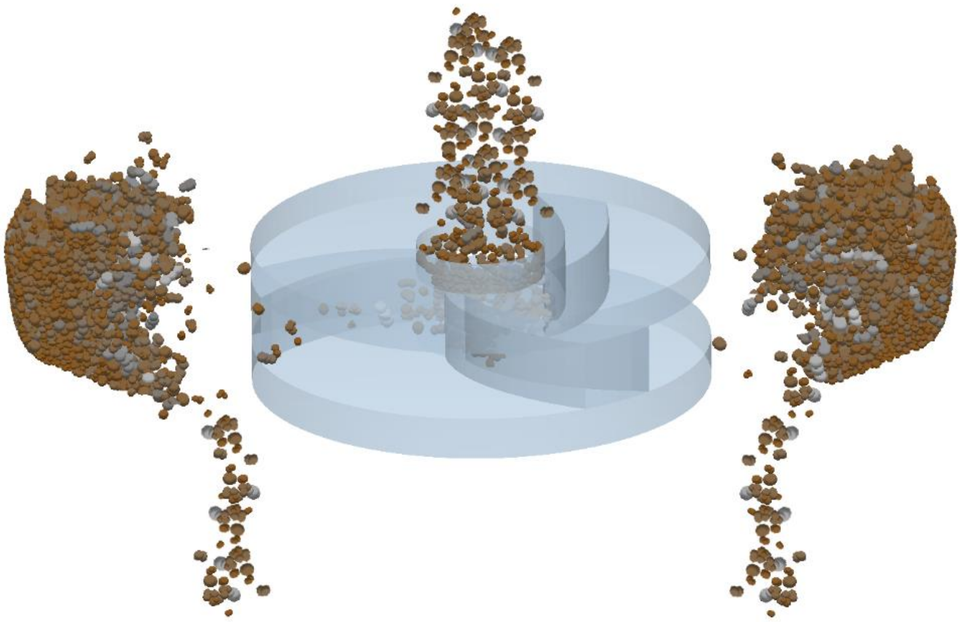
THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Modeling of Vertical Shaft Impact Crushers

Simon Grunditz



Department of Industrial and Materials Science

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Modeling of Vertical Shaft Impact Crushers
SIMON GRUNDITZ

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Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
A visualization of a rotor inside a vertical shaft impact crusher and particles passing through it onto the crushing chamber walls.

Chalmers Reproservice
Gothenburg, Sweden 2021

To my family and friends

Abstract

One of the largest products in most civilized societies is concrete used to build various types of constructions. To create this product, a mixture of cement, chemical binders, and rock aggregates are combined and then poured into molds where it hardens. The sand part of the rock aggregates is either from natural sources, like gravel, or manufactured crushed rock. VSI crushers can be used to create this machine sand but existing mathematical models make it hard to plan new sites and achieve a viable replacement to the natural sand.

In this thesis, the use of vertical shaft impact crushers to crush aggregate rock to rounder particles is investigated. The main aim of this is to develop and further the understanding of the relationship between the machine and material properties with respect to the resulting crushed product with the purpose to achieve an improved product. In order to gain a better understanding of the underlying mechanics of particle breakage, DEM has been used to obtain particle collision energies. Several different product size distribution models have also been used to better predict the behavior of different crushers and feed sizes. To facilitate this, a framework to improve sites has been developed.

The resulting framework simulates existing VSI machines and optimizes the machine parameters with respect to the specified feed material and PSD to create sought products. The framework can also be used to optimize existing sites which increases the effectiveness in terms of minimizing energy usage and waste products.

Keywords: VSI, DEM, Breakage Modeling, Energy Modeling.

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Finally, I would like to extend a warm thank you to all of my family and friends around the globe. Your support has been a constant reassurance during my work.

Simon Grunditz

Gothenburg, March 2021

List of Publications

Appended papers:

Paper A. Simon Grunditz, Magnus Evertsson, Erik Hulthén, Magnus Bengtsson, *Prediction of Collision Energy in the VSI Crusher,* proceedings of European Symposium on Comminution and Classification 2015, Gothenburg, September 2015.

Paper B. Simon Grunditz, Magnus Evertsson, Erik Hulthén, Magnus Bengtsson, *The Effect of Rotor Tip Speed of a Vertical Shaft Impactor on the Collision Energy Spectrum,* proceedings of Minerals Engineering Conference Computational Modelling 2015, Cornwall, June 2015.

Paper C. Simon Grunditz, Magnus Evertsson, Erik Hulthén, Gauti Asbjörnsson, *Fit-for-Purpose VSI Modelling Framework for Process Simulation,* Minerals 2020, 11(1), 40.

Work Distribution:

Paper A. Grunditz and Evertsson initiated the idea, Grunditz developed the model and implemented the code, Grunditz wrote the paper with Evertsson, Hulthén and Bengtsson as reviewers.

Paper B. Grunditz initiated the idea, Grunditz developed the model and implemented the code, Grunditz wrote the paper with Evertsson, Hulthén and Bengtsson as reviewers.

Paper C. Grunditz and Hulthén initiated the idea, Grunditz and Asbjörnsson developed the model and implemented the code, Grunditz wrote the paper with Evertsson, Hulthén and Asbjörnsson as reviewers.

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Appended Papers:

Paper A: Prediction of Collision Energy in the VSI Crusher

Paper B: The Effect of Rotor Tip Speed of a Vertical Shaft Impactor on the Collision Energy Spectrum

Paper C Fit-for-Purpose VSI Modelling Framework for Process Simulation

Introduction

The aim of this chapter is to:

- *Introduce the background of the research project.*
- *Provide an overview of the needs of natural sand in society.*
- *Introduce the vertical shaft impact crusher (VSI) and how it works.*
- *Describe the need for innovation in the tuning of production in the aggregate sector.*

1.1 Aggregates and their Position in Society

Modern society has been built with a heavy reliance on natural materials, one of the largest sources being rock aggregates. Used to construct houses, offices, industrial buildings, roads, railroads, airports, harbors, it is an everyday part in the life of most citizens, even if we do not consciously realize it. The processing and transport of rock material into different construction materials accounts for a significant portion of the annual energy consumption in most countries.

Historically, from early Roman times until the development of the comminution processes, the only possibility was utilizing local sources of rock aggregates, which is often referred to as natural aggregates. Early sources included ground deposits of rocks and dredging water aquifers for pebbles. These were screened and slotted into different bins, creating different size fraction groups and names.

By sorting the rocks according to their size, some of the rocks suitable for specific applications can be extracted. Their size serves the different building projects the best while some other sizes, such as filler, prove more challenging to incorporate. Gravel, sand, and macadam are often used for various construction projects. Over time and thanks to product development and increased needs, machines to crush rock were designed and instead of dredging, hillsides were excavated with explosives to feed the machines with large boulders that were ground down to more malleable material.

Through technological developments and innovation over the centuries, a product heavily based on rock material has been iterated upon. The use of concrete today is a cornerstone in the construction sector and early versions of concrete use date to early ancient times. Concrete is a mixture of sand, rocks of different sizes and a chemical binder, cement that locks the mixture in place once it settles and water. It is pourable and can be used to create large objects on site with precise measurements at a low cost, compared to chiseling and shaping a solid rock and transporting it.

Over time, the usage of rock aggregates from natural sources has decreased in many parts of the construction sector. One of the reasons for this is that the properties of crushed rock material proved to be better in certain applications. Roadways for cars and trains, for instance, saw an increase in performance when using crushed aggregates. The interlocking properties of angular rocks compared to smoother and rounded rocks from natural sources, a visual example seen in Figure 1, made this transition easy in this instance, but for other applications, it has been significantly more difficult.

Figure 1. Photographs of 4 different types of rocks with varying levels of roundness and angularity.

Concrete is a material that has been designed with natural gravel as the main ingredient and as such, the recipes used today, still rely heavily on it. A characteristic property of gravel from dredged waterways is its smooth appearance and round shape. This is due to the slow process of erosion over a long period of time that has allowed the particles to become rounded. These properties help to improve the rheology of a concrete mixture, making the pouring of the concrete easier and minimizing the amount of binder material needed in the mixture. The ease to which gravel can be accessed from waterbeds and streams made it a common resource. However, the location of natural gravel in waterbeds and local streams has proven to have a purifying effect on the ground water and therefore, to remove it, is a non-sustainable approach.

Compared to crushed rocks, natural sand and aggregates are a finite resource, and the Swedish government has taken a stance that efforts to stop the use of natural gravel are to be increased. A tax on natural gravel was instituted and has been incrementally increased, while the number of natural gravel quarries has dramatically decreased in recent decades. While there are still natural gravel sites in Sweden operating today as seen in Figure 2, the total amount of supplied material is decreasing each year, as is the number of natural gravel permits issued [1].

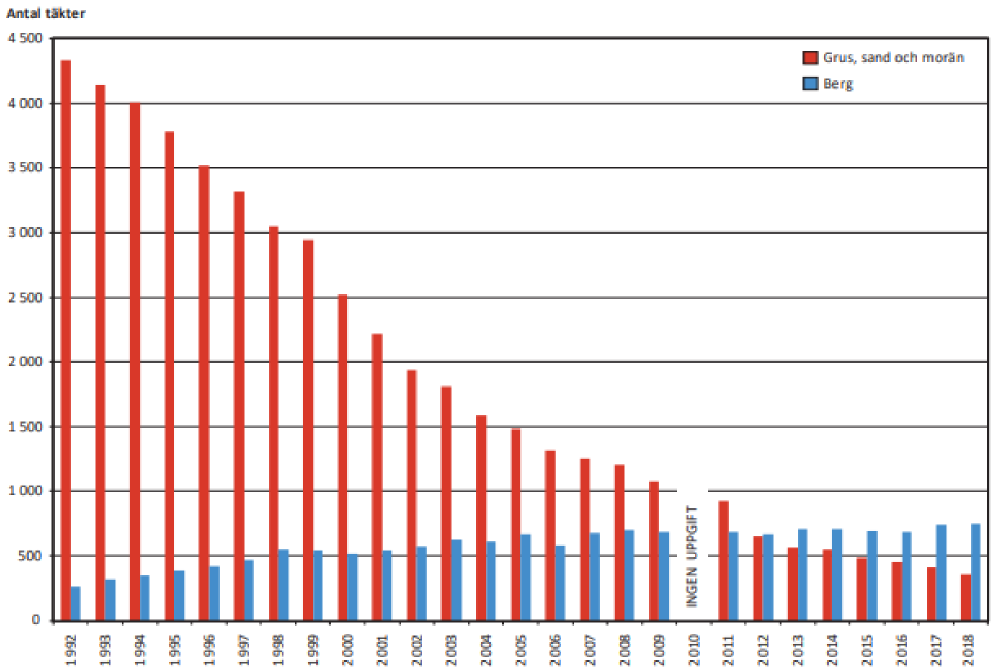

Figure 2. Types and number of quarries operating in sweden sorted for each year.

A method to create a replacement product for natural aggregates is needed, and one of the most viable ones currently is the use of autogenous impact crushing.

1.2 The Vertical Impact Shaft Crusher

While most crushers used in the primary and secondary stages of crushing work by having two surfaces compress particles between them, a vertical shaft impact (VSI) crusher instead relies on impact energy. By having the rock particles flung against each other at high rates of speed, the resulting impact creates a high chance for areas of the rocks that are sharp and angular to be abraded off. The resulting swarm of fragments helps smooth out and round the particles further. A cross section of a VSI with a rock box configuration can be seen in Figure 3.

These particles are sometimes called manufactured sand, given their similar characteristics to their natural counterparts but can be created by crushing any solid rock, which removes the need for long logistical transport. Particles become rounder, including the fines, which is different compared to other common comminution machines. The difficulty in achieving a manufactured sand that is a suitable replacement is the excessive creation of fines while crushing. The product from VSI crushers have been used to show that this resulting product can be used instead of natural gravel. In other words, it has been used to remove the dependency on natural gravel in some regions, but some plants have not achieved this.

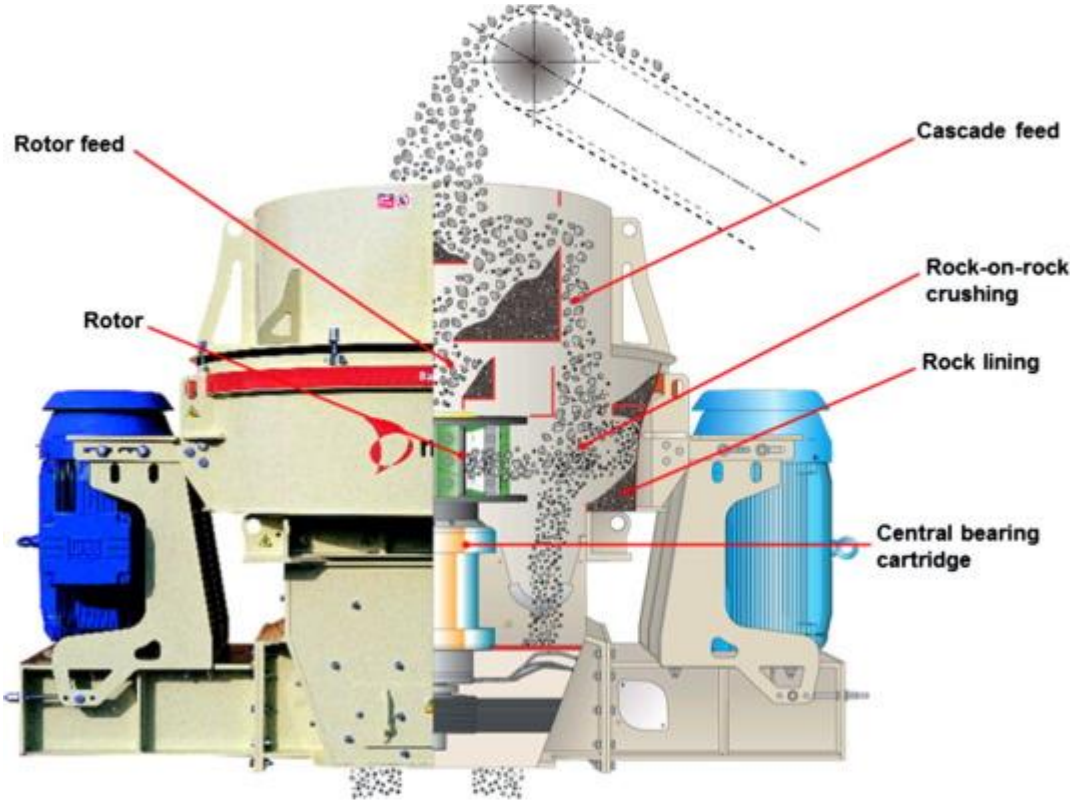

Figure 3. A vertical shaft impact crusher is shown from the side with a quarter section cut out.

Quarry and crusher sites are sourced with material that will have different characteristics and properties. Some similarity in terms of rock type may appear, but the usual approach is to treat them all as a specific site and not group them together. For example, two different sites may both be categorized as having granite material but may have large grain boundary sizes in the structure while the other can have considerable amounts of mica. This is one of the reasons why a plant design that works at one quarry does not necessarily work at another. Adjustments and changes must be made to consider the variations in the material to make it both a technical and financial success.

In addition, each site will have a different set of customers for their aggregates and crushed rock product assortment. They have different requirements and specifications to meet depending on their concrete mixture recipes and will therefore ensure that the producer conforms to these requirements and specifications. Concrete recipes require consistent ingredients to achieve reliable properties and usage in construction.

Given these variations in conditions and customer needs, each site needs to be adjusted to match all of these needs and then designed to meet them. This may include changing machine parameters, setup and process controllers to achieve the production goals.

This process and optimization to reach a set level of productivity is complex and time consuming. The level of cost, in terms of money, time and other resources, may result in sites processing natural gravel to remain in operation, despite increasing regulations and heavy added environmental taxes that are applied to the natural gravel. A process to ease this transition, establishing new sites or change sites currently depending on natural gravel to artificial gravel, is needed. To tackle such a challenge, further understanding of the dynamics of a vertical shaft impactor crusher is needed in addition to trial and error experiments.

1.3 Need for Tool Improvements

The current costs and resource investment to create or update a site to allow for artificial gravel production are still high barriers and are one of the main reasons why some regions still rely on natural gravel. The increased cost from high regulatory fees is still outweighed by the potential costs to switch over and the time needed to reach a product that can replace the natural gravel in the supply chains. There may also be a fear of scarcity in regard to a replacement product.

To enable the transition to better tools, knowledge is needed to help reduce the gap and ease the change in sites. There are existing models that allow for estimating energy usage and product prediction that can be incorporated into a practical tool to facilitate plant owners and operators to plan and test new configurations without the need to heavily invest in experimental testing.

Simulation tools are a useful way to enable planning and potential effects of changes to sites when moving towards increased gravel production. However, the amount of knowledge of the inner workings of VSI crushers required to create simulations with reasonable fidelity is high. One of the challenges in investigating the particle behavior in a impact crusher is that any observation tools or cameras would be exposed to a harsh, destructive environment. Gathering quantitative data is therefore difficult and expensive.

An alternative way to study particle dynamics is to simulate the conditions using the discrete element method (DEM). By setting up virtual particles and tracking their movement through a VSI, a large dataset of information about the machine can be studied and understood. The residence time of a particle inside the crusher, the average impact energy of particles as they collide with the rock wall in the crushing chamber and how it varies from larger to smaller particles are of interest. The method allows for an analysis of single particles or compiling a large set of data points to find averages and deviations, although it does not provide breakage behavior.

DEM simulations are extremely slow due to the large amount of computational processing they require. A few seconds of real-time operation of the crusher may take several months of processing time on high-end computers. These simulations are, however, relatively easy and cheap to setup compared to a site reconfiguration. Larger configuration changes, such as rotor tip speed, geometry and wear, are easy to implement compared to an experiment on site. With more accurate information about the particle behavior inside, a more reliable model can be produced to predict the performance of vertical shaft impact crushers and allow for better tools that can in turn lead to a decreased reliance on natural gravel deposits.

2. Objectives

This chapter aims to:

- *Introduce the research outline*
- *Formulate the research questions.*

2.1 Research Outline

While used in several crushing plants today, VSI crushers are complex machines. They are affected by numerous factors, such as the material properties and machine parameters. The aim of this research is to gain a better understanding of the relationship between these variables and how they contribute to the crushed product and its attributes to achieve an improved product and process.

The objectives of this research are thus to increase the knowledge of particle trajectory and energy distribution as well as develop a model for simulating VSI crushers and their perfomance. To facilitate this analysis, numerous experimental tests and DEM simulations are required. Several site surveys of Swedish quarry sites were performed. Data from a previous study were also used throughout this research.

2.2 Research Questions

The research objectives of this work can be described by the following formulated research questions:

RQ 1 – What interactions in a VSI crusher between the material and the machine affect the performance?

RQ 2 – How can the knowledge of impact energy and particle breakage be combined to create a usable model?

RQ 3 – How can such a model be calibrated to make it robust and reliable and how would such a model be validated?

RQ 4 - How can these models be applied to allow for industrial and product development?

2.3 Research Papers

These research questions will be addressed throughout this thesis and answered at the end. The focus of each included paper can be seen in Table 1.

Table 1. Visualization of the focus areas of the different papers included in this thesis.

	Papers		
Research Questions	A	B	C
RQ 1	●	•	
RQ 2	•	●	•
RQ 3		•	●
RQ 4			●

A	The Effect of Rotor Tip Speed of a Vertical Shaft Impactor on the Collision Energy Spectrum
B	Prediction of the Collision Energy in the VSI Crusher
C	Fit-for-Purpose VSI Modelling Framework for Process Simulation

3. Research Approach

This chapter aims to:

- *Introduce the approach used in this research.*

The research approach used in this work is a problem-based approach that has been adapted from Evertsson (2000) and Asbjörnsson (2015), as seen in Figure 4.

The initial stage was the identification of a problem. Knowledge about the relevant area of research is essential in establishing a foundation. Background studies and observations have been the source of this knowledge. This work has investigated the previous attempts to make replacement products. The possibilities of using a VSI crusher to create natural gravel had not been fully explored at the time.

After the problem has been defined, concrete and defined observations of data have been conducted. Visits to crushing sites and sampling of material at different points are the observations made in this work. These have formed the basis for modeling work that strives to predict future outcomes. To ensure the accuracy of the modeling and its usability, verification of the results is performed. Once verified, the potential of the model in industrial applications and implementation is explored, which ultimately provides a solution to the initially posed problem.

A large part of the research has been carried out in an iterative manner where modeling and verifications are evaluated before either moving towards the next phase or improving the model in the previous stage. So, either new phase of the approach is started, or the work goes back to the previous stage. This could, for instance, result in a refining of the modeling work or obtaining further observations by more testing or additional literature review.

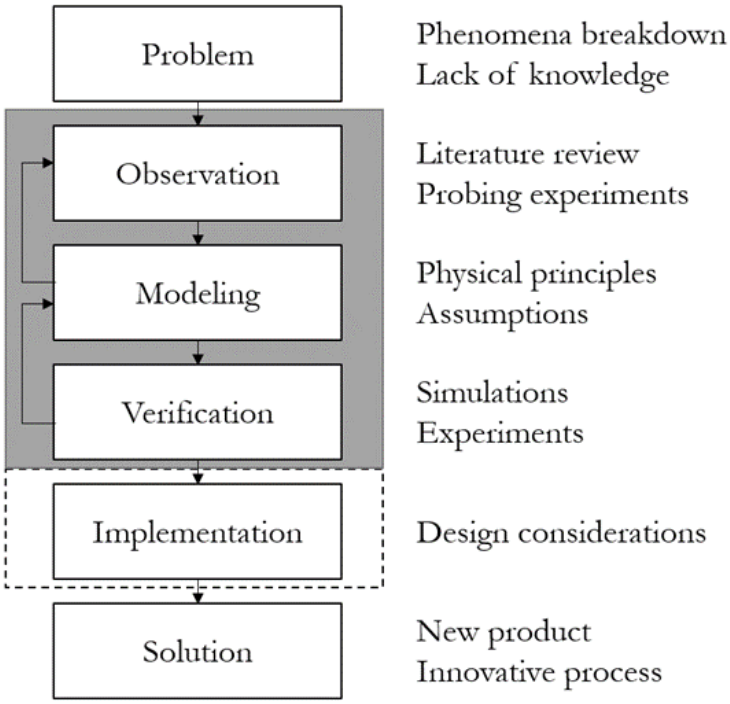

Figure 4. The applied problem-oriented research model as envisioned by Evertsson 2000.

4. Frame of Reference

This chapter aims to:

- *Describe the theory used throughout the research*
- *List previous works and describe more thoroughly the VSI.*

4.1 VSI in Detail

A Vertical Shaft Impact crusher is a simple machine relative to others, e.g., a cone crusher, but the internal rock mechanics interactions are complex and difficult to fully capture with models. There are several variations and designs, but most have the same basic functionality. However, there are several different manufacturers, including Metso, Sandvik, and Magotteaux, but the different models on the market rely on the same principals. By dividing up the machine into a few sections, as seen in Figure 5, the different behavior in different interaction fields can be visualized.

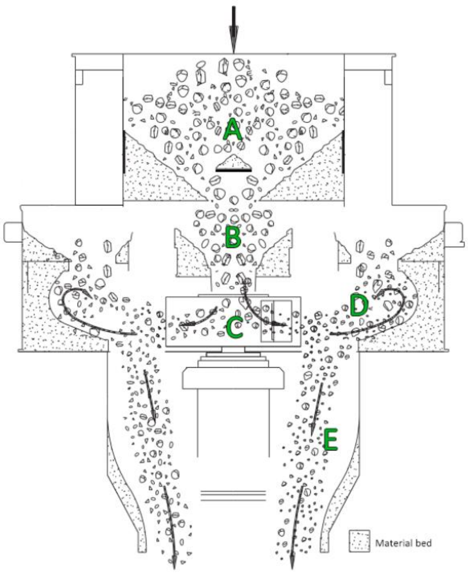

Figure 5. Cross section of a principal vertical shaft impact crusher

Section A in Figure 5 is a hopper where the material is fed into the VSI crusher. This is commonly achieved with a conveyor belt that feeds directly onto the top part of the crusher. The hopper can store a small volume of material.

In the center of the hopper is a circular hole that leads material into the feed tube which is a part of section B. The feed tube is partially covered by a feed plate that prevents material from falling directly into the feed tube, thereby avoiding excess wear from higher velocity due to greater fall distance. The feed tube is simply a circular cylinder that keeps the material from escaping and leads it onto the spread plate while protecting the top parts of the rotor. The function of this section is to guide the material and protect the other components from wear and damage by controlling where the feed particles end up.

Section C is where the feed tube connects with the center of the rotor. Particles fall in and onto the bottom of the rotor, which is equipped with a spreader plate to protect the rotor and make the particles flow outwards in equal proportions to the number of exhaust ports towards them. This path of movement is in theory equal for all exhaust ports, although some minor variations will occur due to wear and material buildup in the rotor.

Once the particles have passed through the rotor and are propelled out of the rotor at high speeds, they enter the crushing chamber, section D. This is where particles will expend most of their kinetic energy.

Particles are flung towards the outer walls of the crusher, where a bed of particles will build up and protect the walls. When the VSI crusher is first run and has been entirely emptied, particles will hit the walls and create a bed of particles along the surrounding walls of the rotor. This bed of particles is where collision with other particles and most of the breakage will occur.

There are variations in the design of vertical shaft impact crushers that have a large effect on the performance and cost, including the use of either a rock box or anvil configuration. The prior is designed with large voids in the crushing chamber walls and rotor to allow crushed rock material to become trapped and accumulate. The constant impact of new particles creates a hard-packed wall that allows breakage of the particles. In the case of the wall breaking instead of the particle, the newly created void is quickly filled with new rock material. This is cost effective in terms of wear but reduces the amount of size reduction overall than that of an anvil configuration. The operational expenses increase with the use of anvils in the crusher but may be profitable at certain sites and configurations. In this setup, large, angled metal plates are lined along the crushing chamber walls, leading to particles having a lower chance of suffering a glancing impact and being more likely to result in straight collisions with a significantly more durable material. This leads to more downtime and costs due to maintenance and replacement of wear parts, in addition to particles not receiving as much abrasive action. These particles end up being less round than their rock box counterparts.

4.2 VSI Modeling

To facilitate modeling of the VSI, different aspects need to be captured. Several approaches to model VSIs have been carried out, each with different focus areas and methods. There are several phenomena occurring in the crusher at the same time, and some methods will encompass more of these than some that focus more on isolating single factors and their effects.

One of the earlier and most comprehensive modelling efforts at a VSI rotor was performed by Rychel [2]. The generalized geometry inside the rotor over time when in operation is assumed to be static given that new material fills any voids that over time and will essentially grind down the objects that stick out. The high speed of rotation will force particles out into the crushing chamber following the length l, with an origin from the discharge plate. Along the route, the particle will speed up and its speed, v_{abs}, out from the chamber is the assumed breakage velocity to which the particle will be subjected. The generalized particle path from the center to the exhaust port of the rotor can be seen in Figure 6.

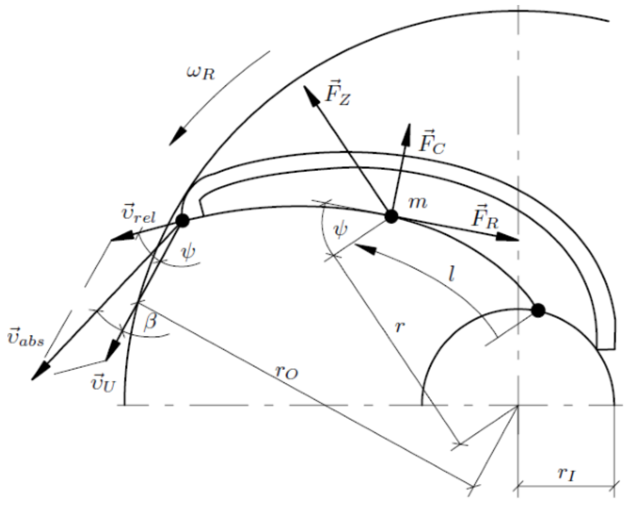

Figure 6. Rychel's modeling of a particle traveling through a VSI rotor [2].

To further understand how these characteristics, such as size and overall shape profile, affect the impact energy and product outcome, further studies have been conducted. A large statistical set of particles in a study by Vogel et al, was subjected to set levels of kinetic energy and impact onto a solid wall [3]. By repeating this numerous times for each particle until breakage occurs, for a large sample size, a statistically significant response model was created [4]. Each size of particle was shown to correlate to lower levels of energy to achieve breakage. The study concluded that larger particles were more likely to have flaws and weakened barriers, as well as lower particles being broken down to their smallest grain size boundary.

The categorization was created by Unland and showcases some of the different types of breakage or damage particles will in general receive when subjected to loads [5]. Splitting, chipping and crumbling are more common in VSI crushing. Once particles have lost their kinetic energy, they will fall out of the crushing chamber and into the last section, E in Figure 6. Particles fall down a shute and out of the crusher, usually onto a conveyor belt.

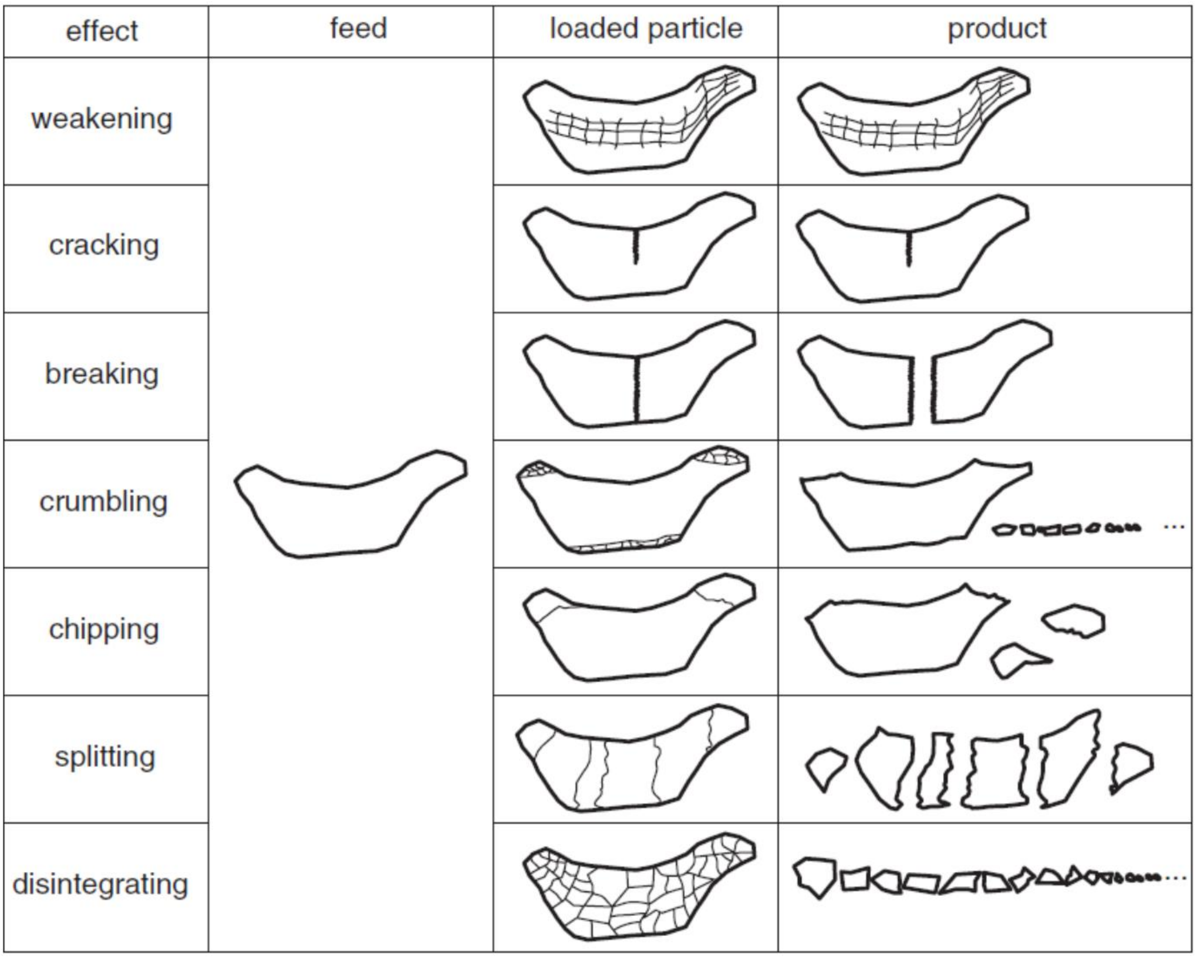

Figure 7. Comminution effects on particles subjected to loading events from Unland [5].

To model the behavior of the vertical shaft impact crusher, the particles that are fed into it need to be captured. Bengtsson et al used established standard measurements from industry and properties to characterize feeds [6]. The shape of particles is used to model the overall roundness of particles, with higher values meaning particles are closer to a perfect sphere. This provides a higher volume-to-surface ratio, which is beneficial in reducing cement usage and correlated with improved concrete rheology. The purpose was to model VSI crusher behavior in addition to mills.

The assumptions on perfect geometry, perfectly spherical particles and a constant speed in mathematical modeling can completely miss important aspects that will influence the results. To further test the conclusions arrived at by Rychel and to further expand the understanding of the behavior of high impact breakage from a VSI more specifically, the Julius Kruttschnitt Mineral Research Centre (JKMRC) has created a device that allows for subjecting particles to high levels of impact energy that is, very similar to a

VSI [7]. The JK rotary breakage tester features a VSI rotor, feed tube and crusher chamber with an anvil configuration. With the removal of the product outlet, all the resulting particles from an impact can be collected, sieved, and analyzed to measure how much a particle has been reduced in size and how its shape has been altered. Each run features a single particle with breakage occurring upon the metal anvils in the crushing chamber.

How the particle to particle interaction affects the crushing result is not captured in these tests and few studies have been successfully performed where this is achieved. In a few grinding experiments, a SAG mill was filled with material and approximately a dozen extra particles with a slightly radiated isotope inside them. By scanning for these and running the mill, the trajectory of the particles inside the machine was established. The breakage and tracking of daughter fragments were not attempted. The energy to which particles are exposed means that any equipment inside an operational crusher would have to withstand repeated levels of said impacts to obtain results over time.

4.3 DEM in Detail

One approach to gain a better understanding of the particle dynamics inside the crusher is to use a method that allows for simulating the behavior of particle and granular material in general and applied settings. One useful method for this is by using the discrete element method.

The discrete element method is a numerical method used to simulate particle (granulate) flow and the stresses, displacements, and energy of particles of different sizes. The granular material is modeled as an assembly of rigid particles and the interaction between each particle is explicitly considered. The particle shapes and geometries are specified by the user. Spheres or ellipsoids are commonly used to represent particles either with single spheres or clusters of spheres. A representation of a rock particle can be seen in Figure 8, where three spheres with differing radii intersect. By adding more spheres, a higher level of complexity and resolution can be obtained. This allows us to more accurately represent the sharper edges and jagged corners of rock particles. However, every added sphere contributes to an increase in the computational complexity and thus requires more time to process.

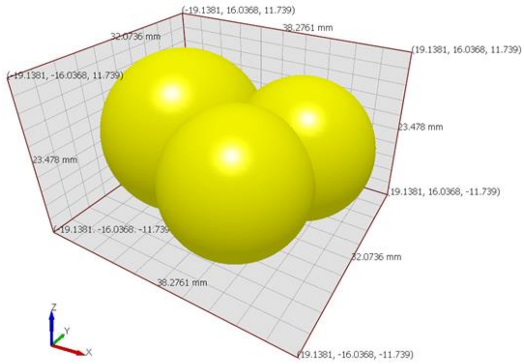

Figure 8 A rock particle represented by three spheres in a DEM model.

To mathematically analyze real world objects, a representation of them can be made. The geometry of the objects needs to be presented as mathematical equations; in other words, they need to be described using CAD geometry that is then used in the simulation to represent different objects. For rock particles, scanning hundreds of single particles is performed to generate a database. With this high-resolution data, an algorithm is used to process the particles. This recreates the particles with as few spheres as possible while minimizing volume differentiation from the original particle.

Beyond particle and solid geometry, the boundary conditions and parameters for the simulation need to be addressed. Particles are generated and given an initial speed when they appear in the space. This usually means that they are fed or arrive to the localized area of simulation from a conveyor, falling from a hopper or bin [8].

To calculate the contact forces and impacts, a mathematical model is required. The Hertz-Mindlin contact model in a nonslip configuration is the default model used within the DEM simulations. It is a nonlinear elastic model and is thus well suited to the noncohesive interactions that are used within the computational models. The model uses a spring-dashpot response for contacts between particles and geometry, a Coulomb friction coefficient μ for shear interactions and a second spring-dashpot response for tangential or rolling friction interactions. This model tends to produce high-resolution results but can, however, be computationally expensive to implement due to the smaller time steps required compared to other models.

There are several software programs that make use of the DEM, such as LIGGHTS, Rocky and EDEM. One of the common software programs is EDEM, which has a set of built-in models such as linear cohesion that is useful in simulating sticky particles, as well as hysteric spring that allows for plastic deformation in simulations. There is no consensus on which contact model is preferred, but they are often seen as having different application areas. For instance, when adhesion of particles due to moisture is to be included in a simulation, the adhesive elastoplastic contact model would be more appropriate to obtain aggregate clumping simulations [9].

The timesteps used to advance the simulation are based on several factors, such as the particle size and maximum speed. If the timestep is too large, the particle will be able to pass through the geometry since collisions, velocity and direction are only updated during the timesteps. Conversely, with lower time steps, a steep increase in the computational time required is observed [10]. Breakage modeling is a complex area that is still evolving and improving. In this thesis, we will use the DEM for energy analysis but not breakage simulation.

4.4 Process Simulation

A model that can simulate the output of a VSI with adequate machine parameters given will allow the machine to be used in a simulation tool. With models that can describe the behavior of other comminution machines, such as conveyors, screens, cone crushers and jaw crushers, a process simulation of an entire plant can easily be erected. The aggregate producers have an array of different machines that serve varying purposes at their sites. Some sites have different setups to shift production rates, but generally, they do not change very often. A machine is often dependent on the machines preceding it which makes it important that its input reflects the upline stream.

By starting with the rock material and letting it flow through the different machines, the dynamics of the process are more accurately accounted for and provide a more realistic result. The products can easily be compared, and the machines that bottleneck the flow can be altered or removed to help reach the sought production objective.

The software uses pre-existing models and is mainly meant for plant owners and operators to easily be able to assess current or new sites and the machines needed to reach certain production goals. Some of the software programs are JKSimMet, AggFlow and Plantsmith. These software programs provide a static simulation of the comminution process. Static here means that time is paused and that massbalance is the end goal. Iterations are performed until massbalance is achived, or a solution is unreachable. Some events that hamper the overall plant performance, such as downtime for repairs and maintenance, are not considered in this thesis because a snapshot of the performance of each machine is the focus. An example of the Kållered VSI plant that has served as the basis for some of the experiments can be seen in a plant layout (Figure 9).

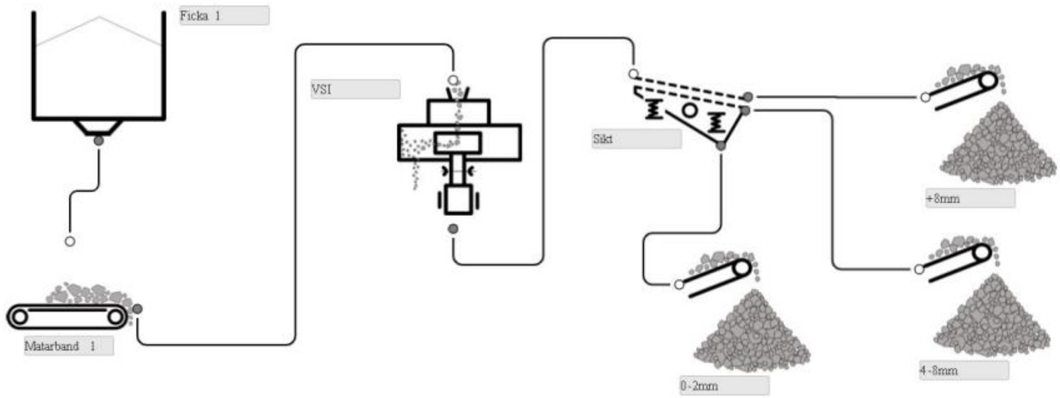

Figure 9. A crusher plant overview map of the Kållereds VSI subsection made in the Roctim Plantsmith process simulator.

4.5 Concrete

One of the most energy demanding ingredients in concrete is the cement. Extracted from inorganic sources, such as lime and calcium silicate, it heavily contributes to the CO2 emissions of concrete and society in general. The calcination process requires a high thermal energy level. Cement is responsible for approximately 4-8% of world emissions of CO2 [11].

The different recipes for concrete will call for varying amounts of cement and studies have been conducted at several sites in Sweden to see how the hydration ratios affect the concrete performance. Less use of cement in these recipes can produce a large energy and carbon emission savings, especially considering the large amounts of concrete used globally each year.

The quality and shape of the rock aggregates used in concrete can heavily impact the amount of binder needed to create a viable product. The basic principle in concrete is that the rock particles are connected to each other with a chemical binder. Concrete can easily flow into different shapes and forms while it is wet, and after it is dried, the concrete hardens and maintains its shape.

Having rounder particles means that the surface-to-volume ratio is reduced, resulting in a lower amount of cement required to produce valid concrete in addition to resulting concrete having an improved rheology. This in turn means that a significantly large reduction of emissions per ton of concrete can be realized. A higher control and requirement of the rock aggregates used is, however, a prerequisite for this.

5. Methodology

This chapter aims to:

- *Describe the methods used in the research*

With the research questions in focus, the goal for the different methods used is to further the knowledge of what happens inside the crusher to allow modeling and ultimately, validate the results and the model. Throughout the research, a parallel approach to data acquisition has been used. One of the goals of the modeling is to acquire results such as experimental runs of the machine at the same settings. To build a better understanding of how the machine works, work has been done to minimize the difference between the simulations and the testing environment where possible.

By keeping these two tracks parallel in setting up and evaluating the data, a large pool of data points was accrued during the research. This allows for more robust testing of the model, and this can be applied to a larger set of scenarios. For this research, a key motivation has been that most models can be made to fit, but the overall validity when tested is beyond the specific experiment and simulation setups. The strength of a model is whether it is sufficiently robust to be applied to a wide range of configurations and how accurate the model is then.

To further investigate the behavior of particles inside the VSI crusher, the DEM has been used to extract the particle collision energies (Paper A) and the relative location of such collisions (Paper B). Once the data have been established, processing is performed using MATLAB scripts. This allows us to look at average particle energies in correlation to their size in addition to setting up models that predict the VSI performance. To allow for a comparison between the simulations and a real crusher, testing is carried out to acquire experimental data.

5.1 Energy Modeling

There are several ways to model the energy present in particles and breakage. In this chapter, the different methods used are presented.

5.1.1 DEM

The machine that was the subject for all simulations and CAD models was a full-scale Metso Barmac SE 5100 VSI crusher. Two different rotor tip speeds were used in these experiments. The rotor with a radius of 255 mm was rotated at 2622 to 1873 rpms, which translates to a rotor tip speed between 70 and 50 m/s. Such a rotor can be seen below in Figure 10, where the rotor was isolated in the DEM to simulate the initial start-up phase of an empty VSI crusher. The particles quickly filled the empty pockets and allowed for later simulations to assign solid geometry to certain sections.

For the modeling of the rotors, a simplification of the material inside is performed to reduce the computational loads. This process is performed by isolating the rotor in a simulation and filling the rock beds inside it. The particles that are stuck and fail to be expelled form the basis of the solid walls into which they are translated. Since the rocks that end up in the rotor bed have a low probability of escaping, the rotor is redesigned with solid material beds to emulate the "dead" material that fills it, thus requiring fewer computational resources.

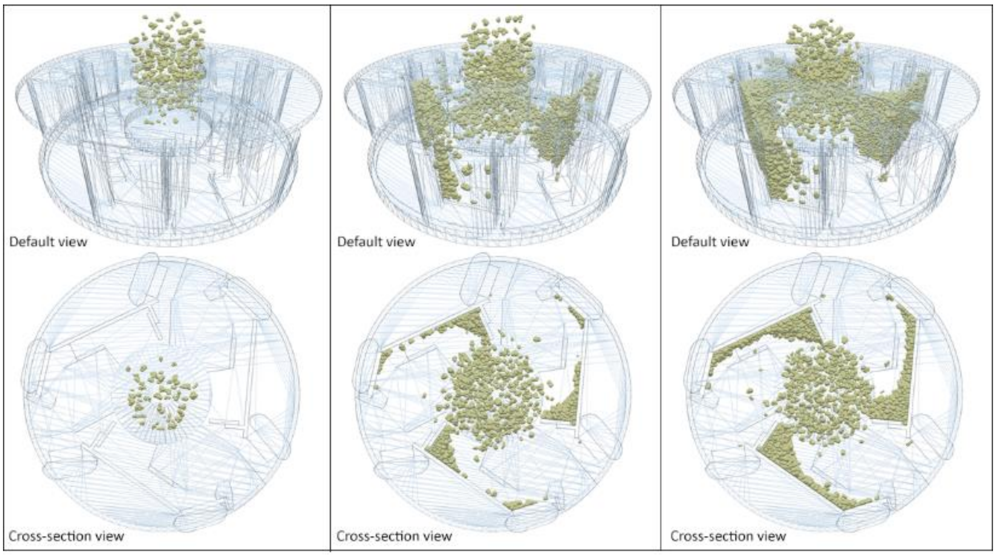

Figure 10 Three snapshots of a DEM simulation of a VSI rotor being fed material and its consequent material buildup.

5.1.1 Postprocessing

The amount of data from a DEM simulation can be very large and usually includes particle IDs, coordinates in 3 dimensions, collision energies, and kinetic energy. The sheer number of data points means that data processing has to be performed to sort and analyze the data in more detail. To facilitate this process, MATLAB scripts were used to create graphs based on the DEM simulations and energy levels plotted on mass specific levels.

5.2 Modeling Simulation

With the use of MATLAB modelling, we can collect particle information from the different DEM simulations and extract average collision energies and the overall movements of particles. This also allows us to model the VSI crusher output and optimize it to find accurate parameters for specific material and machine settings.

It is difficult to fully predict the breakage of a particle due to the numerous factors that are involved. Several studies and drop-weight tests on particles of different materials have already established a baseline understanding of how higher levels of energy lead to increased probabilities of breakage. Because it has been shown to be reliable in other works, the selection-breakage theory has been used in this research [12].

All particles that fall into the crushing environment are assumed to fall into one of two different categories: selection for breakage or passing. By being selected for breakage, that part of the model does not dictate how large the size reduction is, just the fact that material is cast off. This theory has robustness to predict selection conditions for particles based on the material's resistance to breakage, the energy applied and the number of impacts it is subjected to. The breakage selection equation, seen in Equation 1, consists of f_{mat} as a material and particle property, $W_{m,min}$ as the minimum energy required for breakage to occur, x as the particle size, k as the successive number of impacts and $W_{m,kin}$ as the kinetic energy the particle has upon collision. S is the fraction of particles that will obtain sufficiently high impact energy and produce breakage. The remaining number of particles will pass through as unbroken particles.

$$S = 1 - e^{-f_{mat} x_i k \left(W_{m,kin} - W_{m,min}\right)}$$

Equation 1 Selection-breakage function.

After a particle has been evaluated and assigned a breakage status, an appropriate method is needed to ascertain how the new daughter fragments will divide themselves into size bins. A function for the appearance of originating particles and how they statistically subdivide is used. A particle can only be reduced into smaller fragments (as seen in Figure 11), meaning that for a predetermined number of size bins, a lower triangular matrix or appearance matrix can be obtained, while the size of these bins can always be altered.

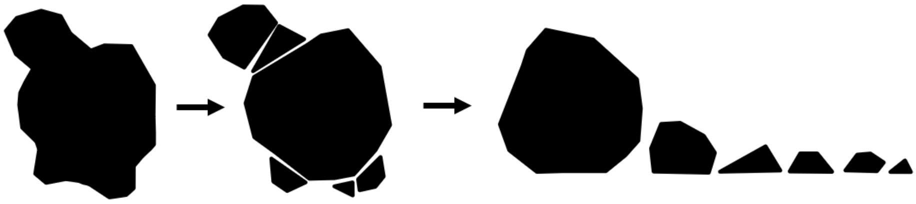

Figure 11 A visualization of particle breakage and size sorting

The equation used to generate the appearance vector for each originating particle relating to its daughter particles can be seen in Equation 2.

$$a_{i,j} = \beta_1 + \beta_2 x_i^{\,1} + \beta_3 x_i^{\,2} + \beta_4 x_i^{\,3}$$

Equation 2. Appearance function to model daughter fragment generation upon breakage of a particle.

By using the selection part of the particles and breaking them down into smaller particles according to the appearance value a VSI model can control the spread of daughter fragments, the energy required to break a particle and the material properties related to strength and shape.

5.3 Physical Experiments

The main purpose of the experiments carried out in this research was to obtain the effects of different material fed into a VSI crusher in combination with machine parameters such as rotor speed and size. The resulting output of the VSI crusher can be broadly adjusted by lowering or increasing the rotor tip speed. A higher speed results in increased collision energies and different PSD products. The physical experiments to gather data have been based on belt cuts of feed and product material into the VSI.

The conveyors and VSI machine are halted and a length of material along the conveyor is taken as the sample. The sample is then dried, sieved, and analyzed according to standard procedures to ascertain the particle size distribution. Stopping the VSI to gather material from the ingoing and outgoing belts is currently the most practical way to assess the effect of a VSI on a product flow basis. While the main goal is to observe the effects inside the VSI crusher, tracking particles in motion in a harsh environment is difficult and costly in comparison to belt cuts.

Material was tested in several places in Sweden with the same crusher setup. These sites each provided data for 3 different rotor tip speeds while using the same top size for the feed material. Table 2 shows all the sites and the properties of the material used. For the source listing, 'One Feed' indicates that for multiple speed setting samples, only one feed sample was taken and 'Unique Feeds' mean each speed setting was accompanied with a feed sample. The feed variation was assumed to not vary enough to significantly affect the product.

Table 2 Material data from all the sites used in the study along with their locations. (Paper C)

Geological type	Site Location	Top size	Source
Diabase	Ubbarp	19 mm	One Feed
Diorite	Borlänge	11.2 mm	One Feed
Dolomite	Glanshamar	11.2 mm	Unique Feeds
Gneiss	Umeå	19 mm	Unique Feeds
Gneiss	Atle	19 mm	One Feed
Gneiss	Össjö	4 mm	One Feed
Gneissic Granite	Skyttorp	11.2 mm	One Feed

Gneissic Granite	Önnestad	11.2 mm	One Feed
Granite	Tierp	11.2 mm	Unique Feeds
Granite	Gävle	4 mm	Unique Feeds
Granite	Gävle	11.2 mm	Unique Feeds
Granite	Gävle	11.2 mm	Unique Feeds
Granite	Kållered	16 mm	Unique Feed
Granitic Gneiss	Enhörna	19 mm	One Feed
Granitoid	Bro	10 mm	Unique Feeds
Granodiorite	Sunderbyn	11.2 mm	Unique Feeds
Limestone	Forsby	19 mm	One Feed
Porphyry	Kiruna	10 mm	Unique Feeds
Quartzite	Gåsgruvan	19 mm	One Feed

5.4 Fit-for-purpose Framework

By applying a previously described selection breakage modeling approach and basing it on the impact energies of particles inside the VSI, the rotor speed and the material data, we construct a framework. This allows deployment of the model at current, new or planned sites to reliably predict the product that can be expected with varying rotor speeds for the site-specific material.

$W_{m,min}$ is a characterization of the energy level required to achieve particle breakage, while the F_{mat} property encompasses not only the material properties but also the properties arising from different particle shapes. The properties of these site-specific materials are, however, not often known in regard to the minimum energy to break it, $W_{m,min}$, or what its particle and material properties, F_{mat}, are. A routine to quickly establish these values was developed during the research and the overall process can be seen in Figure 12.

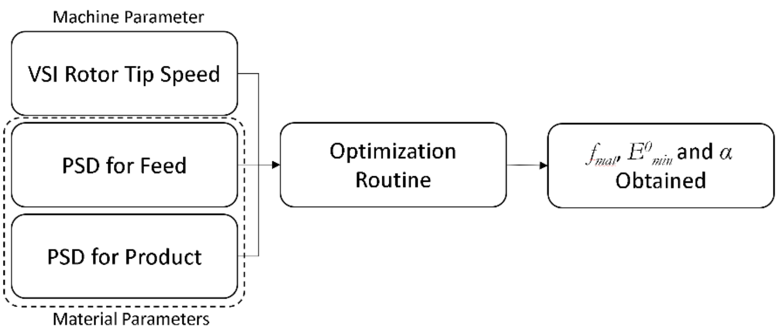

Figure 12. The overall modeling process for a new site where the material has not been calibrated and then adequately mapped to the material database.

The approach involved fitting the predicted model to two separate PSD curves obtained through the same crusher but at two different speeds. Similar feeds were used to minimize the variation. The fitting was performed by an error optimization function, as seen in Equation 3, to minimize the error between each predicted and experimental product while taking the speed into consideration. The f_{mat}, and E^0_{min} values were the results obtained from this approach.

$$\min_{\{\beta_i, f_{mat}, E^0_{\min}, \alpha\}} E = \sum_{i=1}^{n} \left(\left(P_{i_{Exp,High}} - P_{i_{Sim,High}} \right)^2 + \left(P_{i_{Exp,Low}} - P_{i_{Sim,Low}} \right)^2 \right)$$

Equation 3 Error optimization function.

5.5 Validation

To assess the model, validation experiments and simulations were conducted. The results of the validation are an indicator of the strength and robustness of the model. This means that the model is not solely a unique match for a single plant and setup but can also be extended and usefully applied on a larger scale.

A VSI crushing plant in Gladö, Sweden, was selected to serve as the data basis for the validation tests. The plant was run under normal operating conditions, and a quick stop was initiated. As described above, materials from after and before the two VSIs at the plant were extracted and analyzed. These served as the comparative data used to assess the validity of the model. The feed data and material properties were used in the model to produce two product curves. These curves were then compared with the plant product data.

A common size measurement in the comminution industry is P80. The value is given as a size and means that 80% of the cumulative particles from the smallest to the largest will fall under the specific size. Similar values for P20 and P50 were also extrapolated from both the experimental data and the predicted data to allow for a comparison and error rate of the VSI modeling framework.

6. Results

This chapter aims to:

- *Describe the results obtained through the research*

In this chapter, a focus on answering the research questions will be maintained while also covering the results from the different methods. The results from the DEM modeling are centered around the particle kinetic energies they give off in the crushing chamber of a VSI. Some intermediate steps are carried out to simplify the DEM models and make a full simulation feasible. MATLAB modeling uses the data from DEM modeling to establish averages of the particles inside a VSI crusher. This is also a large part of the fit-for-purpose framework and validation. The main goal of the experiments was to gather data to compare the simulations to.

6.1 Energy Modeling

There are several ways of modeling the energy present in particles and the resulting breakage. In this chapter, the results from using the different methods are presented.

6.1.1 DEM

The DEM simulation of the VSI crusher was initially performed on the rotor as an isolated component to facilitate a reduction of particles in larger full-scale simulation of the crusher. The fed particles from the center top while the rotor was spun filled up the pockets and created a rock bed, as intended for this type of rock box VSI crusher. Figure 13 shows the amount of material and the number of particles that get stuck in a rotor due to the rotational speed. These particles generated a large number of collisions and took considerable computational effort to maintain. The solution of replacing the complex rotor with a simpler 3D model based on Rychel's model was performed and the angles were compared to the DEM simulations.

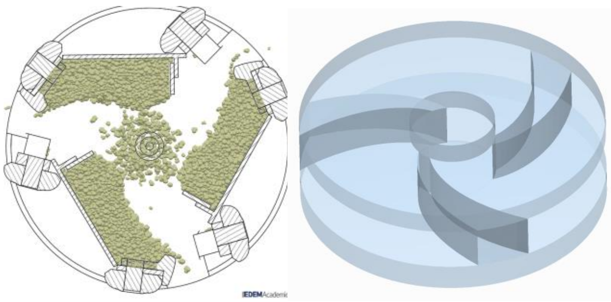

Figure 13. DEM simulation of a VSI rotor and the simplified resulting 3D model to the right.

The DEM models were then set up with different rotational speeds and produced large files of particle positions, speeds, collision energies and unique IDs. All of these data were then processed with various MATLAB scripts to allow for further analysis, further described in Paper A, B and C.

6.1.2 Postprocessing

The location of each particle at any given time can be plotted over a large timespan. By using the location of particles and observing the collision energies, we can plot the location where the particles are expending their energies. There are three zones that have a higher density of collisions, likely due to the design of the rotor, which has three exhaust ports. It is also clear that the solid geometry becomes the limiting factor to the maximum distance a particle can attain. This is even clearer in Figure 14 and is due to the solid geometry that houses the particle.

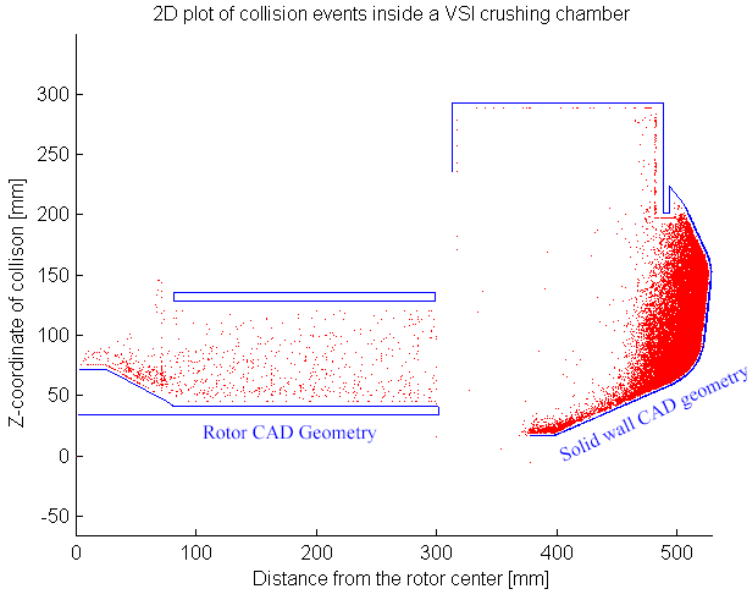

Figure 14. 2D scatterplot mapping collisions inside the VSI crushing chamber with regard to length from the rotor center and positional height. The blue lines represent where the solid CAD geometry is positioned in relation to the collisions. (Paper A)

Through observation of the data, it becomes evident that there are a few outliers just past the rotor. These are probably particle-particle collisions inside the crusher chamber. The distance a particle has to travel before it collides with another particle or geometry has been investigated and shown in Figure 15 as a probability of collision at different distances from the rotor center.

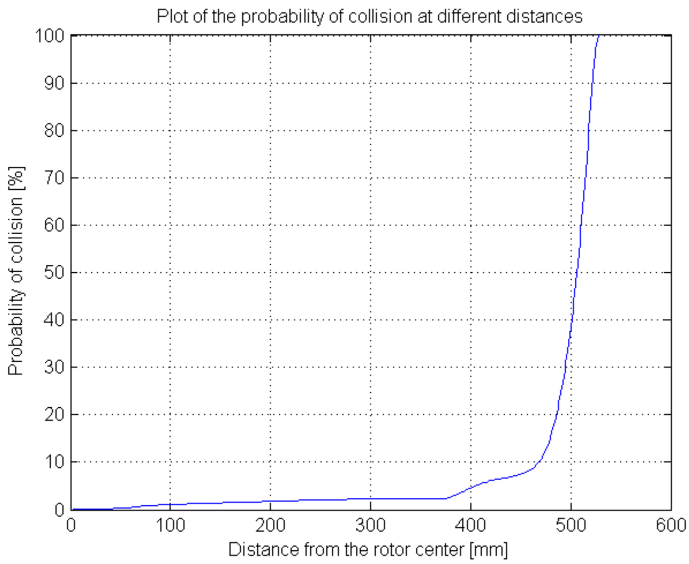

Figure 15. A plot of the cumulative probability of collision for a particle inside the VSI crushing chamber. (Paper A)

Another factor that was extracted was the average level of collision energy a particle experiences at different distances away from the rotor center. Since smaller hits, redirections and nudges by other particles register as collisions, it is important to see where the larger collision events occur and what their kinetic energies are. By sorting all of the collisions in the DEM simulation of the VSI crusher and taking its mass into account, a spectrum of collision energies can be visualized, as shown in Figure 16. Every single contact each particle has to another particle is counted as a collision and these collisions occur over a time span of approximately 1 second run time of the DEM simulation.

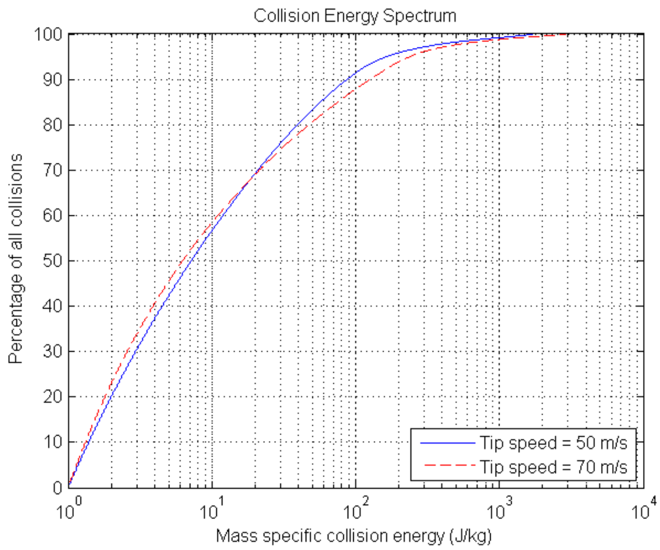

Figure 16 Visualization of the different VSI rotor speeds plotting the percentage of particles at different collision energies. (Paper A)

6.1.3 MATLAB Modeling

By using the breakage selection method in conjunction with the optimization routine, a prediction of the product of each site can be modelled and visualized. As seen in Figure 17 the predicted product follows the line relatively closely, but the fitting function cannot find values that allow it to fit better.

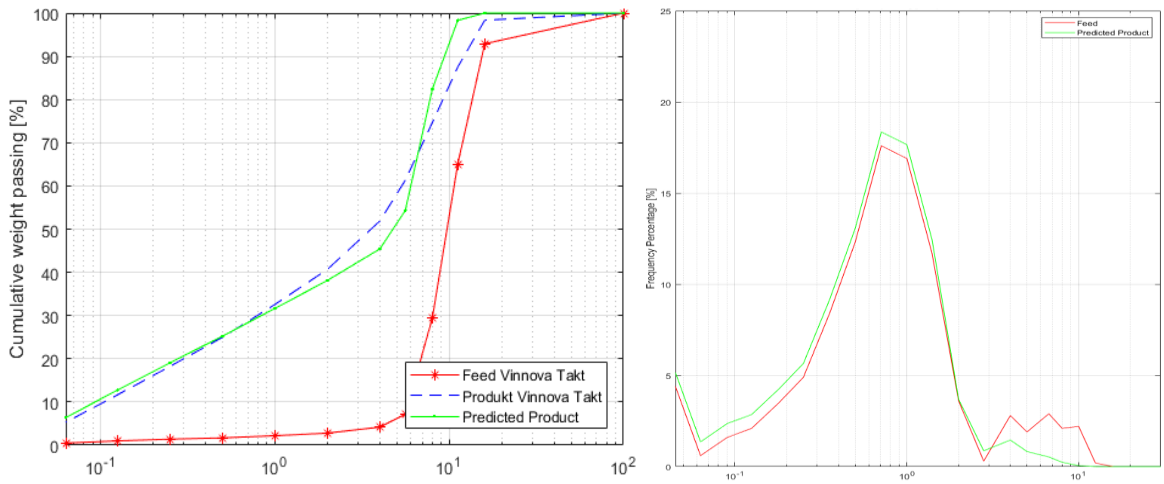

Figure 17. In the right graph is a cumulative PSD of an initial model attempt and on the left graph is a frequency PSD of the same model. The horizontal axis is the particle size in milimeters.

Initially, the selection breakage was optimized while observing only one speed, attempting to calibrate the model to it and then extrapolating to different speeds. The low level of robustness for other speeds and feeds meant that the initial modeling attempts could not be used in a wider type of situation with changing materials and machine parameters.

To address this issue, the optimization routine presented in previous chapters was introduced and run as an error function to minimize deviations from the experimental product and simulated product. This method of modeling the different sites formed the basis of the fit-for-purpose framework and presented in Paper C.

6.2 Experiments

By calibrating data from the experimental sites, a database of F_{mat}, $E_{0,min}$ and α was established to characterize the properties of different types of geological rocks. The property values all converge on expected ranges for rock materials and can be seen in Table 3. The experiments carried out can be used as a basis for predicting products of other sites with similar geological types.

Table 3. Material data from all the sites used in the study, along with their locations and calibrated values. (Paper C)

Geological type	Site Location	Top size	Source	F_{mat}	$E_{0,min}$	α
Diabase	Ubbarp	19 mm	Default Feed	0.25	21.04	0.94
Diorite	Borlänge	11.2 mm	Default Feed	0.75	16.29	0.94
Dolomite	Glanshamar	11.2 mm	Individual Feeds	1.3	14.83	0.91
Gneiss	Umeå	19 mm	Individual Feeds	0.8	18.61	0.92
Gneiss	Atle	19 mm	Default Feed	0.68	22.8	0.88
Gneiss	Össjö	4 mm	Default Feed	1.73	29.22	0.99
Gneissic Granite	Skyttorp	11.2 mm	Default Feed	1.7	15.79	0.93
Gneissic Granite	Önnestad	11.2 mm	Default Feed	1.32	26.54	0.86
Granite	Tierp	11.2 mm	Unique Feeds	2.18	16.74	0.96
Granite	Gävle	4 mm	Unique Feeds	1.45	20.48	0.92
Granite	Gävle	11.2 mm	Unique Feeds	2.08	19.39	0.9
Granite	Gävle	11.2 mm	Unique Feeds	1.63	17.91	0.82
Granite	Kållered	16 mm	Individual Feeds	1.36	15.45	0.85
Granitic Gneiss	Enhörna	19 mm	Default Feed	2.02	15.48	0.91
Granitoid	Bro	10 mm	Individual Feeds	0.06	28.02	0.81
Granodiorite	Sunderbyn	11.2 mm	Individual Feeds	1.92	23.48	0.95
Limestone	Forsby	19 mm	Default Feed	2.35	25.22	0.82
Porphyry	Kiruna	10 mm	Individual Feeds	0.39	16.83	0.88
Quartzite	Gåsgruvan	19 mm	Default Feed	0.25	21.04	0.94

6.3 Fit-for-purpose Framework

The PSD comparision results for each dataset originating from one site can be visualized, as seen in Figure 18. The dashed lines represent the model's estimation for the product, and the solid lines are the tested product curves for the corresponding speeds. Last, the black solid line indicates the feed or feeds in the dataset. Of the three rotor tip speeds, only two have been used to train the model, the highest and lowest speeds, while the middle speed has been used to verify the response of the model.

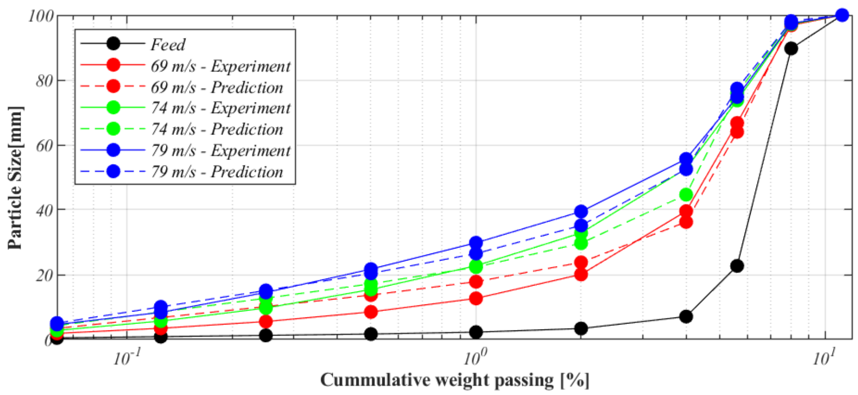

Figure 18. Particle size distributions from one of the sites and the corresponding simulation results.

By running all the datasets through the same optimization routine, similar results were obtained for each site to those achieved for Figure 19 but with different levels of magnitude relating to the feed used and material properties. While these properties include a multitude of factors that affect particle breakage and size progeny, some parameters are more prevalent than others and will vary less between sites. Two factors, F_{mat} and $E_{0,min}$, were calibrated from each site with the use of experimental data.

E^0_{min} is a characterization of the energy level required to achieve particle breakage, while the F_{mat} property encompasses not only the material properties but also the properties arising from different particle shapes. These parameters are dependent on many variables within the material but generate a perception of the strength of the different material types.

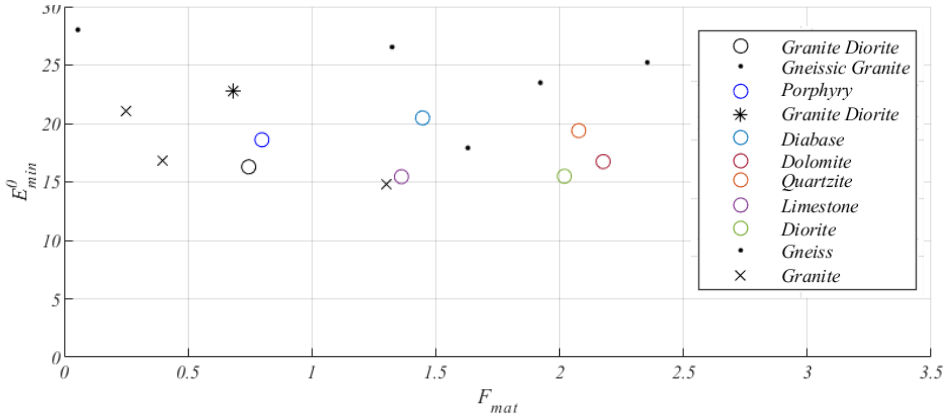

Figure 19 A scatter plot of the f_{mat} and $E_{0,min}$ values for different geological types and sites analyzed.

6.4 Validation

The models created and calibrated with the methods described above have created accurate models within normal operative speeds. Values of P20, P50 and P80 were extracted from the simulated product data and were compared to similar points interpolated from the experimental data; the values can be seen in Figure 20. These sets were compared to each other to assess the accuracy and range of the model. In large part due to the optimization method, the values for P50 were the least differing while the tail ends were often more spread away from the experimental data. Some variation in the experimental data is also assumed to be linked to the belt cut method of samples taken from the sites but is generally considered to be negligible.

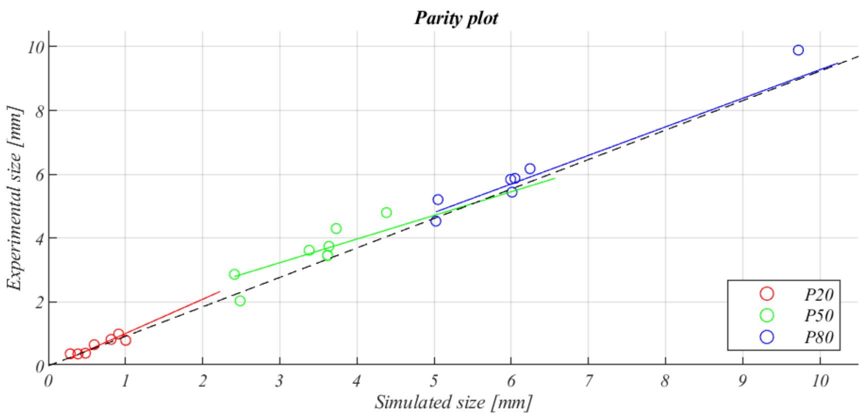

Figure 20 A parity plot of the P20, P50 and P80 values from the experimental data compared to the simulated data using the developed models. (Paper C)

To test the robustness and validity of the model, the PSD predictive capability was explored. Speeds exceeding beyond the rotor tip speeds the model was trained with have been tested to highlight the model's flexibility to work beyond it's the range of the training data. In Figure 21, predictions were made for tip speeds of 85 m/s (15% higher kinetic energy than training data) and 65 m/s (12% less kinetic energy than training data).

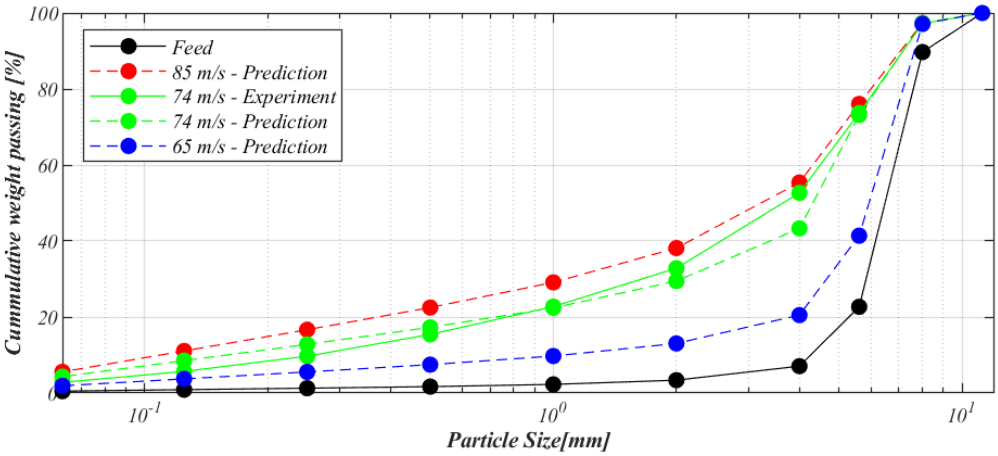

Figure 21 Particle size distributions from one of the sites and the corresponding simulation results for speeds exceeding the training data of the model. Note that the training speeds were still 69 m/s and 79 m/s, not shown in the figure. (Paper C)

7. Discussion

This chapter aims to discuss:

- *The answers to the posed research questions*
- *The strength and validity of the fit-for-purpose modeling approach*
- *Future work to increase the models performance and understanding of the VSI crusher*

7.1 Answers to Research Questions

The four research questions, posed at the beginning of this the thesis, guided the work and will be discussed in numerical order.

- RQ 1 – What interactions in a VSI crusher between the material and the machine affect the performance?

The number of interactions inside a VSI crusher is difficult to conclusively state. The work in Paper A presents the effects that changing rotor tip speeds have on particle velocities. Increasing the rotor tip speed will lead to higher levels of collision energies for particles inside the crusher chamber. The relationship between the size of the rotor, rotational speed and kinetic energy is also investigated in this paper.

Particles inside a rotor designed to form a rock bed will create a geometry that is shown in Paper A. How particles form a crusher bed due to their trajectory inside the rotor is visualized while also showing a rough estimate for the total amount of particles inside the VSI crusher when the material that forms the rock beds is assumed to be static.

This assumption is also used in Paper B when evaluating the particle collisions and it explores the location and expenditure of the collisions of particles in the crusher chamber and rotor. The number of exhaust ports is clearly shown to affect how many flows of particle material will move throughout the crusher chamber.

- RQ 2 – How can the knowledge of impact energy and particle breakage be combined to create a usable model?

The work in both Papers A and B analyzes the magnitude of the collisions that occur in the VSI crusher and establishes that particles will on average experience one large collision during their residence time. This information is used in Paper C to run the models that estimate the resulting particle size distribution.

As seen in Paper C, the models introduced extensively use the energy to calculate the effects of the particle impacting the rock bed in the crusher. The radius of the rotor and the rotational speed provide the kinetic energy input used in the model to Paper C and show how the impact energy used to predict the particle breakage can be implemented.

- RQ 3 – How can such a model be calibrated to make it robust and reliable and how would such a model be validated?

Paper C thoroughly shows how the model can be trained and the material parameters back-calculated. Initially, a single set of training data was used, but the resulting models were overly sensitive. By establishing an error optimization problem and training the model with two different datasets run at significantly different rotor tip speeds, a more robust model was obtained.

The modeling work in Paper C establishes a groundwork for establishing a material database that allows prediction of new sites that lack material data. Paper C shows an attempt to extrapolate the model to accurately predict the products resulting from rotor tip speeds beyond those obtained through testing. The possibility of evaluating VSI rotor tip speeds showcases the strength of the approach.

- RQ 4 - How can these models be applied to allow for industrial and product development?

As shown in Paper C, the models can be used to tweak and tune the crusher model for existing quarry sites. This allows plant operators to more easily plan and schedule the production of different categories of particles. More control and tools that allow planning can be used to decrease energy consumption and reduce the production of low-value products such as filler material.

7.2 Validity

The VSI model presented in Paper C has shown the versatility of the model. It can be used for several different rock-box type VSI crushers if the radius and speed of the machine are known. Wider rotor exhausts and an increasing number of ports are not explicitly modeled but are assumed to be similar to a 3-port crusher.

The model can also extrapolate and predict products for speeds and feed sizes that have not previously been tested. These results can easily be incorporated into process simulations as a part of the entire comminution product. The model relies on feed samples from newer plants to create greater accuracy. A larger database of material properties might mitigate this.

In its current state, the model cannot account for cascade settings or the use of anvils in the crusher chamber. The effect of these changes on the VSI may prove useful in the deployment of VSI crushers to certain sites but is currently not covered by the model.

7.3 Future work

While the back calculation of the material parameters provides a good fit for the purpose result, a laboratory analysis of the material should be performed. This would show how much the difference from the model values and material values are while also building up a larger database of material characteristics. The goal would be to determine the $E_{0,min}$, f_{mat} and α values in a laboratory setting.

Larger, more spread-out testing of viable materials is also encouraged. Most material tests conducted have been at established sites that are using or considering VSI crushing on a larger scale. How well other material sources can perform or be used as replacements is unknown. As a result, material testing from other sites that are not currently considered for VSI crushing should be conducted. This would show how far the sites are from achieving the goal of replacing natural sand with artificial sand.

There is a need for a larger dataset of geological compositions. The f_{mat} parameter is a generalized material parameter, and splitting into strength, shape and abrasive resistance might lend more detail and predictability, given a sufficiently large material dataset.

If VSI crushing is more heavily adopted, it would most likely lead to an increase in filler production. This naturally leads to an increased incentive to find more products that can make use of this relatively unwanted material. New concrete recipes and customizing concrete production to specific sites should also be considered.

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