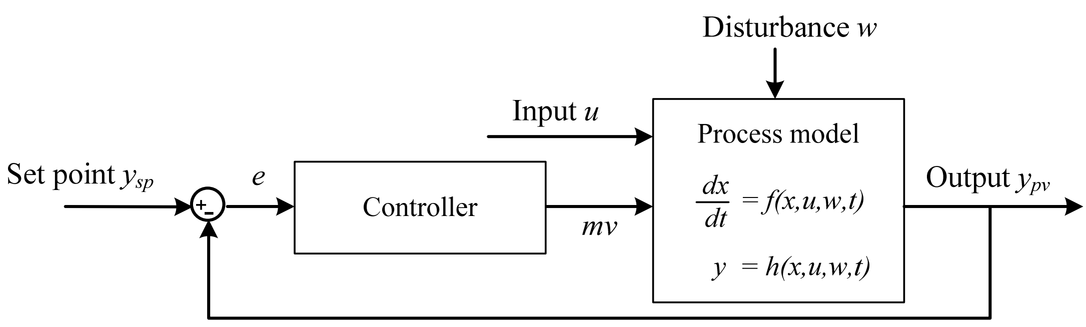


Figure 18. General representation of a feedback control loop. Modified from Marlin [51].

The feedback control loop works by manipulating variables ($mv(t)$) to change the measured control variable to a desired level in order to minimize the error ($e(t)$ in Eq. 5.12), which is the difference between the process value ($y_{pv}(t)$) and the desired process value ($y_{sp}(t)$) (Eq. 5.11).

$$e(t) = y_{sp}(t) - y_{pv}(t) \tag{5.11}$$

$$\lim_{t\to\infty} e(t) = 0 \tag{5.12}$$

The controller usually regulates the process in order to compensate for the effect of disturbances in the process (w) or an altered reference value (y_{sp}). The most commonly used controller is the proportional–integral–derivative controller (PID controller – Eq. 5.13). The PID controller, as the name indicates, uses these three mathematical functions to regulate the process and compensate for the error.

$$mv(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{d}{dt} e(t) \tag{5.13}$$

With the proportional part, the adjustment output is proportional to the calculated error, denoted with a K_P. This part will however not eliminate the error completely. With the second part of the PID controller, the integral, a zero error can be achieved by calculating the adjustment output which is proportional to the integral of the error (K_I). The last part of the controller, the derivative, provides rapid adjustments based on rate of change of the error (K_D) [51].

A PID controller, such as illustrated in Figure 19, has been applied in Papers A-D for many of the needed control loops. The controller compares the set point ($y_{sp}(t)$) and the actual process value ($y_{pv}(t)$) of the corresponding level and regulates the process accordingly. The level signal which is a function of the mass-flow and the geometry of the production unit is sent from the monitored production unit model to the controller model as a scalar signal. How the controller reacts to changes in the process is dependent on the value of the parameters K_P, K_I and K_D in Eq. 5.13.

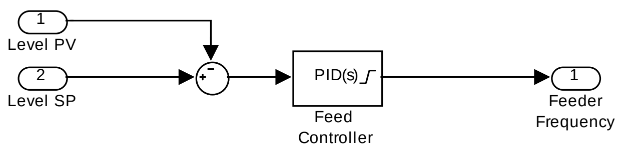


Figure 19. PID controller for the feeder frequency in MATLAB/Simulink.

DYNAMIC SYSTEM RESPONSE

How a model responds to a change in operation is crucial for the dynamic behaviour of the system. One way of simulating the step or impulse response of a system is with a differential equation or with a corresponding transfer function which can be derived analytically or empirically. Step responses from a first order system, second order system and a pure delay are illustrated in Figure 20 and given in Eq. 5.14-5.19.

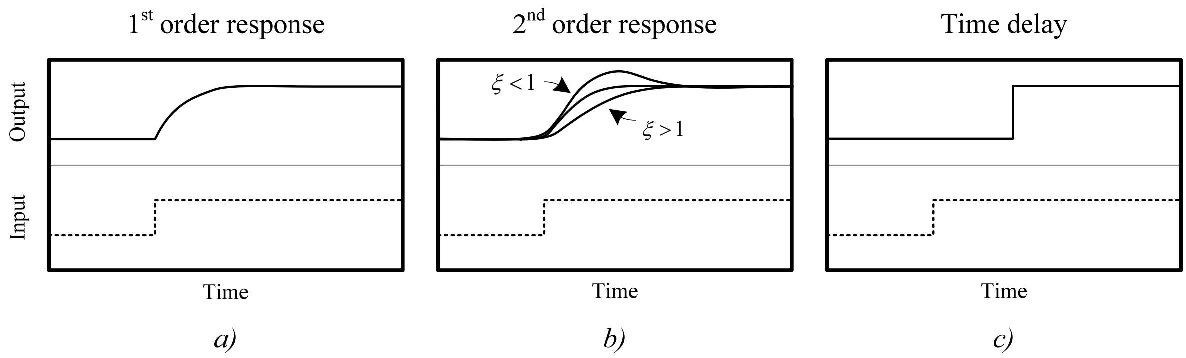


Figure 20. Step response for first order system (a), second order system (b) and a pure time delay (c). Modified from Marlin [51].

The response of the first order system (Figure 20a) is usually given by a simple first order differential equation or by the corresponding transfer function which is illustrated in Eq. 5.14 and Eq. 5.15. The time constant, which is denoted with a τ, is the time which the system takes to reach 63.2% of the final steady-state value which is equal to the steady-state process gain (K_p) and the difference in the forcing input ($u(t)$).

$$\tau \frac{dy}{dt} + y(t) = K_p u(t) \tag{5.14}$$

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_p}{\tau s + 1} \tag{5.15}$$

Similar to the first order system, the second order system is described with both a second order ordinary differential equation (Eq. 5.16) and the corresponding transfer function (Eq. 5.17). A second order response can also be achieved by having two first order systems in a series. As with the first order system, the second order system is described with a time constant τ and the forcing function $K_p u(t)$. However, an additional factor is included, the parameter ξ which is termed the damping coefficient. The damping coefficient determines if the step response which is depicted in Figure 20b, is overdamped ($\xi > 1$), underdamped ($\xi < 1$) or critically damped ($\xi = 1$). If the parameter ξ is too low the system will continue oscillating over a long time.

$$\tau^2 \frac{d^2 y(t)}{dt^2} + 2\xi\tau \frac{dy(t)}{dt} + y(t) = K_p u(t) \tag{5.16}$$

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_p}{\tau^2 s^2 + 2\xi\tau s + 1} \tag{5.17}$$

The third part illustrated in Figure 20c is the dead time or transportation delay of the system. The dead time is the delayed step response of the system, the change in the input parameter u does therefore not affect the system output $y(t)$ until after the determined delay time θ has passed, as illustrated in Eq. 5.18 and Eq. 5.19.

$$y(t) = u(t - \theta) \qquad (5.18)$$

$$G(s) = \frac{Y(s)}{U(s)} = e^{-\theta s} \qquad (5.19)$$

In Paper B and C, a first order transfer function with delay was applied to the feeders installed throughout the circuit. In Figure 21 the MATLAB/Simulink model for representing the system response is illustrated. However, as previously discussed the dynamics of the system are often represented with an ordinary differential equation. In Figure 22 the differential equation for representing the second order system is demonstrated as a model in MATLAB/Simulink.

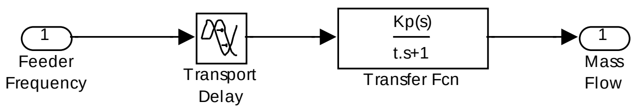


Figure 21. Dynamic response of a feeder which is a first order system simulated by a transfer function and a delay.

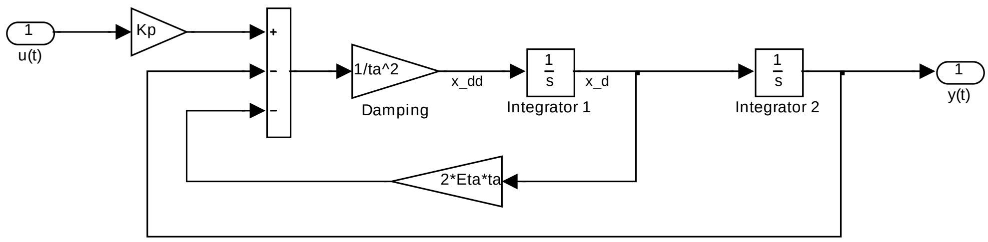


Figure 22. Representation of Eq. 5.14, the second order system without delay as a differential equation in MATLAB/Simulink.

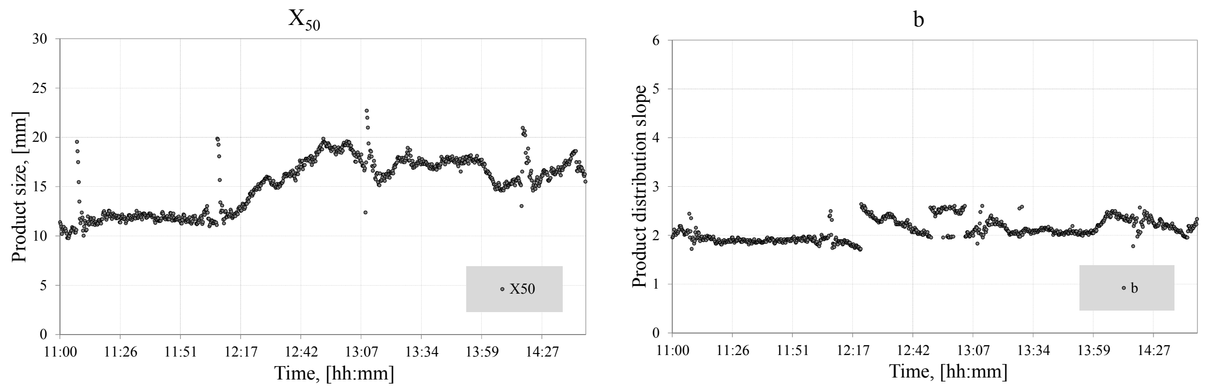
Wear

The crushing process is constantly affected by wear which causes gradual performance deterioration. How the wear affects the process is dependent on multiple factors. These include the characteristics of the equipment subjected to wear, the geometry of affected components and the properties of the rock material: mineral content, particle size distribution, moisture and more. In Section 4.3 a handful of research work is presented which has focused on wear in comminution circuits and on specific equipment.

In Paper A, a specific focus was on the effect gradual wear has on a cone crusher and how it affects the product mass-flow in the crushing circuit. The studied plant was an aggregate plant 80 km north of Gothenburg, which produces high-quality aggregate products from granitic gneiss, ranging in size from 0-2 mm to 16-22 mm. All 10 conveyors in the tertiary phase of this plant were equipped with power meters that monitored and logged the electrical power draw. From these data, the mass-flow could be calculated and changes in the particle size distribution estimated.

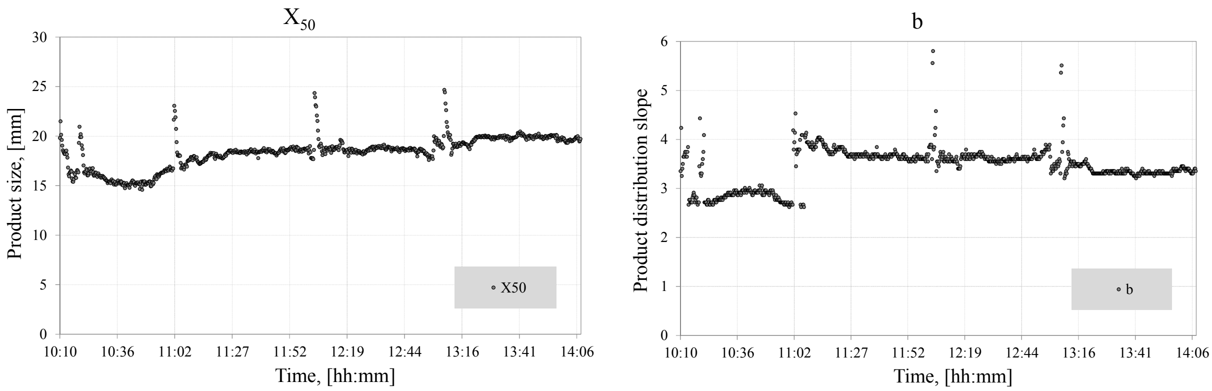
In Figure 23 and Figure 24 the calculated change in particle size distribution, due to wear, is expressed as the change in the size of the 50 % passing (x_{50}) and the shape of the particle size distribution curve (b) as a result of a fitted Swebrec function to the logged production data. In Figure 25 the calculated change in the x_{50} parameter is displayed together with interpolated data between the measured CSS. Approximately one hour separated each measurement.

Figure 26 shows the collected data, which is presented as a change at defined intervals, from the calibrations. Fitting a linear regression to the data points provides a simplified indication of the wear trend that occurred during the experiments. Looking at the wear rate in each single run, the rate varies between 0-3 mm/hour but when calculated together the wear rate becomes close to constant just below 1 mm/hour.



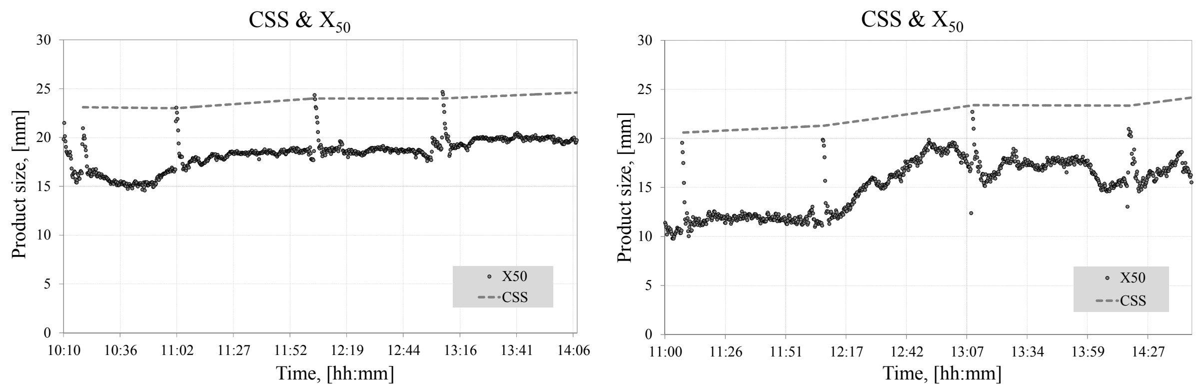
(a) *(b)*

Figure 23. Calculating the change in the particle size distribution, x_{50} (a) and b (b), over time from the logged process readings.



(a) *(b)*

Figure 24. Calculating the change in the particle size distribution, x_{50} (a) and b (b), over time from the logged process reading.



(a) *(b)*

Figure 25 The trend of CSS (dotted grey line - interpolated between tests) and x_{50},(black dots – calculated from logged process readings) as a function of material flow through the crusher at two of the experiments, (a) and (b). The results are close to parallel. Spikes in the x_{50} curve indicate an interruption in the process due to calibrations or mechanical failure.

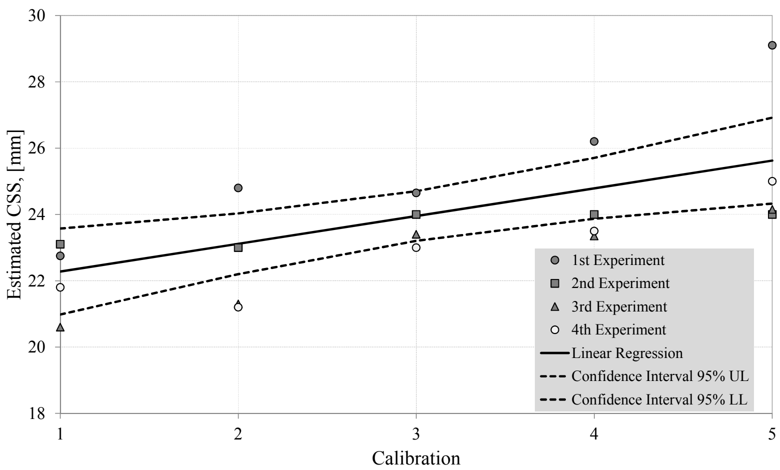


Figure 26 Wear trend (black line) generated from the results of the calibration with a calculated 95% confidence interval (black dotted lines).

Eq. 5.20 was formulated to describe the changes in parameter x_{50}, given that the particle size distribution of the feed remains close to constant. Parameter a_1 is a function of the incoming particle size distribution and the condition of the crushing chamber which represents the ratio between the initial $CSS(t_0)$ and x_{50}. The parameter a_2 represents the wear rate depending on the amount of crushed material ($m_{crushed}(t)$) per hour.

$$x_{50} = a_1 CSS(t_0) + a_2 \int_{t_0}^{t} m_{crushed}(t)dt \tag{5.20}$$

6 APPLICATION OF DYNAMIC SIMULATION

The aim of this chapter is to:

- *Describe the application areas for dynamic simulations.*
- *Explain how the published papers are applied to the areas.*

The setup of the dynamic simulator is dependent of the aim of the simulation. The aim of the simulation can be to simply evaluate the average performance of the system, similar to the use of steady-state simulation. However, the dynamic simulations can even be applied in broader perspective as it provides more detailed information about how the different parameters vary with time.

A dynamic plant simulator is a versatile simulation tool, capable of simulating plant performance with high fidelity. However, how the models are constructed is dependent on the purpose of the simulations. In Chapter 6 a deeper insight will be given into the application areas of the dynamic simulator and the results from Papers B, C and D are presented.

6.1 PLANT PERFORMANCE

The traditional use of crushing plant simulators is to model and evaluate plant performance. In order to evaluate the performance of a particular plant a flowsheet of the plant is arranged so that it represents the layout of the plant. The plant can be an actual plant or a fictive plant, which usually affects the purpose of the simulation. Configuration of the equipment is done by entering equipment settings, such as CSS and screen apertures into appropriate equipment models. Additionally the ore characteristics of the feed material are defined, such as particle size distribution, material density and work index. After this has been done the simulation will determine the behaviour of the process over time and the performance of the system. The steps above are applicable when dealing with steady-state simulation. However, when it comes to dynamic simulations additional aspects of the operation need to be considered.

Since the material accumulates within the system the material flow needs to be controlled with both interlocks and regulatory controllers. If long-term simulations are done for determining annual production or equipment availability, DES needs to be applied.

How the plant performance is defined is determined by the aim of the simulation. Usually plant performance is defined by the particle size distribution being produced or the mass-flow through the circuit. Since the level of information is higher with dynamic simulation in contrast to traditional methods, additional factors such as plant saturation, plant maximum performance and plant stability can be determined and evaluated.

In Paper B the crushing section of a platinum concentrator was modelled and simulated, see Figure 28 and Figure 29. The plant was modelled in MATLAB/Simulink (Figure 29). The modelled section consists of three cone crushers (a coarse crusher CR001, intermediate crusher CR002 and a fine crusher CR003), single vibrating grizzly with sloth width from 80 mm, two double deck screens with top deck at 85x85 mm and bottom deck at 40x52 mm and two bins that are approximately 660 m^3 and 300 m^3, respectively. The incoming feed is a PGM ore (Platinum Group Metal) which has been crushed with a primary crusher down to approximately 0-250 mm.

From a steady-state modelling perspective the plant would be modelled as depicted in Figure 27, with mass-balance in point A and B and the performance determined by the crushers combined capacity. This will however give an unreliable result of the plant actual performance, since material handling affects how the crushers operate. The modelling approach in Figure 28 is therefore more suitable.

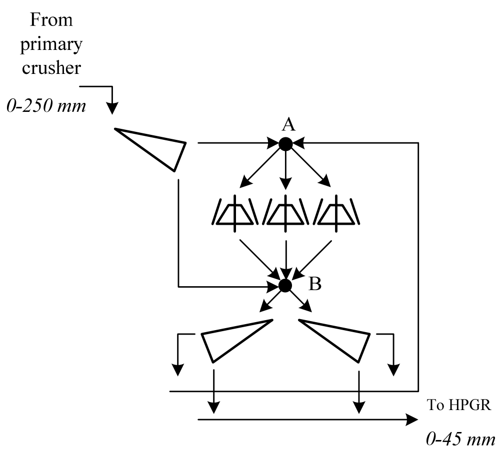


Figure 27. A steady-state view of the plant.

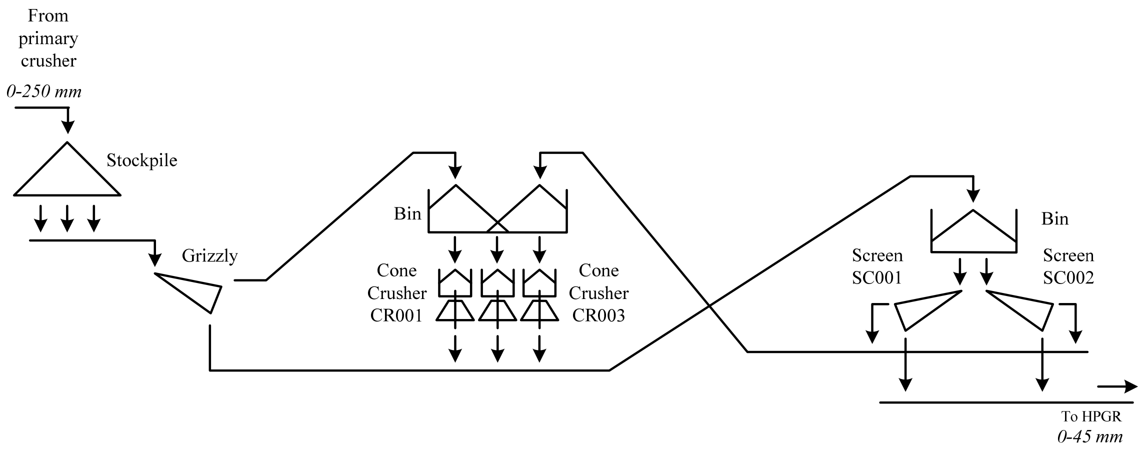


Figure 28. Flowsheet of the crushing section of the platinum processing plant as presented in Paper B.

The general purpose of Paper B was to study how the plant operated under different operating conditions and find out what level of plant performance could be achieved. Four different scenarios were simulated from different combinations of two factors. The scenarios were configured according to the setup of the plant and from the measured process data, which was collected during two major surveys done prior to the simulation work.

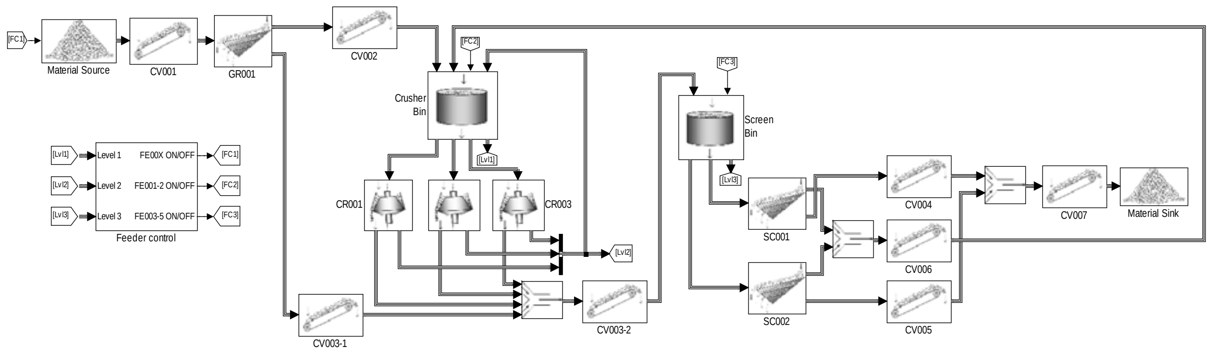


Figure 29. The section modelled in MATLAB/Simulink together with the plant control. The broad signal lines between the production units represent the material signal presented in Eq. 5.1 while the thin signal lines are process values ($y_{pv}(t)$) and desired values ($y_{sp}(t)$) explained in Eq. 5.11.

It was the effect of these two different factors which was of special interest. Namely, reducing the CSS of the coarser crusher and increasing the throw of the finer crusher. The configuration of the simulation for the different scenarios is listed below.

- *Reference simulation.*
- *Reducing the CSS of the coarse crusher (CR001), from 55 mm to 40 mm.*
- *Increasing the throw in fine crusher (CR003) from 38 mm to 44 mm.*
- *Reducing the CSS of the coarse crusher (CR001) and increasing the throw in the fine crusher (CR003).*

Every scenario was simulated with the same disturbances. The disturbances were in the form of variations in the particle size distribution and the mass-flow and each scenario was simulated until it reached steady-state performance. The simulation result from the 1250 tph target throughput in Scenario 1 is shown in Figure 30. Under these conditions the plant was stable and able to hold the target throughput of 1250 tph without any major fluctuations. However, in Figure 31, input feed rate was increased up to 1500 tph which caused the process to start fluctuating. Under these conditions the plant was not stable and an overall performance achieved which was lower than the target feed rate.

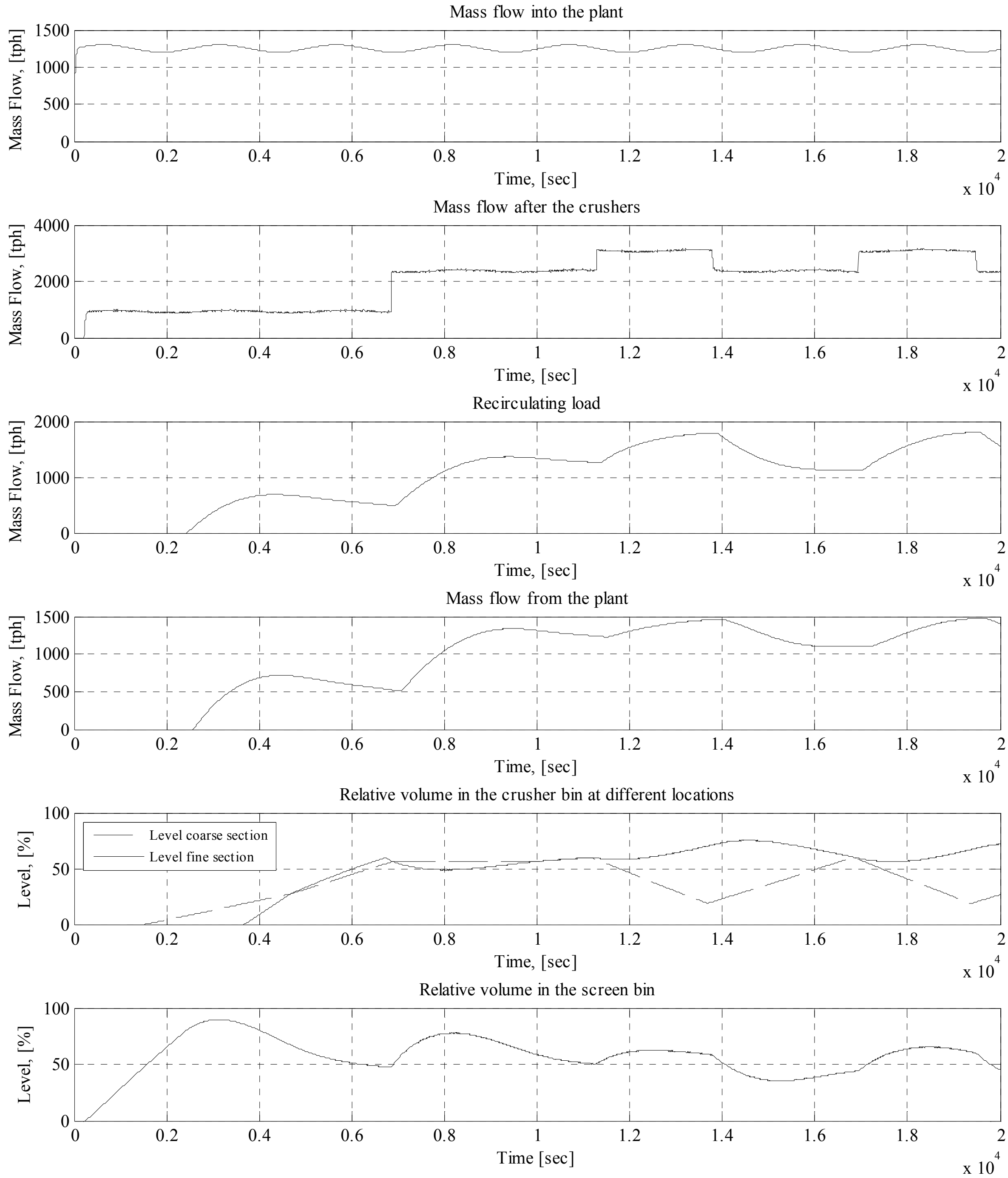


Figure 30. Simulation results from simulating 1250 tph in Scenario 1. The process is relatively stable with minor fluctuation.

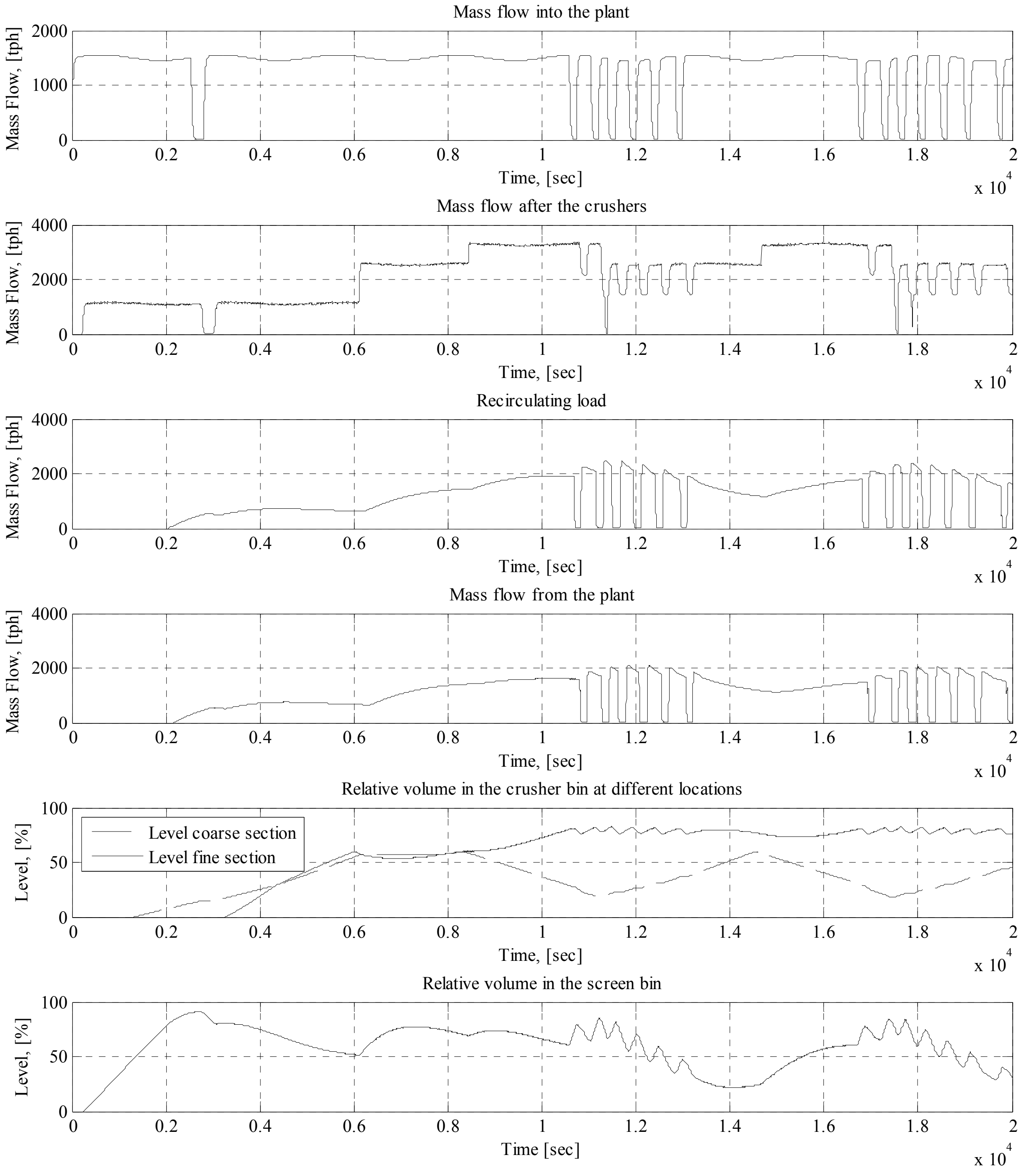


Figure 31: Simulation results from simulating 1500 tph in Scenario 1. The process starts experiencing major fluctuation after approximately 3 hours.

6.2 PROCESS OPTIMIZATION

A control system is needed to regulate the feed rate in a dynamic simulation. The control system can be developed and optimized in advance before being applied to the plant using the simulator as a development platform.

The development of advanced process control often entails the usage of dynamic models for predicting the behaviour of the system. This is to counteract the effect a change in the process has on the production before it occurs in the system. The models have to be sophisticated enough to be able to predict the performance of the system under different conditions.

In Paper C the purpose was to tune an existing control algorithm which was developed in an earlier PhD project, by Hulthén [10]. The control algorithm in question is a Finite State Machine (FSM) which controls the eccentric speed of a crusher by making discrete step changes ($\Delta Speed^{+}$ and $\Delta Speed^{-}$) with defined time intervals (*LongTime*) while observing the performance of the circuit. How the FSM works is illustrated in Figure 32.

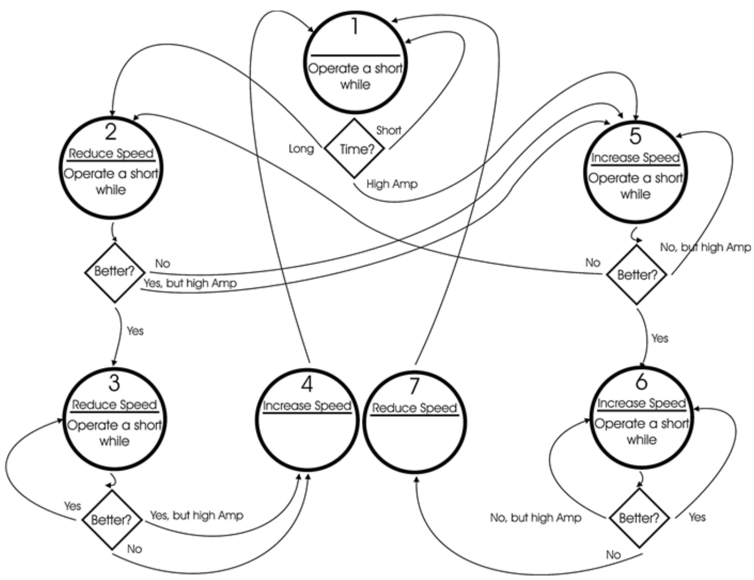


Figure 32. The FSM used for selecting appropriate speed [10].

These step changes in speed and the length of time interval between each step has previously been selected manually to give the best performance possible. However with the FSM connected to a dynamic model of the circuit (see Figure 33), the numerical value for the step change in speed and the length of the time interval can be optimized. For the optimization of the FSM algorithm an evolutionary algorithm called genetic algorithm (GA) was used. A GA is an optimization algorithm which searches for the optimal settings by gradually improving the generated solution until the best solution is achieved. The fitness function ($\varphi_{\text{Performance}}$) used for the optimization routine is defined in Eq. 6.1, i.e. the relation between the total capacity and the amount of recirculating material (defined in Figure 4a and Figure 4b).

$$\varphi_{Performance} = \sum_{i=1}^{m-1} p_i - p_m \qquad (6.1)$$

The modelled plant is a tertiary crushing stage in an aggregate quarry as described in Paper A. This particular plant is equipped with a frequency converter which enables control of the eccentric speed of the crusher by altering the frequency to the motor. This crushing stage is designed with a Metso Nordberg HP4 cone crusher and two triple-decked screens which produce products ranging from 0-2 mm up to 16-22 mm, the modelled plant is illustrated in Figure 33. Incorporated into the model is a sub model representing the frequency control, in which the code for the FSM is implemented.

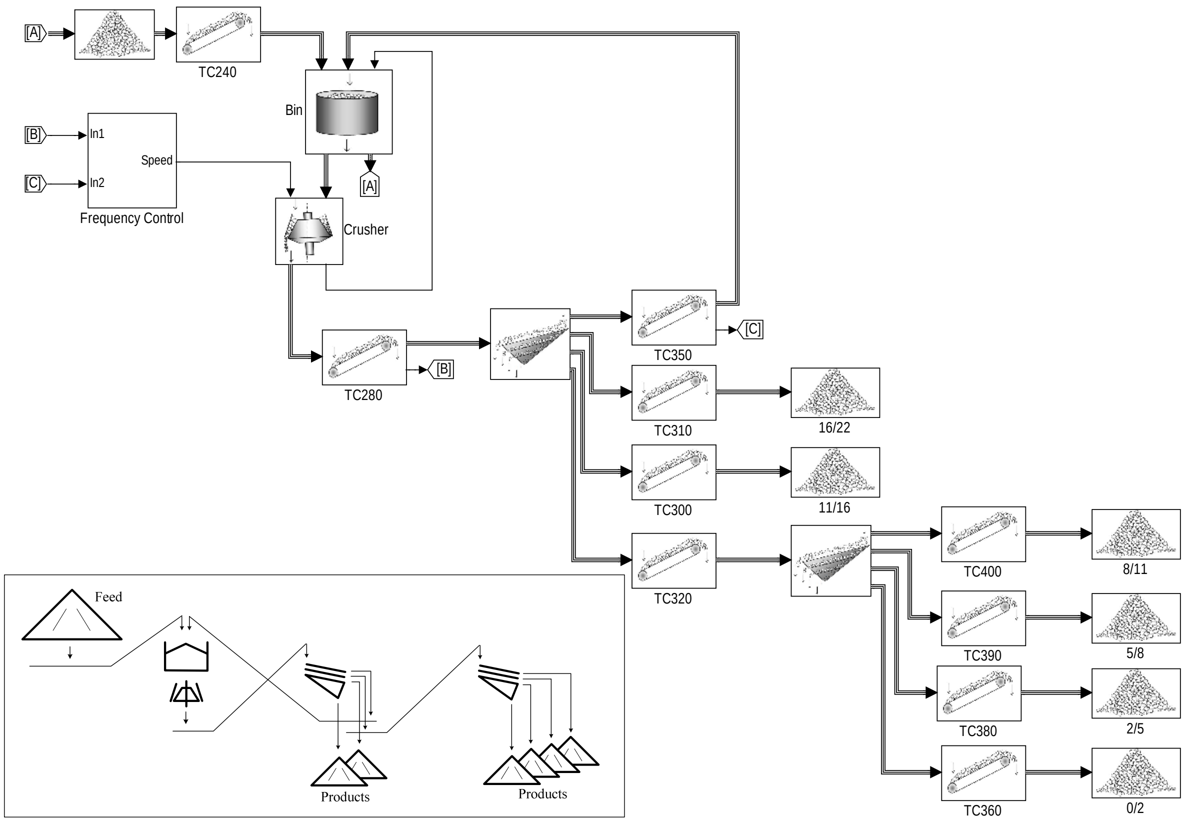


Figure 33. The modelled process in MATLAB/Simulink and the simplified layout of the plant in the embedded picture. The broad signal lines between the production units represent the material signal presented in Eq. 5.1 while the thin signal lines are process values ($y_{pv}(t)$) and desired values ($y_{sp}(t)$) explained in Eq. 5.11.

Using dynamic simulators to develop a control system makes it possible to test the control system in a controlled environment prior to commissioning of the plant. Unexpected consequences can occur if a control system is implemented without a rigorous quality control of the code itself. The code may be different for two plants that have identical production units and configuration since the rock material and the management of the plant can be different.

6.3 OPERATOR TRAINING

Operators are responsible for managing the process in order to obtain a stable production of high quality products and high throughput. The operator's capability in making fast and effective decisions is therefore important. Operator training is often a manual process which is conducted by verbal interaction between an experienced operator and an inexperienced operator. The operators' cognitive ability in detecting and analysing information from the process can therefore be limited for a novice operator.

In Paper D a system architecture for enabling operator training with a dynamic simulator was designed. The fundamental basis of the system is the dynamic simulation which represents the behaviour of the entire system, where both the performance of the system is determined and discrete events initiated. Running in parallel with the dynamic simulation is a Programmable Logic Controller (PLC). Data from the simulated process is sent to the PLC where the control system sends control commands, such as changed set points, back to the simulation depending on the conditions of the simulated process. With a PLC connected to the dynamic simulation an existing control algorithm can be used and connected to the simulation, further increasing the fidelity of the system. The operator interacts with the simulation through the HMI. With the HMI the operator should experience the impression that he or she is operating an actual plant. Finally there is an Open Platform Communications (OPC) server which handles the communication between each component in the system. In Figure 34 the designed system architecture is depicted.

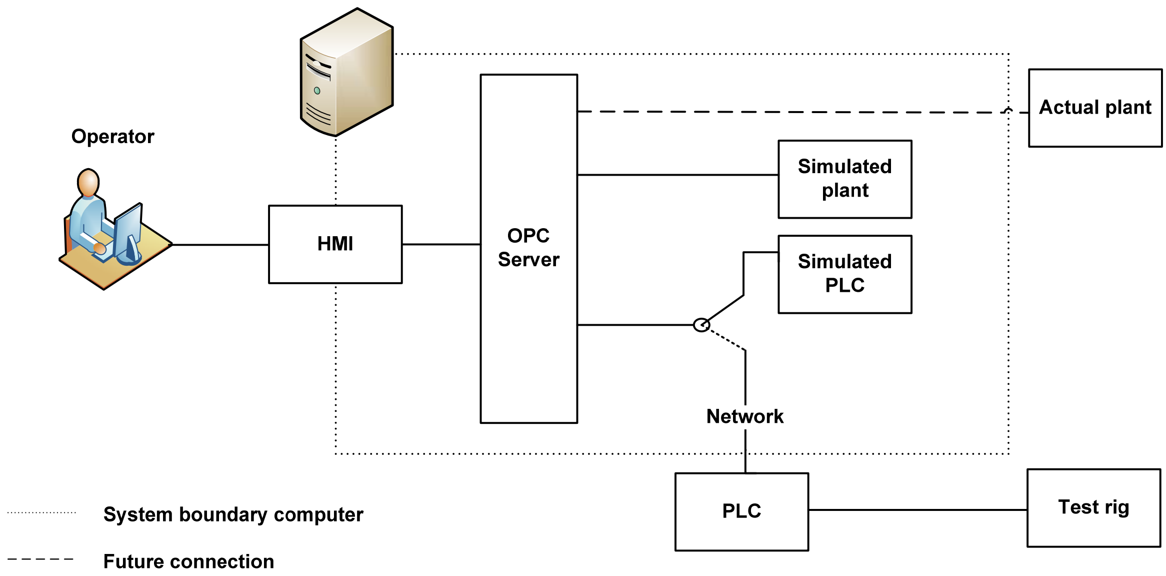


Figure 34. System architecture for enabling operator training.

With simulation based operator training, the operators can test different scenarios without risking affecting the plant production. Moreover, with this setup specific scenarios can be constructed depending on what the purpose is with the training e.g. to respond correctly to a malfunction or to plan the operation in order to achieve the highest possible throughput.

7 RESULTS & DISCUSSIONS

The aim of this chapter is to:

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

The application areas discussed in Chapter 6 are diverse in many aspects but share the same fundamental base, the dynamic simulator. In this chapter results from Papers B, C and D are presented.

7.1 PLANT PERFORMANCE

The plant performance evaluation described in Paper B and in Section 6.1 shows how it is feasible to use dynamic simulation in order to evaluate the performance of a crushing plant. The simulations, which were run with different scenarios, revealed that the plant reaches performance saturation at different levels depending on how the process is configured, see Figure 35.

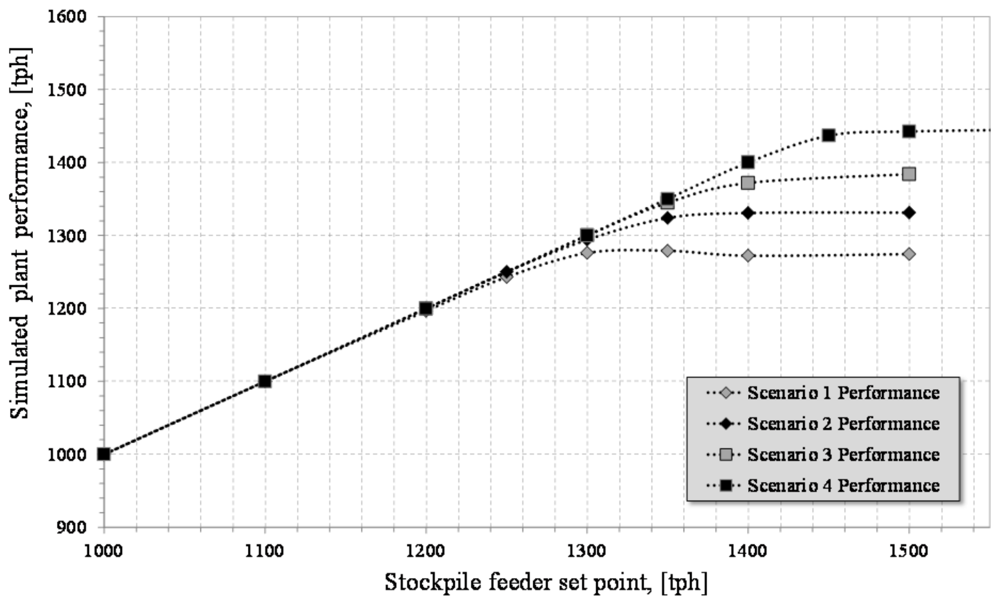


Figure 35. Average plant performance for different feed rates and plant configuration.

The results from the simulated scenarios in Figure 35 illustrate how the plant´s average performance reaches a maximum level at a certain feeder target feed rate. This is where the interlocks start interrupting the process and shutting on and off the incoming feed into the circuit making the process unstable. Up to this point the plant experiences steady-state behaviour. The reference scenario (Scenario 1) was able to produce approximately 1275 tph in an uninterrupted operation. While, Scenario 2 and Scenario 3 were able to increase the overall capacity by 4.7 % resp. 8.2 %. The combined factors in Scenario 4 revealed a possible 13.3 % increase in plant capacity.

The validation experiment of the scenarios gave a promising indication of the fidelity of the simulation (see Figure 36). By running the Scenario 1 and Scenario 2 where the CSS of crusher 1 was reduced from 65 mm to 50 mm the overall plant performance increased by 4.9 %, from 1291 tph to 1354 tph compared to 4.7 % simulated.

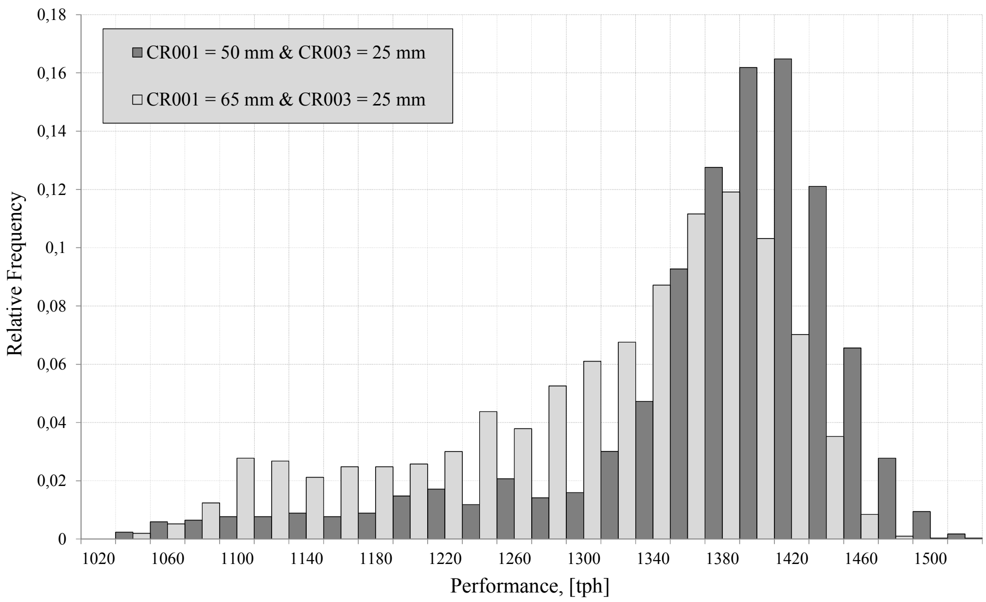


Figure 36. Plant performance for two different settings of crusher 1 (CR001).

When reducing the capacity of crusher 1 by running the crusher at a smaller CSS the overall plant performance was increased. By running crusher 1 with a smaller setting the rock material was crushed more in the initial pass and less material was recirculated to crusher 3.

7.2 Process Optimization

In Paper C tuning of the FSM control parameters was performed. The FSM is used for selecting appropriate eccentric speed for the crusher in order to achieve optimum performance. By running a GA, optimum control parameters can be found within a given interval. As discussed in Section 6.2 the algorithm parameters ($\Delta Speed^{+}$, $\Delta Speed^{-}$ and *LongTime*) are selected manually. At the selected crushing plant these parameters were set to:

- $\Delta Speed^{+}$ = 60 rpm
- $\Delta Speed^{-}$ = 60 rpm
- *LongTime* = 480 sec

Simulation results from running the process with the existing settings are illustrated in Figure 37 while the simulation with the optimized parameters is illustrated in Figure 38. The mass-flow is shown in the upper graph and while the speed set point is shown in the lower graph. The process was simulated for 12000 s which is approximately the time between each calibration and a disturbance was initiated at 6200 s to represent a short stop in the incoming feed rate.

By optimizing the step change for the frequency converter a theoretical increase in production is possible. When comparing the current manually selected parameter against the optimized parameters, which are listed below, an increase of 0.5 % was estimated.

- $\Delta Speed^{+}$ = 91 rpm
- $\Delta Speed^{-}$ = 48 rpm
- *LongTime* = 544 sec

It must be kept in mind that these 0.5 % add on to the manually tuned algorithm which gave about 5 % improvement to the process [10]. Thus a method for automatically tuning the algorithm was achieved.

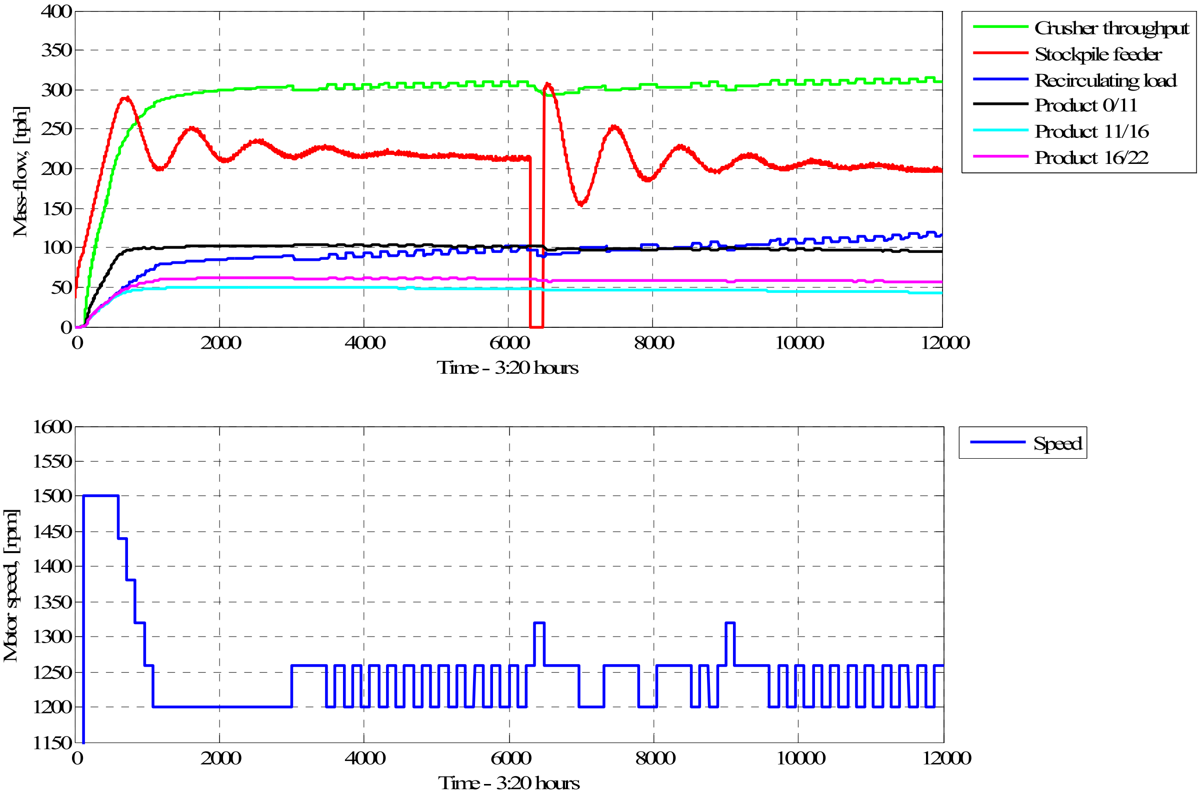


Figure 37. Simulation results with existing settings. The upper graph illustrates the mass-flow on different conveyors while the lower one illustrates the change in speed set point during the simulation.

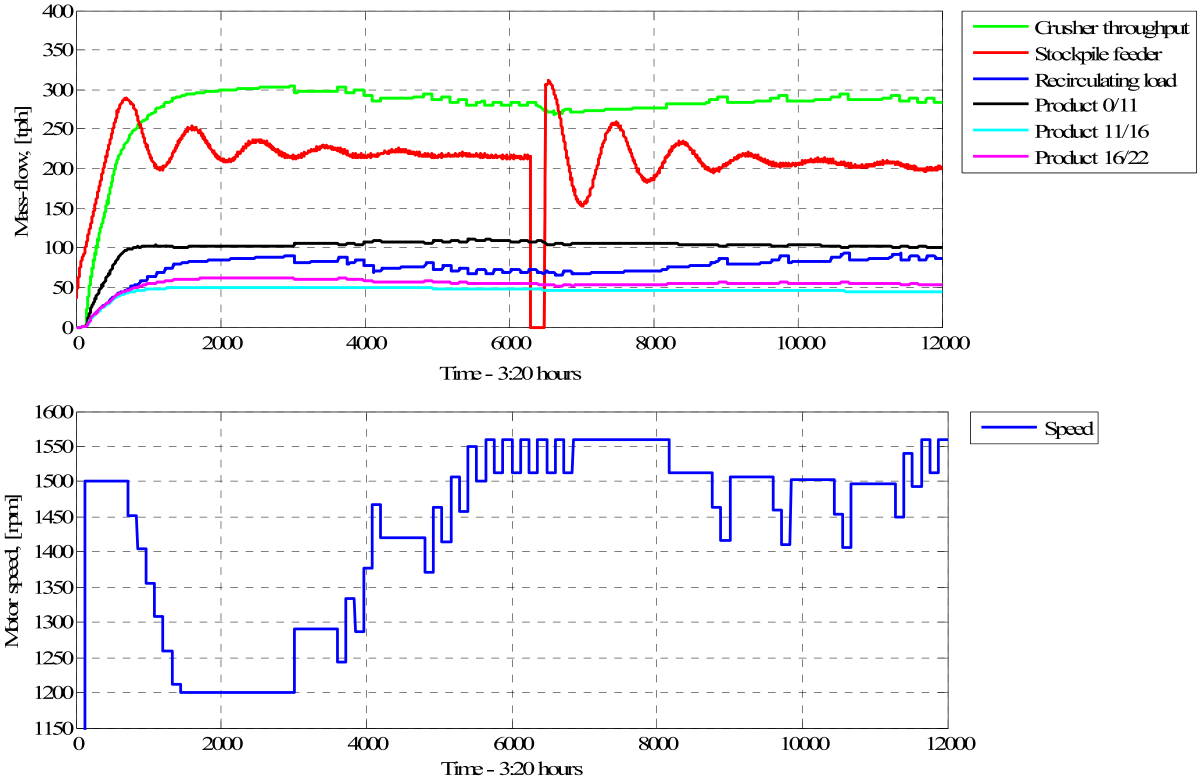


Figure 38. Simulation results after the optimization. The upper graph illustrates the mass-flow on different conveyors while the lower one illustrates the change in speed set point during the simulation.

7.3 OPERATOR TRAINING

The system structure presented in Section 6.3 and in Paper D was built in the CRPS laboratory with all the necessary hardware and software needed to enable operator training, see Figure 39. The system consists of a couple of standard PCs with an Iconics HMI software and a OPC server installed. Together with the PCs are two displays for the HMI and a screen used to visualize what is happening in the simulated process with predetermined video sequences depending on the outcome from the DES. This can be used to show the arrival and departure of the trucks, a front loader loading the primary, material flow on conveyors and more. A test rig is mounted close to the operator station to emulate different signals. On the test rig a Schneider-electric M340 PLC was installed for handling the control, with multiple slots for analog and digital inputs/outputs, a frequency converter, a small asynchronous motor and multiple switches. This all helps to create as realistic work experience as possible for the operator.

The ground work for creating a functional operator training simulator has been done. The identification of appropriate cases for operator training is essential for the functionality of the system. This can both be cases where a new operator is being introduced to the plant and allowed to familiarize himself with the system by running different scenarios in a controlled environment or for evaluating the HMI/SCADA which can be used to evaluate a new design of the visual layout or new implementations to the system.

By performing operator training, the operators' capability in reacting to changes in the process increases and becomes more effective. With an operator training simulator the operator is able to interact with the process without risking any potential damage to the actual equipment, thus providing the operator with valuable hands-on experience.

Figure 39. The simulation computer running a plant simulation while information is being transferred to the operator's screen.

8 CONCLUSIONS

The aim of this chapter is to:

- *Present the most important conclusions drawn in this thesis.*
- *Answer the research questions stated in Chapter 2.*

The purpose of this work was to investigate how crushing plants operate during changed conditions and develop a simulation platform for representing the dynamic behaviour of crushing plants. During the development of the simulation platform different applications areas were tested for the implementation of the dynamic simulations.

8.1 GENERAL

Dynamic simulation of production processes has the ability to provide the user with deeper understanding about the simulated process. The details provided are usually not available with traditional steady-state simulations. However, similar to a steady-state simulation the purpose of the dynamic simulation needs to be clear in order to get relevant information regarding the process.

As depicted in Figure 9 in Chapter 5 there are a number of factors that can affect the plant performance. How some factors affect the process is clear, for example changing the aperture on the screen will give different cut point for the mass-flow. However, other factors are more difficult to interpret and predict, such as equipment failure and operator decisions.

Extensive research exists on specific equipment. In this field of research the focus has been on stead-state models during the past decades. With a relatively small amount of work the models can be altered to provide dynamic behaviour. However, validating equipment and plant models are always difficult when considering normal operating conditions. The crushing process is constantly fluctuating due to variations, which makes it difficult to confirm models since the cause of variation is hard to identify. Taking samples from the process only provides a snapshot of the process at a particular place and at a particular time.

8.2 ANSWERS TO RESEARCH QUESTIONS

The following answers are given to the research questions stated in this thesis:

RQ 1: What factors can cause dynamic behaviour in crushing plants?

Multiple factors affect the performance of a crushing plant. Plants operate under harsh conditions and involve highly abrasive material, due to these conditions the process is subjected to considerable wear issues. The wear will have different effects on the process dependent on where the wear occurs. Parts of the plant in which production is critically affected by wear are the crushers and the screens. The wear will gradually change the performance of the crusher, producing larger particle size distributions due to the properties of the rock material and the size reduction of the particles being crushed. Wear rate on screens is not as high as on a crusher but the aperture size is critical in order to ensure the quality of the material.

Apart from the gradual changes, the process experiences discrete changes as well. The changes are usually caused by a change in operating conditions or by different settings of the equipment. Change in set points or interlocks are examples of factors that experience discrete changes. How the system responds to discrete changes is dependent on the characteristics of the each individual production unit.

In dynamic simulations the transport and storage of material within time-dependent equipment can cause process fluctuation if the design of the plant or the control system is not adequate to keep the process stable. When the material is transported with conveyors between different production units the material experiences a time delay and if the storage capacity is small in the subsequential production unit the control system needs to be able to take that into consideration and regulate the flow in order to keep the process stable. Studying the example in section 7.1, the plant experiences a steady-state operation up to a certain target feed rate, after that the average plant throughput levels out due to process dynamics as illustrated in Figure 40.

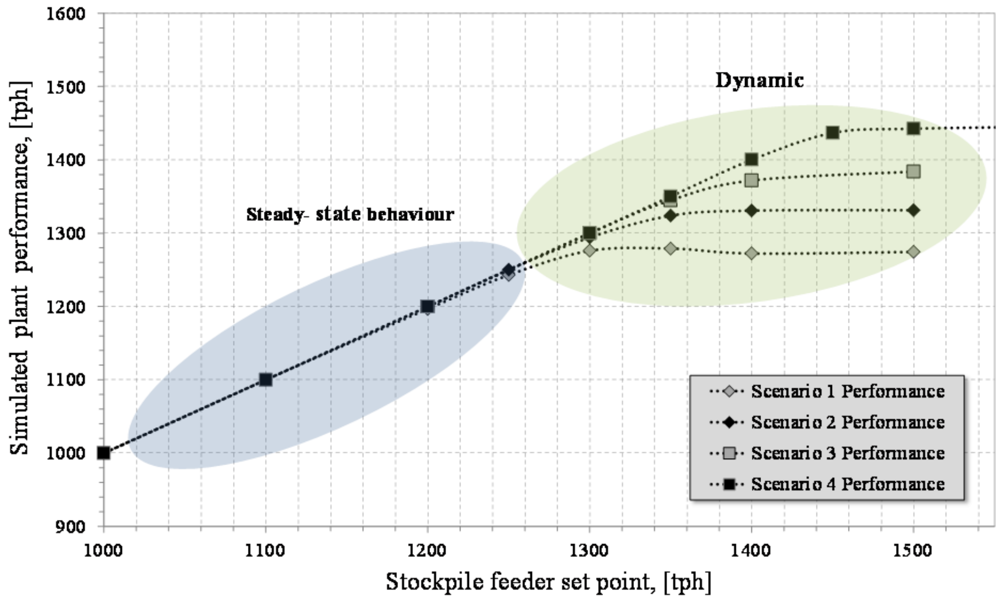


Figure 40. Plant's average production performance. In the blue area the plant operates in steady-state while in the green area the plant experiences fluctuation and limited throughput.

Stochastic and systematic variations have not been addressed much in this thesis. However, their contribution to the dynamic behaviour of the process should not be neglected. Since the rock material is usually blasted from solid bedrock, the geological properties of the rock vary from one position to the next. Subsequently, when the blasted rock material enters the crushing circuit the variation in the rock properties is fairly similar within each batch. However, the difference between each batch could cause observable change in the process.

RQ 2. What methods and techniques exist, and should be used to represent dynamic crushing plant behaviour?

Traditional steady-state simulations are not adequate to represent time-dependent behaviour properly. However, there have been a number attempts to compensate for the lack of time perspective in state-state simulation by running multiple step simulation in order to represent the dynamics. In Svedensten et al [14] the effect of wear and process variation on production was estimated by running state-state simulation together with Monte Carlo simulation, which was used to estimate the performance distribution of the plant. In King et al. [52] the step changes in the process were evaluated by running multiple steady-state simulations in a sequence.

Dynamic simulation is defined in this work as continuous simulations with sets of differential equations, capable of reproducing the dynamic behaviour of a system. The fundamental parts of dynamic systems are the accumulation of mass and dynamic response. The material flow in a dynamic system is not constrained by the instantaneous mass-balance in contrast to steady-state simulations. Instead it follows the principle of conservation of mass, which is usually described with a differential equation including the mass-flow in and out of the system and the mass which is retained within the system over time. The dynamic step response describes the change in the system from one state to another, it can be modelled with a differential equation, a transfer function or an algebraic equation.

When simulating long-term conditions, the implementation of DESs is necessary in order to obtain reliable results. With a DES the simulation is not continuous any more. Instead the change in state is initiated at a specific time, making it discrete. With SimEvents a discrete event perspective can be added in the modelling environment making the plant simulation a hybrid one i.e. a combination of discrete and continuous simulation.

Different platforms exist that support the modelling of dynamic systems. During the work in the present project two different platforms have been used and validated, SysCAD (Kenwalt) and MATLAB/Simulink (Mathworks). Both platforms are highly capable of simulating the dynamic behaviour that occurs in a crushing plant. Even though SysCAD is able to deliver a built-in equipment library it is author's opinion that MATLAB/Simulink is the more attractive choice when it comes to development of a dynamic simulator.

RQ 3. How can dynamic simulations assist in evaluation of effects of step changes and other variations on crushing plant response and production?

Changes in a plant can occur due to external or internal changes. External changes are changed operating conditions due to factors that cannot be or are difficult to control, e.g. different moisture content due to rain and different mineral composition in the rock material. Internal changes means changes that are controllable such as changed settings of crushers.

The dynamic response to changed operating conditions can be modelled in different ways. In Section 5.2 the different equations used in this thesis to model a step response in a system are explained. These equations include the general differential equations and the transfer function used to describe a step change in a system. How the system reacts to a step change is however dependent on the fundamental principle of the actuator involved. This way of simulating step changes has been used to simulate the change in operating conditions for both external and internal factors.

From an overall plant perspective it is difficult to estimate a change in plant performance after a changed operating condition without the help of simulations. How the plant performance is affected by changed performance in a single production unit is determined by the plant configuration and control. Crushing plants often reach a stable operating condition after a certain time period. However, when a change in operating conditions occurs the plant will deviate from the previous performance value and stabilize at a new level for the performance value. The time it takes for the plant to establish a new steady operating condition is determined by the time it takes for the change in the process to affect other production units, the dynamic response of each unit and the control system´s capability in reacting to the change.

RQ 4. How can dynamic simulation be used for industrial purposes?

Three main areas of industrial use for dynamic simulation have been identified in this licentiate thesis. The three areas are described in detail in Chapter 6 and are as follows:

- Plant performance
- Process optimization
- Operator training

For all three areas the use of dynamic simulation has shown to be essential. How the dynamic simulation is applied varies between each area and also within each area, depending on the general purpose of the simulation. In the process layout simulated in Paper B a steady-state simulation was not sufficient to give reliable results due to plant configuration and control. With dynamic simulations a more accurate estimation of the plant performance was possible.

For process optimization, as illustrated in Paper C, control algorithms can be connected to a dynamic simulator before implementation in the actual process is done. This makes it possible to test and fine-tune the algorithm with the help of dynamic simulation.

For operator training, as illustrated in Paper D, the operator needs to be able to interact with the process and make process changes in real-time. With dynamic simulation running in real-time connected to an HMI this becomes possible, thus minimizing the need of interrupting the actual production.

9 FUTURE WORK

The aim of this chapter is to:

- *Discuss what has been found important for future work but so far not researched.*

The work presented in this licentiate thesis has been focused mainly on modelling and exploratory studying of different applications for implementation of dynamic simulation. With dynamic simulation new applications become possible compared to the use of steady-state simulations, applications such as operator training and control algorithm development. Each application is relatively time consuming to setup. A more easy-to-use graphical user interface and refined model structure would reduce the configuration time.

Validation and verification of equipment models for respective applications are becoming more and more important with more explicit implementation since different implementations have different constraints on effectiveness with respect to efficiency. Control algorithm development requires for instance high accuracy, while little or no constraint on computational time. New and more advanced models should therefore be created, models that are able to predict the production unit's behaviour more accurately.

Both long-term plant simulations and simulation of operating conditions for operator training rely on the representation of discrete events. DES is a different type of simulation technique than continuous simulation, which is used for dynamic simulation, as discussed in Section 5.2. Implementation of SimEvents into the MATLAB/Simulink models should be done to add an additional dimension of discrete events into the plant simulation.

Operator training is an area in which little research has been done. The system structure with the capability to perform operator training has been built at Chalmers University of Technology. A case study should be done to further develop this area of application. Operator training for aggregate plant operators is limited. However, much knowledge can be gained from related industries such as the mineral industry where operator training is more customary than in the aggregate industry.

Tuning of real-time optimization algorithms has been demonstrated in this thesis. This type of application, i.e. development of control algorithms, is the most common use of dynamic simulations. With increasing development in sensor technology and increasing cost benefits of implementing these technologies, new opportunities are being created for further development in process and equipment control. Control algorithms can be tested and validated with dynamic simulation instead of moving directly into implementation.

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