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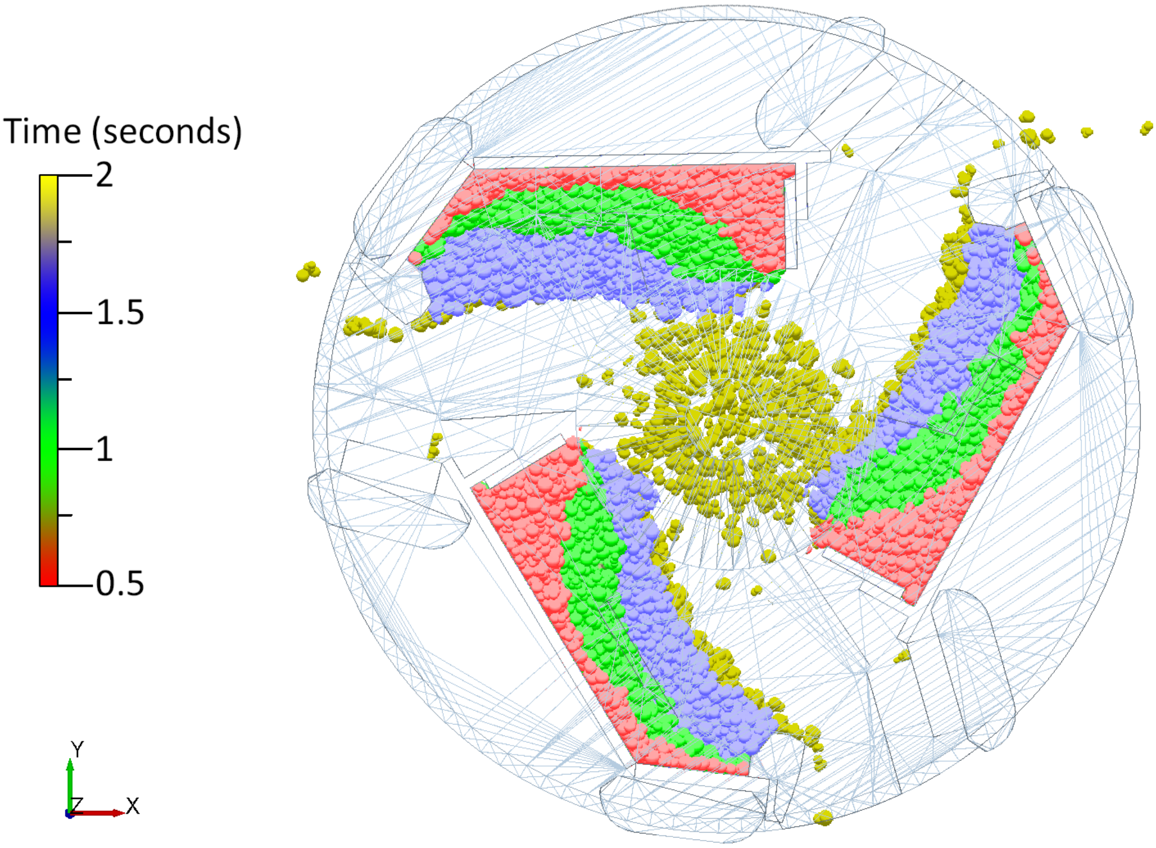

Modeling and Optimization of a Vertical Shaft Impactor for Production of Artificial Sand

Master of Science Thesis

Simon Grunditz

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2015

REPORT NO. XXXX/XXXX

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Technical report no xxxx/xxxx

Supervisor: Carl Magnus Evertsson, Professor

Department of Product and Production Development

Chalmers University of Technology

SE 412 96 Göteborg

Sweden

Telephone + 46 (0)31-772 1000

Cover:
An image depicting the simulation of filling of a rotor inside a VSI with regards to time. Created using EDEM Software.

Printing Company (Chalmers Repro Service)
Göteborg, Sweden 2015

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Summary

Vertical Shaft Impact crushers have been used for a long time to reduce the size of particles and to give particles a cubical shape profile. Very few investigations have been performed on the inner workings of the VSI crusher and even fewer attempts have been made to model the particle breakage and collisions that occur inside it.

The objective of this thesis was to investigate how the geometry of the rotor and the operating parameters of the VSI affects the output of the crusher. This will create a better understanding of the dynamics inside the crusher and will allow future designs to be more optimized towards specific particle size distribution and shape profile goals.

The investigation was performed using Discrete Element Method, which is a numerical method for simulating systems of particles, to model the particles and Computer Aided Design to represent the crusher and rotor geometries in the system. The modelled VSI is based on measurements from a Metso Barmac 5100SE VSI crusher taken from a mobile crushing plant located in a quarry in Gävle at the time.

Eight different rotor designs were created in a systematic way using a Design of Experiments approach. Each individual rotor was then placed inside a VSI and a DEM environment was created to produce collision data which was then extracted.

Several MatLab scripts were written to enable data re-structuring and interpretation. An analysis of the particle attributes and collision energies was made for each unique rotor design and then compared to each other in order to find what variables had the highest impact on breakage and shape.

Further work needs to be done in order to gain even more detailed knowledge about the particular types of breakage, the required energy levels for specific particles sizes and in order to create a mathematical model that predicts the particle size distribution given regular operating parameters and feed material data.

Keywords: DEM, VSI, Comminution, Optimization, Rotor

To my family

Acknowledgements

The first thing I would like to do is to acknowledge and thank my supervisor, Magnus Evertsson and also my co-supervisors, Erik Hulthén and Magnus Bengtsson, for their guidance and patience. Johannes Quist helped me to understand and use DEM for which I am very grateful.

Hanna Sundström and Martin Hernå provided me with constructive feedback and were indispensible as my opponents during my presentation of this thesis for which I am ever grateful for.

I would also like to thank all of my colleagues, former and present, at the Chalmers Rock Processing Systems research group for their helpful advice and entertaining discussions.

Discrete Element Method (DEM) simulations were conducted using EDEM® 2.6.1 particle simulation software provided by DEM Solutions. Ltd., Edinburgh, Scotland, UK.

-Simon Grunditz
Gothenburg, 2015

Nomenclature

Glossary

MA	Manufactured Aggregates
NA	Natural Aggergates
VSI	Vertical Shaft Impactor
HIS	Horizontal Shaft Impactor
CSV	Comma-Separated Values
CRPS	Chalmers Rock Processing Systems
NIST	National Institute of Standards and Technology
DOE	Design of experiments
CAD	Computer Aided Design
PSD	Particle Size Distribution
CPU	Central Processing Unit
CFD	Computational Fluid Dynamics

Dictionary

Comminution	The reduction of solid materials from one average particle size to a smaller average particle size by crushing, grinding, cutting, vibrating or other processes.
Rheology	The study of the flow of matter. This applies to substances with a complex microstructure, such as muds, sludges, polymers and body fluids.
Computer Tomography	Often shortened into CT or CAT scan. A process that combines a set of x-ray images to produce cross-sections of objects.

Table of Contents

1. Introduction

In this chapter, the starting factors that lead to the project as well as the goals to be achieved will be introduced.

1.1. Background

Aggregates are the most used product, excluding water, in terms of mass in Sweden, and have been for a long time. Domestically, Sweden produces and delivers approximately 80 million tons of aggregates every year [1]. This means that the consumption of every single swede is on average 8 tons of material per year. The reason for this is because it is a necessary component in sustaining a modern society and functioning infrastructure, playing a major part in the construction of roads, railways, bridges, docks and airports. It is also an essential part in the building of industrial buildings, apartment complexes, power plants and other concrete structures.

Historically, most aggregates, consisting of gravel and sand, were dredged from riverbeds and other natural deposits [2].Aggregates that are extracted from these kinds of sources are often called natural aggregates (NAs) but as demands for building materials increased; other methods for creating aggregates were explored and developed. The most common way today to produce aggregates on an industrial scale is by drilling and blasting followed by crushing and screening. Aggregates produced with these methods are often referred to as manufactured aggregates (MAs).

The application areas of NAs and MAs depend on a number of particle and material factors that are in part related to how they are created. NAs are formed through erosion in riverbeds over a large time span which gives the rock particles a rounder form and smoother surface. MAs on the other hand are often made through crushing which generally produces angular rocks with lower sphericity and a rougher surface [3].These differences make it difficult and challenging when NAs are to be replaced.

In many applications, replacing NAs with MAs have led to vast improvements. In roads for instance, aggregates are bound together using a binder called bitumen to create asphalt. The use of angular rocks allows the road to handle a larger load due to increased interlocking between rock particles and slows the weakening of the road through displacement of particles when compared to using rounder particles. This is why the use of NAs in road construction has drastically decreased.

The transition has been more problematic when it comes to the production of concrete, where water and cement form a binding agent that lock the aggregates in place. The liquid mixture is poured into a mold and allowed to harden. A concrete mixture with poor choice of aggregates will not fill a mold accurately, creating a non-homogenous end-product with areas of weakness resulting in lower overall strength and structural integrity [4]. The shape and surface texture of the aggregates used will not only greatly impact the rheology of the concrete mixture in its fresh state but also the strength and content of cement in the concrete in its hardened state [5].

One problem is that the use of MAs compared to NAs generally leads to a larger total surface area in need of binding and this in turn means that the cement-water ratio has to be larger to produce the same rheology and workability for the concrete. Cement is the most costly and CO_2-contributing component of concrete [6] and it is therefore neither economical nor environmentally suitable to use MAs that lead to increases in the water-cement ratio [4].

Another issue with depleting natural deposits of aggregates is that this severely impacts the natural filtration of water that runs through it. The Swedish government has therefore put in effect a set of regulations and goals in order to preserve the remaining deposits [7]. To acquire a permit for excavating these deposits, there must be no doubt that any potential replacements products, such as MAs, will carry a higher ecological and economic cost[8].In 2009, 17% of the total amount of aggregates that were extracted that year were NAs, which is a major decrease compared to 1990 where 70% of aggregates were NA [9].

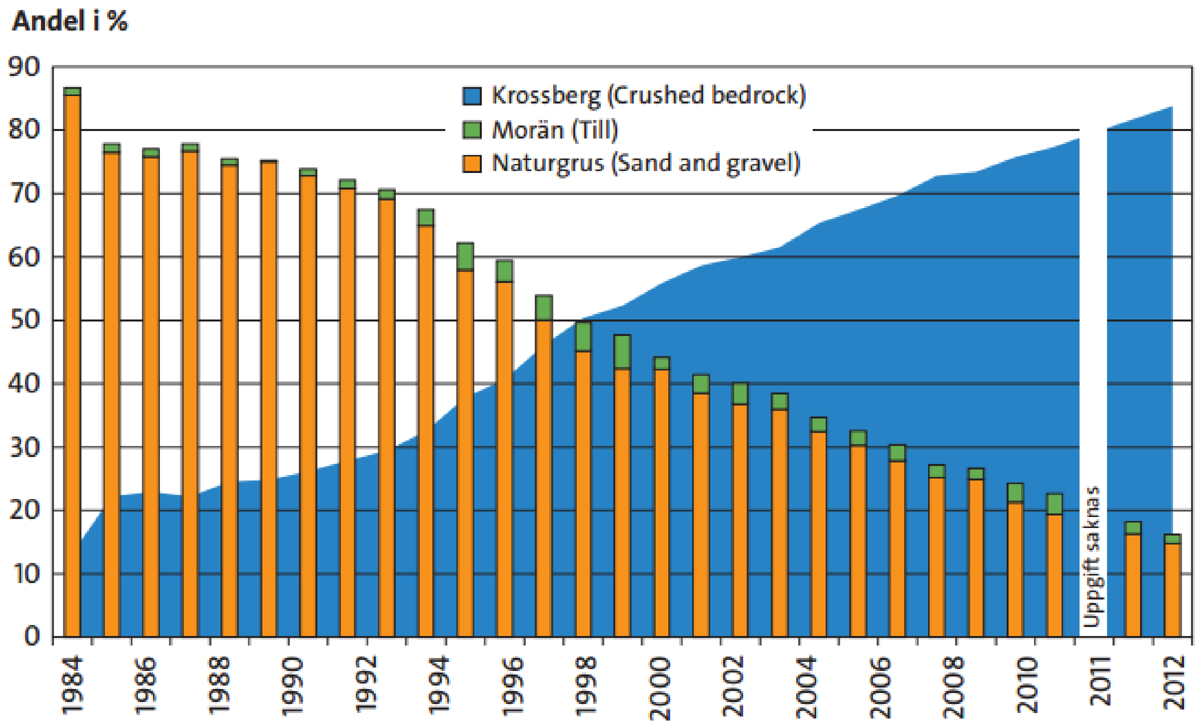


Figure 1. Share of sand and gravel from natural deposits in 1984–2012 in Sweden, as percentage. Graph taken from a report from the Geological Survey of Sweden [1].

It has been shown that using manufactured sand from Vertical Shaft Impact (VSI) crushers can actually result in higher strength of the concrete than natural fine aggregates when using equal cement and water ratios[5]. This indication that VSI crushers have potential in the manufacturing of MAs means that future designs of crushers, with this production in mind, can possibly be improved when it comes to effectiveness, throughput quantity and the shape profile of the particles.

There is a need to obtain further understanding of how the VSI design and operational parameters affects the particle properties of MAs and how it can be changed to improve the quality of aggregates produced. In order to find out what parameters are crucial in the creation of adequate shape profile multiple Discrete Element Method (DEM) simulations will be performed.

1.2. Objectives and Scope

The aim of this project is to investigate the effects of rotor speed and rotor geometry of the VSI on the size distribution and particle shape of the MAs using the current equipment available to the Chalmers Rock Processing Systems (CRPS) research group and also to improve the design of the rotor in the VSI. To achieve this, the current design will be evaluated by making a CAD model of the VSI-rotor and surrounding geometry and using this to build a working DEM environment that accurately simulates the function of the VSI.

The project will try to encompass the analytical, numerical and experimental approaches of VSI-crushing in order to strengthen the validity and results of the outcomes. It will also be limited to making changes only to a specific part of a VSI, in this case the rotor, since a complete overhaul of current VSI-crusher designs is too large of a project to undertake with the resources at hand. Only a single specific model of a VSI crusher will be considered, more precisely a Metso Barmac B5100SE VSI Crusher. The main reason for the choice of this particular model is due to the fact that the CRPS research group has access to one and acquiring a new one is neither economically viable nor justifiable.

1.3. Research Questions

The following research questions are going to be answered through the completion of this project:

1. How does the geometry of the rotor affect the particle breakage inside a Vertical Shaft Impact Crusher?
2. How do the operating parameters of a VSI affect the particle breakage and angle of impact inside a Vertical Shaft Impact Crusher?

Early on in the project, during planning, a set of future obstacles were identified in order to better understand the time demands for different sections of the project. The problems are grouped in a few different sections and can be found below. The solutions to the problems listed are addressed later on in the report.

Problems that relate to acquiring an accurate VSI specification:

- What method and tools should be used to physically measure the VSIs dimensions?
- What level of accuracy is needed in order to match the virtual model with the real one?
- Should wear and tear of the internal components in the VSI be considered and what impact would using new parts have on the simulations compared to worn parts?

Problems that relate to particles and their modeling:

- Can the crushing events in a VSI be accurately modeled?
- What resolution is required for the CAD model to be a good representation of the actual VSI?

- Is it possible to use a breakage model in order to allow particles to be reduced in size?
- Is there some symmetry that can be used to reduce simulation time without negatively impacting the results?
- What are the particle properties of the material bed compared to the particles?
- How should the material bed inside the rotor and in the crushing chamber be handled?
- What is the trade-off between resolution and computational time?
- What material data should be used in the simulation?
- Is there a reference model for the particle movement inside of a VSI rotor?

Problems that relate to handling the simulation data:

- What data needs to be exported from the simulation?
- How should the raw data be interpreted?
- How much data is needed for the simulation results to be considered a good representation of the crushing in the chamber?
- Can a steady state be obtained and if so, what are its criteria?

Problems that relate to the results:

- How can the results be validated?
- Are there outliers or spikes in the data? If so, can they be reasonably explained?
- Can the results be reproduced?

1.4. Limitations and Constraints

In order to limit the sizeand scope of the project, a list has been made to try and narrow down what should and what should not be included in the project.

- The project is planned to be around 20 work hours a week and will span approximately 80 weeks in total. More time will most likely be required but this the set amount that has been used in planning the project.
- This project will study one type, model and size of a VSI crusher, specifically a MetsoBarmac B5100SE VSI crusher
- Any developed physical prototypes have to be compatible with the crusher studied in this thesis.

2. Theory of Crushing

The purpose of this chapter is to introduce rock particles, their attributes and how these can be changed to suit specific applications or to specific products requirements. Following this there will be a description of common processes that are used to alter the rocks and what their advantages are. A method to simulate particle behavior will be presented and how experiment plans can be optimized will follow.

2.1. Aggregates

The word aggregate simply means a whole formed by combination of many other elements. This definition covers a wide range of different things but in construction it usually refers to a mixture of silt, sand, gravel and crushed stone usually used to constitute a concrete mix. The difference between these groups of particles is simply their size, with silt being finer than sand, sand being finer than gravel and gravel being finer than crushed stone. There are a set of different definitions for fractions of these sizes andin this thesisthe PSD EN933-1:1997 standard shown in Table 1will be used.

Upper grainsize D	Lower grainsize d
63 mm	32 mm
32 mm	16 mm
16 mm	8 mm
8 mm	4 mm

Table 1. The different names and corresponding sizes for rocks

Aggregates are usually divided into two categories, manufactured and natural. The difference between these is how they are created. The first type of aggregates are extracted through blasting and crushing using explosives and industrial machines or tools while the latter one is excavated from deposits where natural phenomena such as erosion has formed the stone over a long time.

The practical issue with these different groups is that while the supply of manufactured aggregates can be increased with more equipment, every single use of natural aggregates is depleting the limited reserves. In order to preserve the environment the Swedish government has passed several new pieces of legislature. One of the more important of regulations when it comes to aggregates is the Environmental Code which was updated 2012 to change the requirements for quarry permits. To acquire a permit for excavating these deposits of natural aggregates, there must be no doubt that any potential replacements products, such as manufactured aggregates, will carry a higher ecological and economic cost [8].

2.2. Particle Shape

A particle can be measured in several different ways. At plants, the size of a particle is usually defined by the size of the apertures in screens that the particles can pass through. For instance, a particle that can pass through a square hole with a dimension of 8mm on each side, but does not fall through similar hole with the size of 2mm would be placed inside a fraction called 2-8mm.

Although common, this type of measurement is not very practical for calculations or for determining sizes of particles inside of a simulation. The process of running particles through a screen inside a simulation to determine their size is possible yet not very efficient. Hence, an alternative method is established.

Rocks are 3 dimensional and generally have complex shapes, texture and surface. While there are ways to capture the topology of the rock, for instance with a computer tomography, a more convenient measurement is used. The procedure is to first find the two points that are the farthest apart. This distance is names the length and will be the largest of 3 measurements. The second and third measurements are taken by finding the two points farthest from one another in a second and third dimension, normal to the first dimension.

The final result is a cube with a length, width and height that the rock particle can fit in, with length being the largest distance, width the middle distance and height being the smallest measurement. An illustration of measuring a particle can be found in Figure 2.

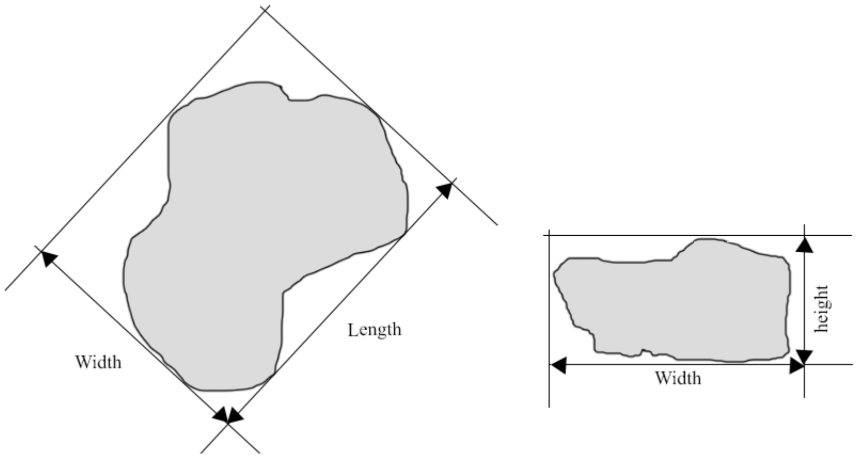


Figure 2. The length and width measurements of a rock particle.

After the method of determination of size has been established, the next step is to find a tool to look at the overall size of a large amount of particles. Fortunately, there is already a commonly used tool called Particle Size Distribution. It is often used to characterize a flow of particles, usually done before and after a comminution machine to see the size reduction effects they have upon the material. An example of how the particle sizes are distributed can be seen in Figure 3.

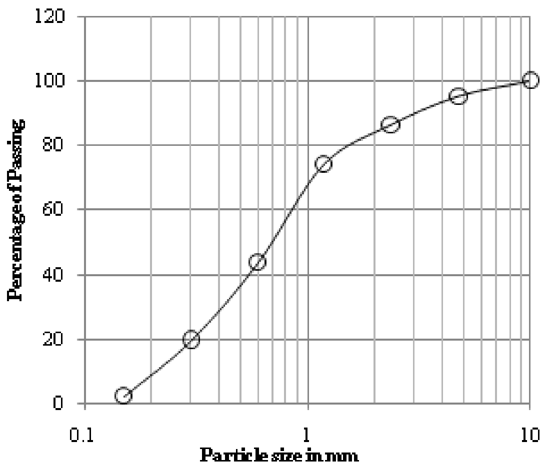


Figure 3. A particle shape distribution graph

2.3. Comminution machines

Comminution of rocks was in the beginning done by hand, with the use of pickaxes. Construction of houses was therefore very slow when using stones. The first macadam roads were constructed with crushed rock through manual labor. Today, there are machines that make this process a significantly easier. This section will introduce some of these machines and their general mode of operation and will thoroughly explain how a VSI works.

2.3.1. Compressive Crushing

Cone crushers are in essence just two cones, a larger one, called the concave, is empty on the inside to allow the second smaller cone, the mantle, to be placed inside it. These two surfaces will form the crushing zone by having the smaller cone attached to the main shaft axis. The gyrating axis moves eccentrically and thus creates a cycle of compression and expansion between the concave and the mantle. This gap is filled with rocks that, due to the nutation of the axis, are crushed into smaller sizes and move down through the crusher. The basic shape of the crusher can be seen in Figure 4where a cross section of the crusher in action shows the flow of the material.

The walls and the mantle of cone crushers are lined with high-resistant wear material and often consist of ring or square segments that can be changed when maintenance is required. They are often equipped with a spindle in order to prevent the material from causing a stop of the flow. Cone crushers tend to be good at size reduction but will often make particles more sharp and angular.

Gyratory Crushers are similar to cone crushers but feature a steeper crushing chamber and less of a parallel zone between the crushing zones. The rocks are reduced at a slower rate and through more crushing events. Similar to cone crusher configuration, the walls are lined with high-resistant wear material in order to ensure a long product lifetime and segmented plates in order to enable quick maintenance. Gyratory crushers are often used as a primary or secondary crusher and features around 5-7 crushing events on average for fed material. Similar to cone crushers, they tend to make particles more angular.

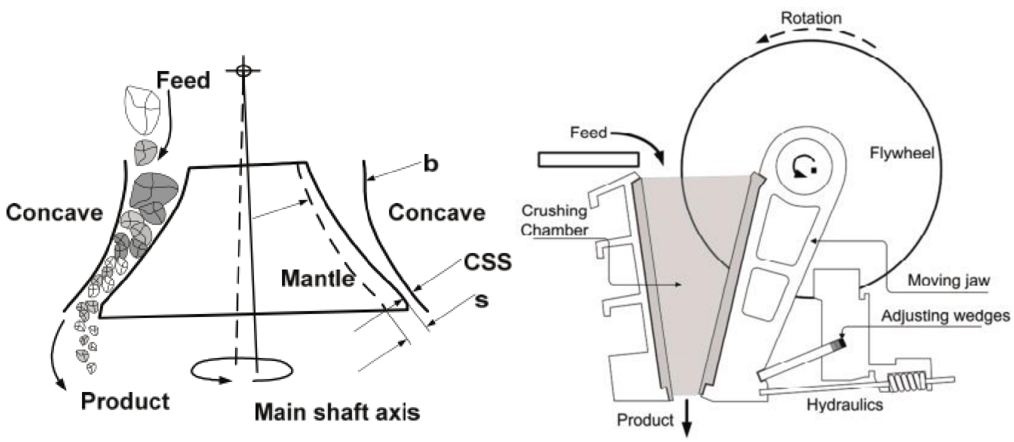


Figure 4. Principle sketch of a cone crusher, Lee [10], and a schematic of a jaw crusher by J. Quist.

The working principle of a jaw crusher is very similar to that of the cone and gyratory crusher but instead of a rotating axis and a conical flow, the jaw crusher features two flat walls, one of which is fixed while the other reciprocates. There are a set of different Jaw crushers classifications that are based on where the position of the pivoting of the swing jaw is. These are Blake, Dodge and Universal crushers with upper, lower and intermediate position of the pivot respectively. These kinds of crushers have only 3-5 crushing events on average for the fed material and the dominating breakage is single particle, form conditioned crushing. The jaw crusher gives high size reduction but also tend to make very sharp particles.

A High Pressure Grinding Roller Consists of two rollers of the same dimension, which are rotating against each other with the same angular velocity. One of the rolls and its bearings can be moved linearly towards and away from the other roller. Material is then fed from the top and through the two rollers which form a compressive crushing zone. The pressure in the material bed is generally around 100-300 MPa. This causes the particles in the material bed to fractured and is very energy efficient when compared to Ball mills. By increasing the pressure, the size distribution goes towards an increase in finer particles.

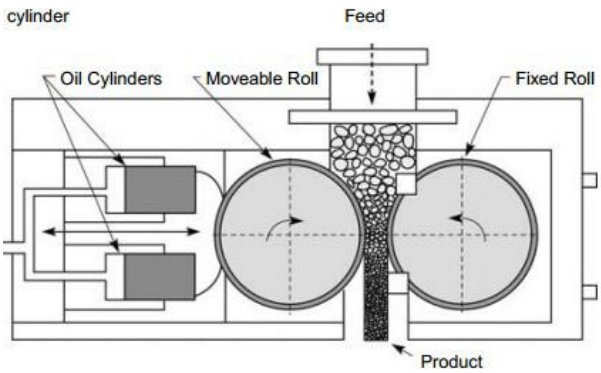


Figure 5. Principle sketch of high pressure grinding rolls

2.3.2. Impact crushing

Hammers are fixed onto the outer edge of a spinning rotor. Material is fed onto the upwards swinging hammers which accelerate them into the anvils attached to the walls resulting in breakage. Particles are often flung multiple times and thus ensure one of the highest reduction ratios for crushing machines.

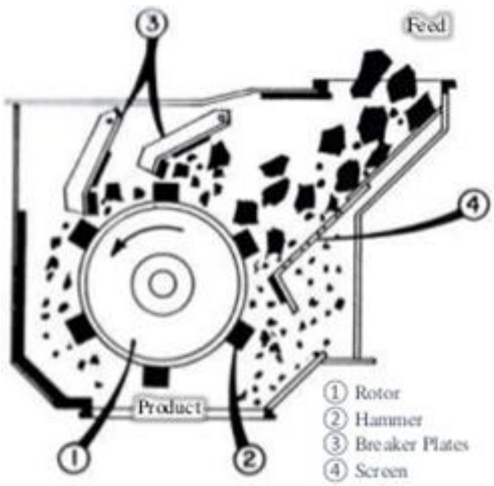


Figure 6.Cross section of a HSI crusher

The issue with using anvils in order to instigate particle breakage is that the wear is very high and costly. This is one of the reasons to why soft rock material and recycled goods are more commonly used than hard rock material since the harder the material the quicker the wear will be. The Horizontal Shaft Impact crusher can be used as primary, secondary or even tertiary crusher and usually creates particles of a rounder quality.

Another energy based crusher is the Vertical Shaft Impact crusher. A VSI crusher is a common comminution machine for crushing particles and improving the shape of particles. There are some different configurations of VSI crusher but the focus will be on describing the general flow of the material that goes through all of the crusher, regardless of how they are set up. There will also be a generalization of the different sections of the crusher and how they relate to the operation. By dividing up the crusher in different sections, A through E, it is easier to discuss behaviors in different interaction fields. These areas can be seen in Figure 7 which shows the cross-section of a principal VSI.

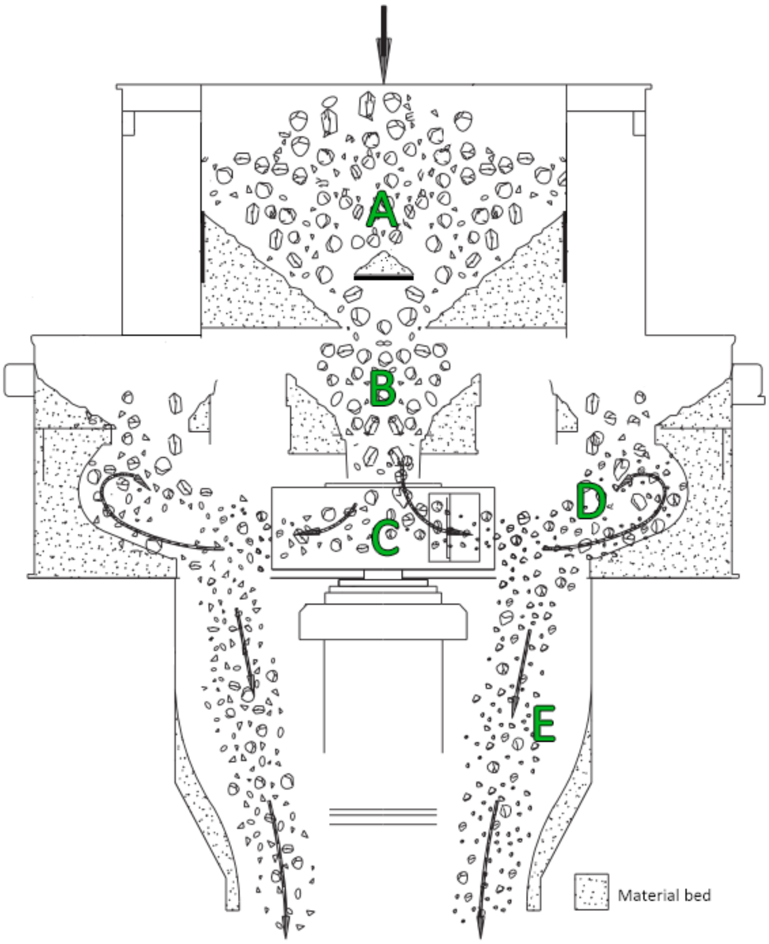


Figure 7. A cross section of a principal VSI crusher

Section A is were material is fed into the crusher. This is usually done with a conveyor belt that feeds directly onto the top part of the crusher, which houses a hopper that can store a small amount of material. In the center of the hopper is a circular hole that leads material into feed tube. The feed tube is part of section B and is simply a circular cylinder that keeps the material from escaping and leads it onto the spread plate and protects the top parts of the rotor.

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 spread plate to protect the rotor and make the particles flow outwards, towards the rotors exhaust ports. The path that particles travel when they go from the center of the rotor to the exhaust ports has been mathematically modelled by Rychel [11]. The general path and its accompanying parameters can be seen in Figure 8.While it is possible to track the forces for a particles throughout the path, the point of highest interest for this study is the outer most point. This is where the rotor radius, the angle of exit (named ψ_i) and the rotational speed of the rotor is has the largest impact on the particles exit velocity. This path of movement is equal for all exhaust ports.

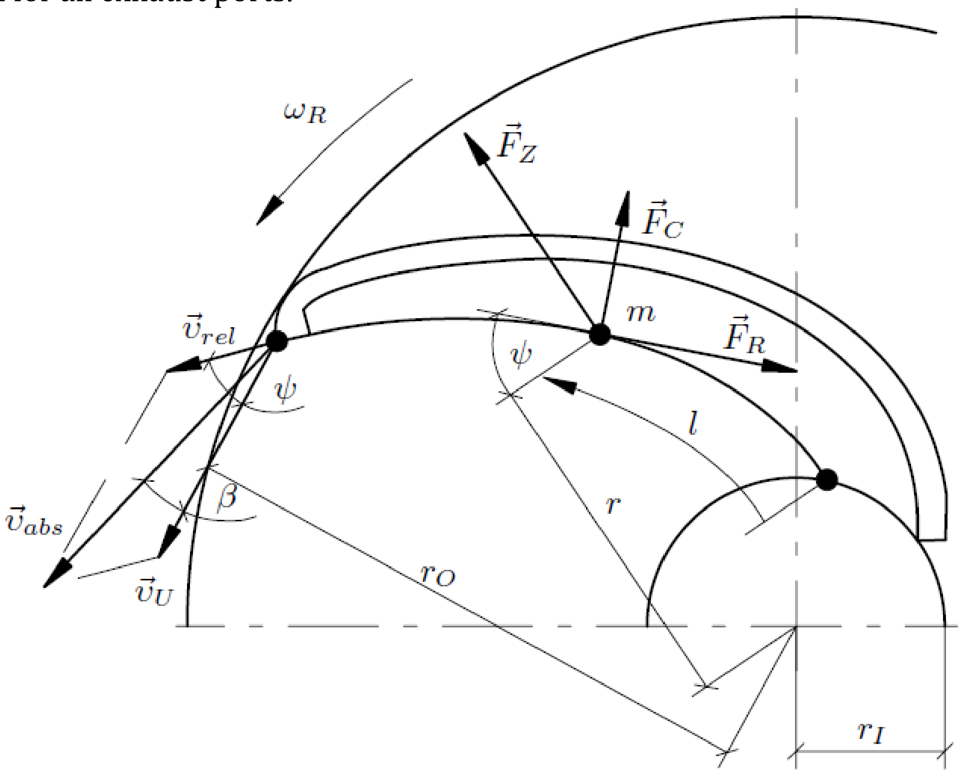


Figure 8. Rychels mathematical description of the path of particles exiting the center of a VSI rotor. From Rychel [11]

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 spend the majority of their time in the crusher. Particles are flung towards the outer walls of the crusher, where a bed of particles will quickly build up and protect the walls. This bed of particles will be where collision with other particles and most of the breakage will occur. Once particles have lost their kinetic energy, they will fall down, out of the crushing chamber and into the last section, E. Particles fall down an empty shaft and out of the crusher, usually onto a conveyor belt. Like the HSI, the particles usually come out of the crusher with a rounder shape than when they entered.

2.4. Crushing Principles

In order to be able to analyze a crushing machine in regards to its parameters, input, output and performance, there is a need to know what types of breakage that are occurring in the machine. A number of authors have studied the types of breakage in several different crushers [12, 13].

Crushing can be divided into two different categories; form conditioned and energy conditioned crushing. Form conditioned crushing is made through compression of two surfaces, the particle is crushed and the overall deciding factor for size reduction will be how large the end gap is between the surfaces. The force used during compression can often be measured and recorded by measuring the power used. This will not give an exact energy calculation for each individual particle but rather it will be as an average on the particles being fed out. Many predictive models have been constructed for several types of form conditioned crushers [14].

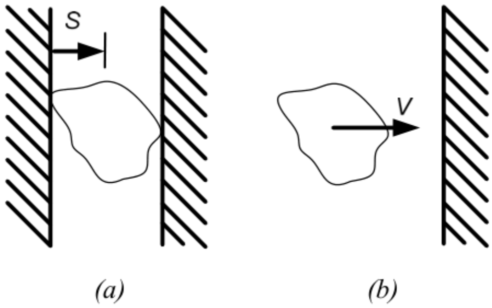
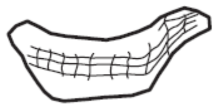
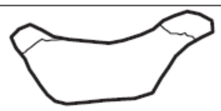
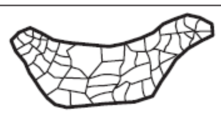


Figure 9. An image of a) a rock particle being subjected to compressive crushing and b) energy conditioned crushing from

Energy conditioned crushing consist of transforming the kinetic energy of particles and geometry into potential energy when they collide. This is often achieved by accelerating particles to high speeds and then propelling them into metal anvils or by having solid metal rods rotate at high speeds in showers of particles. The angle of impact and the magnitude of kinetic energy are crucial in predicting how much energy will be converted.

Attrition is a phenomenon which is observed when the particle is traveling along a surface while making sporadic contact. The repeated impacts will cause the sharp corners of the particle to break off. Since impact rarely occurs perfectly perpendicular to the surface there will often be some attrition in most energy conditioned crushing and even to a small extent in form conditioned crushing. This mixture of energies and modes of collision result in several types of breakage effects that have different names and criteria. An attempt to map them and create a framework has been made and these breakage effects can be seen in Table 2.

Table 2.Comminution effects on particles subjected to loading events from Unland [15].

effect	feed	loaded particle	product
weakening			
cracking			
breaking			
crumbling			
chipping			
splitting			
disintegrating			

3. Method

In this chapter, the process of the project will be shown in detail. From the first drawing to the final design of the simulation experiment plan and lastly the data extraction from the simulations.

3.1. Experimental Design

The goal of an experiment is to verify, refute or to establish the validity of a hypothesis. An experiment is a procedure carried out in an orderly fashion. Experiments are very useful at providing insight into the cause and effect nature of setup when a particular factor is manipulated. To discover and examine the relationship between inputs and outputs, an experimental design is often used. In this study, all experiments are carried out through the use of simulations.

The treatment of a group of parameters with the interest in observing the effect they have on the response is the definition of an experimental approach. The setup and execution of an experiment severely impacts the credibility of the results which means that great care and consideration should be used when creating a testing plan.

Limitations with running experiments is often that it is time consuming and a rigorous test plan level is often found to be expensive regarding e.g. personnel, loss of production or running costs. Another problem is the tremendous amount of data generated from all the experiments. One way to optimize for all these conflicting issues is a type of experimental design called Design of Experiments (DOE).

3.1.1. Design of Experiments

DOE is a systematic, precise method to problem solving and testing applications. It applies established techniques to ensure that the data collection from experiments provide valid conclusions. All of this is performed under the constraints of minimizing costs by effective use of each experiment run.

The basic structure of this systematic approach consists of seven steps:

1. Define objectives
2. Select process variables
3. Setup of experimental plan
4. Execute the experiment design
5. Screening of factors
6. Interpretation and analysis of results
7. Apply results

Define objectives
The first step of this method is to define what the objectives for the experiments are and what process is to be observed. In other words, what should be examined and what kind of results are needed to make relevant conclusions. This systematic approach is applicable to many situations and can be used to solve the following objectives.

1. Comparative
2. Modeling
3. Optimizing
4. Screening

A comparative investigation is focused on obtaining detailed information about whether the change of a single factor has resulted in an improvement or change to the process as a whole. In the second case, the focus rests on being able to create a mathematical model of the process with an output that has a good level of fitness and a good estimate of coefficients that give the function a high level of accuracy. The goal of the third case is to obtain the optimal settings of the process factors. In other words, the mission is to find out what values each factor needs to be at in order to optimize the process. The fourth and final case is used to understand a process and how the chosen input parameters affect the output. The result is often a ranking of the parameters and how much they change the output of the process.

Select process variables
For the selected process, investigate which input and output parameters are important. Find either previous studies, reports or use empirical data to determine what factors should be chosen and then incorporate them into the list of possible parameters.

Set up experimental plan
Depending on what the objectives are and the number and type of factors to be investigated will decide the way that the experimental plan is set up. The variation and number of factors is put into an experimental plan matrix. Different procedures are used to set the variation limits and factor combinations depending on the sought objectives. Some of these methods will be described in later in chapter3.1.2. There are a wide array of other methods for experimental plans, among them Box Behnken, Taguchi method, Placket-Burman design and Neural Networks which have been considered but discarded since they are not suitable for the purposes of this study. They might however prove relevant in future works.

Execute the experiment design
Run through all the experiments as listed in the plan created in the previous step. This step is usually the most time consuming of all steps since the experiments have to be performed. By choosing the right method and plan, the demand on resources can be minimized while still generating useful data.

Screening of factors
This step is sometimes combined with the next one since it uses the results to see what factors have significant response and are worth looking into more thoroughly. If a factor has a low interaction and impact on the response it is often filtered out to allow for the analysis to focus on the important factors.

Interpretation and analysis of results
Of the factors that pass through the screening phase a rigorous set of statistical analysis tools are employed to evaluate if the interactions and effects are significant or merely anomalies. In most cases there are several factors that contribute and interaction effects between parameters are common.

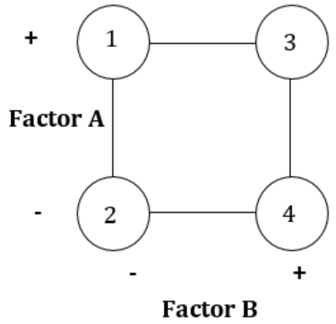
Apply results
The final step is to compare the result with the goal objective to see if the hypothesis has been confirmed or not. Depending on what type of objective was chosen the next step will vary. For instance, if a screening approach was used the next step may be to perform a new set of experiments that narrow down on the most prominent parameters. If the results seem to contradict then a repetition can be used to find the variation of the parameters.

3.1.2. Types of experimental plans

A factorial design in DOE is an experiment plan is a method for examining 2 or more parameters, also known as factors, each with a different set of values, also called levels. By combining factors at varying levels a set of different fractional designs can be created, some of which have special properties and names.

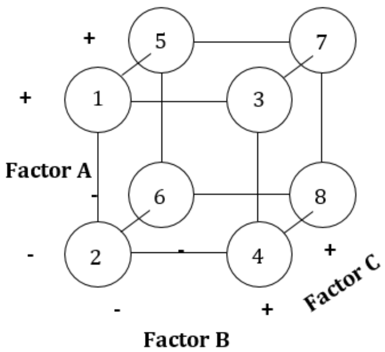
A full factorial design covers all possible scenarios for all factors at a high and a low level (often denoted as + and – signs respectively). In Figure 10, a full factorial design for an experimental setup with two factors at a high and a low level is shown. By using this configuration all parameters are essentially tested, one at a time at different starting conditions. It should be noted that this method is in no means perfect and that if a symmetric function is being tested it will not produce accurate results with only 2 points and would require a different design for its experimental plan.

The advantage of this is that all factor effects and interactions with factors is covered, any increase or decrease in the output can be mapped and the source of the change be found. The drawback of this is that the total number of runs is 2 squared by the number of factors. When several factors are being investigated the number of runs becomes so high that it is often not possible to perform that many experiments either due to lack of time or money. Just increasing the experiment plan to include a single additional parameter would double the amount of experiments needed to make a complete full factorial experiment plan. This increase can be easily seen in Figure 10 and Figure 11.



Run	Factor A	Factor B
1	+	-
2	-	-
3	+	+
4	-	+

Figure 10. An image of a full factorial DoE plan with 2 parameters and its accompanying table of run configurations



Run	Factor A	Factor B	Factor C
1	+	-	-
2	-	-	-
3	+	+	-
4	-	+	-
5	+	-	+
6	-	-	+
7	+	+	+
8	-	+	+

Figure 11. An image of a full factorial DoE plan with 3 parameters and its accompanying table of run configurations

A solution to this is to use a more suitable experiment plan, namely a fractional factorial. The feature of this design is that it allows for several different configurations depending on the type of analysis that is sought. These design are usually classed by level of resolution and generally speaking, a higher level means that you are looking more closely on the effects that each parameter has on one another, called interactions. By deciding on what effects and interactions are sought after and also the number of parameters to be included, it is possible to calculate the minimal number of runs needed.

There are several software packages that feature DoE creation tools and for this specific study the software used was JMP[16]. Not only does it help to create the experiment plan but it can also be used to evaluate the results through the use of a response value.

3.2. Discrete Element Method

The Discrete Element Method (DEM) is a numerical method used to compute the stresses and displacements in a volume containing a large number of particles such as grains of sand. 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.

DEM gives the opportunity to see and study what happens in harsh environments where probes and cameras cannot see or survive, for instance in crushers, ovens, floatation cells etc. It also allows us to calculate the stresses inside rocks and particles and can be used to test new designs and essentially be the first step in prototyping. Friction is idealized, which means there is no energy loss due to heat and nor any breakage due to wear and tear. The large domain of a crusher chamber means that the simulation will be

CPU intensive due to particle amounts and their size. While a CFD coupling is possible, this increases the CPU demand even more, so in this study the air flow effects have been excluded.

In situations where a process needs to be simulated several times, it is possible to save time by exporting conditions where a steady-state has been achieved. Steady-state is reached when the number of particles in the simulation has reached a relatively constant level, as seen in Figure 12. The simulations after the first one will start with a high number of particles and thus eliminating the need to simulate the starting time required for filling the simulation. This saves considerable amounts of time, especially if one has a lot of runs of simulations.

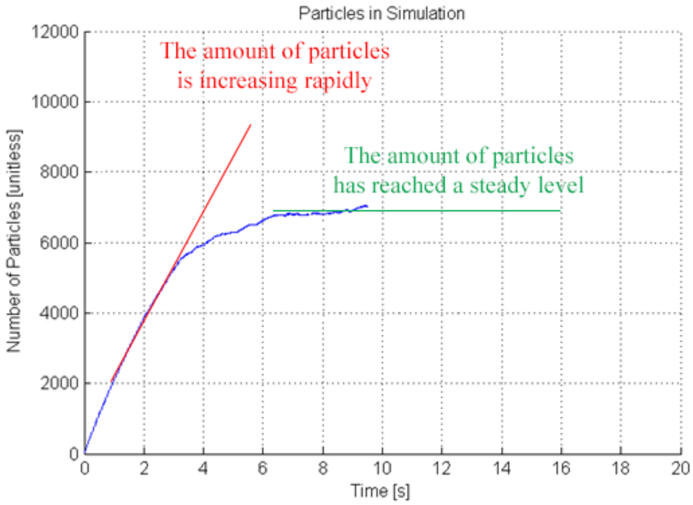


Figure 12. A graph of the number of particles in the simulation any time. The red and green lines show the inclination, in other words, the rate of increase of particles over time.

3.2.1. Physical modelling of real objects and geometries into DEM simulations

In order to apply the mathematics to real world objects, a transformation has to be made. The geometry of the objects needs to be presented as mathematical equations, in other words they need to be made into CAD geometry which is then used in the simulation to represent different objects.

Each particle in DEM is represented through spheres, ellipses or rounded cubes in a single instance or consisting of a cluster of particles. By increasing the amount of basic geometric shapes used to represent a particle, it is possible to increase the level of resolution. However, the more shapes used to represent a particle, the more demanding the simulation becomes. One of the particle types used in this study can be seen in Figure 13.

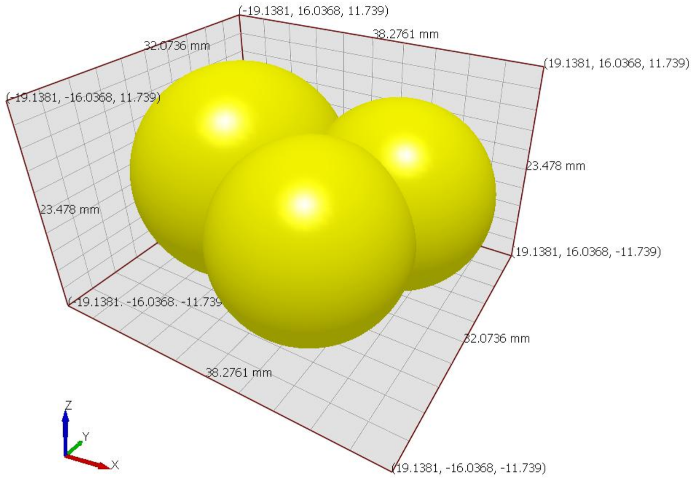


Figure 13. A rock particle represented by 3 spheres in a DEM model.

The Hertz-Mindlin contact model in a non-slip configuration is the default model used within EDEM simulations. It is a non-linear elastic model and is thus well suited to the non-cohesive interactions which are used within the computational models. The model uses a spring-dashpot response to normal contact between particles and geometry and a Coulomb friction coefficient $\mu$for shear interactions and a second spring-dashpot response to tangential or rolling friction interaction.

This model tends to produce the most accurate results however can be computationally expensive to implement due to the smaller time step required as compared to other models. EDEM has a set of built-in models such as *Linear Cohesion* which is useful when it comes to simulating sticky particles and *Hysteric Spring* which allows for plastic deformation in simulations. There is no general consensus on which contact model is the better one but they are often seen as having different application areas[17].

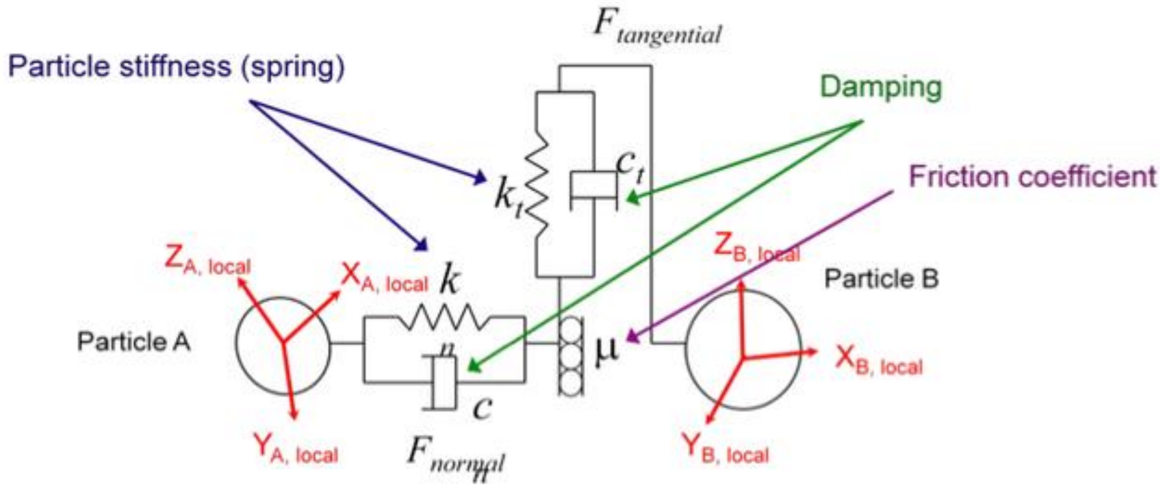


Figure 14. Hertz-Mindlin contact model. Spring dampener configuration. Figure courtesy of EDEM Technical Overview [17].

3.3. CAD modeling

The purpose of CAD modeling is to have a good coupling to reality while also being able to make changes to the measurements and parameters of the model. This means it's essential to have a reliable and structured base for the CAD geometry.

The goal is to create a geometry that is fitted for use in DEM and that also accurately replicates the size and relationships of the crusher and its components. By ensuring that the size matches similar machines in use, validation experiments to help our analysis of the test is possible in the future.

Modeling of the VSI chamber geometry was initially done with drawings, pictures and technical manuals as reference material. The combined information found in these gave a good overview but due to concerns from most crusher manufacturers, there are rarely, if ever, any measurements in the material provided at time of sale.

3.4. Data acquisition

A planned visit to the crushing pilot plant to measure a Metso Barmac 5100 SE VSI crusher and its components was performed early on in the project in Gävle, Sweden, where a mobile crushing plant was currently deployed. The purpose of this visit was to compare the current drawings with an existing crusher.

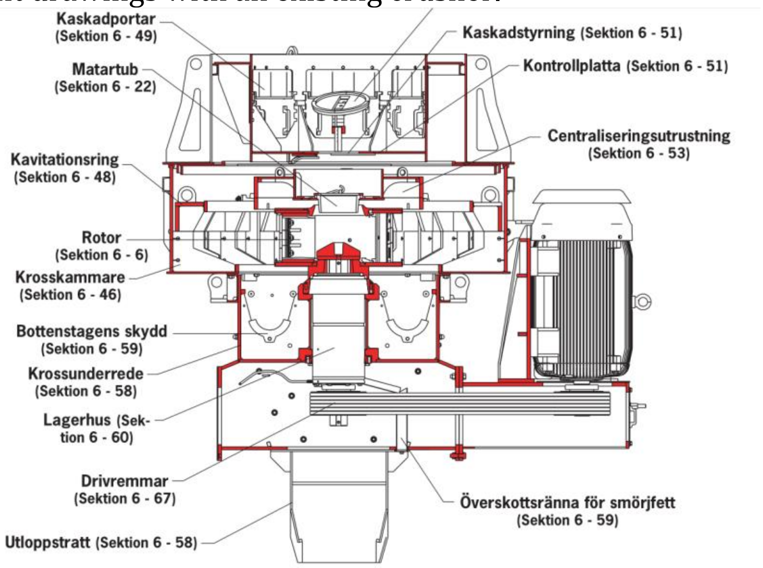


Figure 15. A sketch of the cross section of a VSI crusher

By using a ruler, a Vernier caliper and tape measure on the components one by one, all the sizes and relationships were obtained. The reference material was useful in providing information about the different relationships between components but some components were shown to be inaccurately depicted in the drawings and this knowledge was put to use in updating the drawings.

3.5. Simulations

DEM is useful when there is a need to observe properties that occur in areas that do not allow direct measuring during operation. This can be compared to CFD simulations and their calculations that are used in areas of high turbulence. The presence of a probe or sensor could also have such a negative factor that the retrieved data is, for all intents and purposes, useless when it comes to investigating the normal case.The environment might also be harsh and destructive, meaning that any equipment needed to measure a certain property would be lost before or in the process of retrieving the data.

3.6. DOE matrix and parameter choice

For this study, only the main effects of each parameter is of particular interest which is why a resolution of 3 has been chosen. This will allow us to estimate the main effects but leave two-factor interactions outside of reach. The second choice will be how many parameters to use. For this study, a total of five factors were chosen to be an adequate amount. This results in a 2^{5-2}fractional factorial experimental design of experiments plan seen in Table 3.

Table 3. The general outline of the Design of Experiments plan used for this study. The + and – signs represent high and low values for each factor respectively.

Run	Factor A	Factor B	Factor C	Factor D	Factor E
1	+	+	+	+	+
2	+	-	+	-	-
3	+	-	-	+	+
4	-	+	+	-	+
5	-	-	+	+	-
6	-	-	-	-	+
7	-	+	-	+	-
8	+	+	-	-	-

The next step was to choose specific parameters and their high and low values. With knowledge from the literature read and discussions with experienced individuals, the parameters to be studied were exit angle, rotor radius and number of exhaust ports and tip speed of the rotor and also the static friction value for the material beds.

The original value of the exit angle for the Metso Barmac VSI crusher was established through simulations and then set as the highest value. The lower value was set as 10 degrees less. The lower value for rotor radius was taken from measurements and the higher value was based on the surrounding geometry limitations and set so that a real world rotor of similar size could fit inside the crusher. The number of exhaust ports vary between 3 or 4 and the friction values are either 0.4 or 0.5.

It is important to note that since the rotor tip speed is usually controlled by the revolutions per minute and the rotor radius, the RPM is corrected when the radius is changed to ensure that the rotor tip speed remains the same. The final values for all the parameters can be seen in Table 4.

Table 4. The final DOE fractional factorial experimental plan for 8 runs of simulations

Run	Pattern	Exit Angle (Degrees)	Rotor Tip Speed (m/s)	Rotor Radius (mm)	Exhaust Ports (Unitless)	Static Friction (Unitless)
1	+++++	50	70	300	4	0,5
2	+-+--	50	50	300	3	0,4
3	+--++	50	50	255	4	0,5
4	-++-+	40	70	300	3	0,5
5	--++-	40	50	300	4	0,4
6	----+	40	50	255	3	0,5
7	-+-+-	40	70	255	4	0,4
8	++---	50	70	255	3	0,4

The first simulation was run without any particles present at first while the following ones were partially filled with simulation decks from the first simulation to save resources as explained in the chapter Discrete Element Method3.2. Once these were all finished, the next step was to extract the relevant data.

3.6.1. Data export and Data restructuring

The EDEM software has an export function but it is not customizable to the degree that was needed the purposes of this thesis. This meant that a script or program had to be written to handle the large amount of data points that the program would create. The whole process has been divided into several stages and will be described below.

There is a built-in tool used to export the data into a file of Comma-Separated Values (CSV) with the help of queries. By using the query function it is possible to retrieve the important attributes of all the particles like their collision coordinates, relative velocity at the time of impact, their mass and unique ID number.

The problem is that the data is not structured in a fitting way to allow data interpretation. In order to rectify this, a set of Matlab scripts were created to read, order and write the data to an excel file. Each CSV file that EDEM creates is given a header of information about the queries it contains. This information is the first to be read by the script and each query is assigned a sheet in the excel workbook to allow writing in the next stage.

Following this, the script starts to read from the top and going down until it reaches the end of line flag at the bottom. Along the way it will find query data for each time step included in the exported data, sort it so each data point gets a unique data field in its respective excel worksheet and finally write it out. The end result is a neatly sorted matrix of data for the different queries.

4. Results

From the beginning of the project, the only available source of material to estimate measurements from was reference drawings and photographs. This created a good starting point for the project and also resulted in the first CAD model of the VSI crusher and its components. Drawings created from this first model were printed on paper for all the parts and brought along to the crushing site to assist in the data gathering process. This provided a good schematic for writing down actual measurements and minimized the time needed at the site.

The visit to the crushing plant yielded data that confirmed some of the measurements and assumptions made. For instance, the number of exhaust ports and the radius of the rotor but overall most measurements had to be corrected. It was also discovered that some components were lacking or different from the drawings. The drawings were evidently of another size of crushers of the same model which is why some configurations of components in the drawings did not match up with reality. A new CAD model was created to more accurately represent the crushing chamber and the rotor. A comparison shot of the rotor changes can be seen in Figure 16.

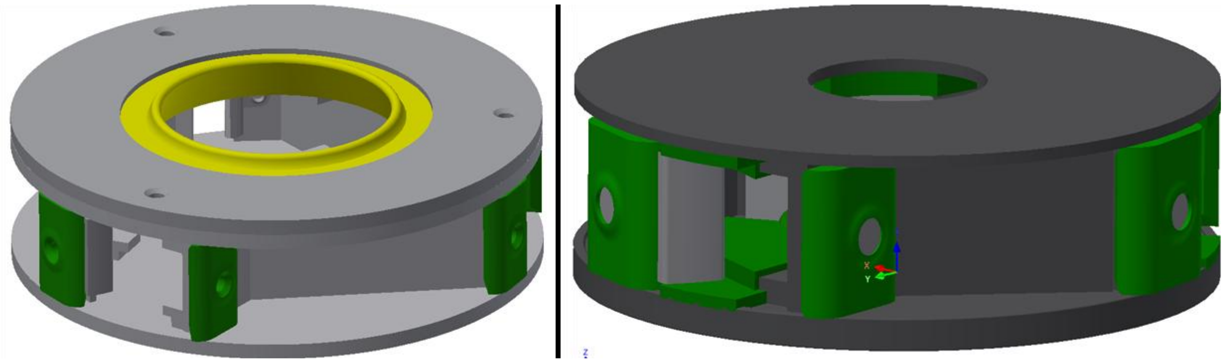


Figure 16. On the left is the first CAD model of VSI rotor on the right is the second CAD model of VSI rotor

Even if the new data provided a more accurate model it is important to note that since the measuring was done with tools, that measure from point to point, there is a limit to the resolution of the data and some phenomena is not captured. For instance, the variation in thickness of components and varying amounts of wear is not captured with this type of measuring.

Wear is common in crushers and it is more prevalent on certain components and leads to changes to the geometry during the lifetime of a component. These changes can lead to a change in the behavior of particles being crushed and thus the resulting product from the crusher. Wear is however a phenomenon that occurs after prolonged usage and not simply after a few seconds of operation. Since our simulations are limited to relatively short time spans, no consideration for the change of the geometry due to wear is made.

Due to the complexity of simulations, it was important to see if any simplifications could be made in order to reduce the resource needed without changing the results of the simulations. The first simulation was run in order to see if the material bed that forms in the rotor is reasonable and if the particle trajectory according to Rychel [11] can be accurately modeled.

By feeding material into the center of the rotor and letting it spin at speeds equivalent to 70 m/s in rotor tip speed, it was possible to build up material in the rotor. The filling of the rotor as a function of time can be seen in Figure 17, which captures the rotor filling at the early stages of the simulation. By plotting the rotor from above at different times, it was possible to see what bed levels had been achieved at different times and this is shown in Figure 19.

What can be seen is that in very short time, the rotor is filled with material and particles can start to flow freely through the rotor and into the crushing chamber. The formula used to calculate particle trajectory path is found in Equation 1 where r_1 is the inner radius of the rotor is, r_1 is any given radius of the rotor and ψ is the angle of curve compared to the tangent of the rotor radius. In this study, this angle is assumed to be constant.

$$\phi = \frac{\log\left(\frac{r_1}{r}\right)}{\tan(\psi)} \quad \text{(Eq.1)}$$

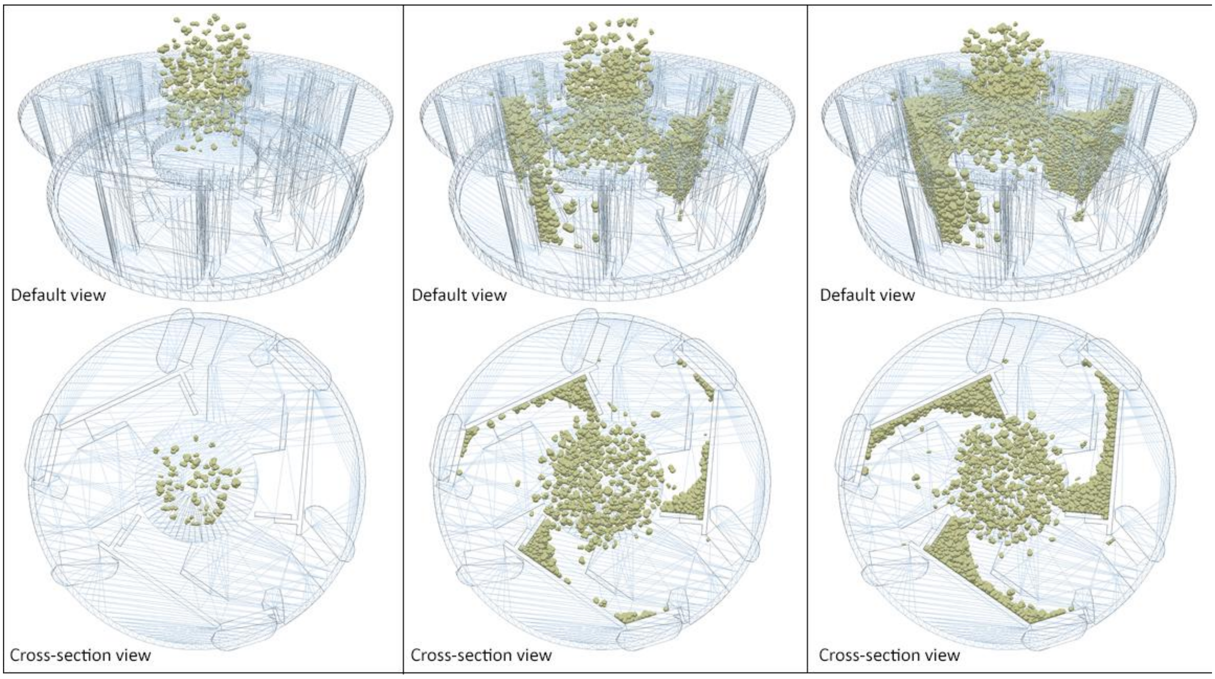


Figure 17. Rotor bed filling with particles with respect to increasing time from left to right.

The particles that make up the material bed inside the rotor however, become a problem. While the rotor is spinning, the trapped particles have a very low chance of getting out into the rotor. Sincethe simulationswill only be running for small amounts of time and the rotor will always be running at a constant speed, the trapped particles can be considered to be a part of the rotor geometry.

In Figure 18 a cross-section view of the rotor after 2 seconds can be seen. The particles are colored according to what point in time they were created. The first layer build up consists of the very first particles and as time passes by new layers are added and particles become trapped inside the rotor bed. There is a symmetric appearance to the exhaust ports and this means that it is enough to investigate a single rotor bed and exhaust port. This focus is shown in Figure 19.

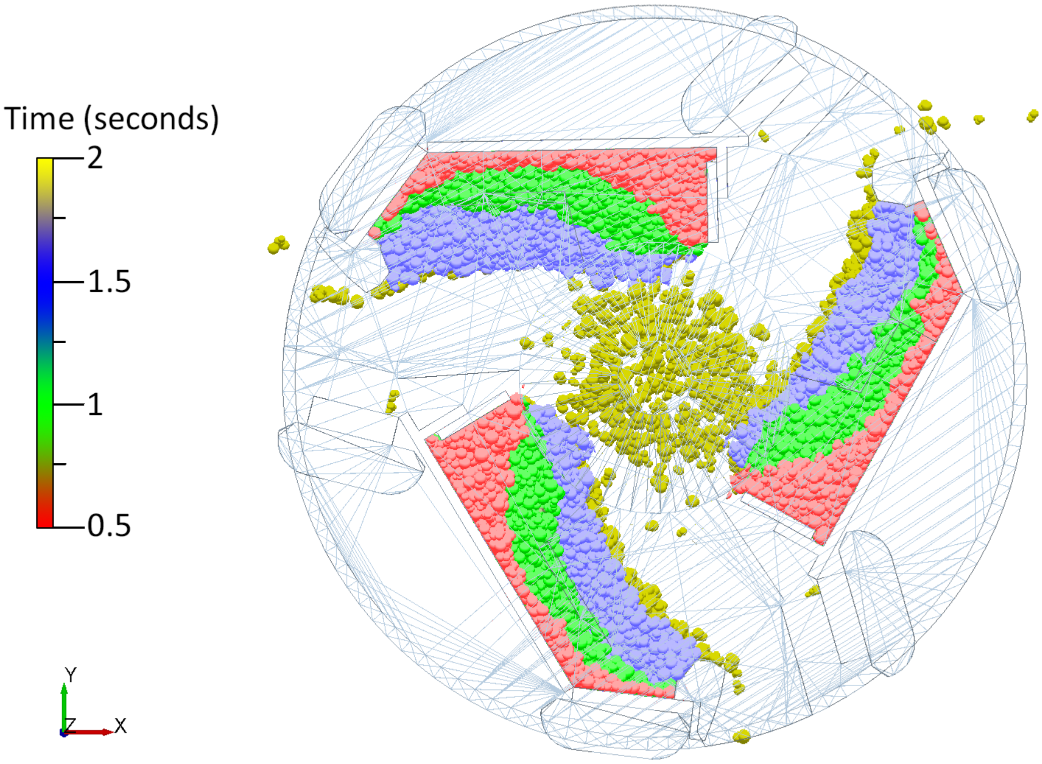


Figure 18. An image depicting the simulation of filling of a rotor inside a VSI with regards to time.

By extracting the exit angle of the rotor and creating a rotor with a solid material bed, the resources needed to run the simulationscan be reduced since a significant amount of particles have been removed. In this stage, a lot of components and details that have no impact on the crushing of the particles was removed or reduced leaving us with a rotor that has no unnecessary components. It is important to note that these components are necessary for a particle bed buildup but that they can be eliminated in order to save CPU resources.

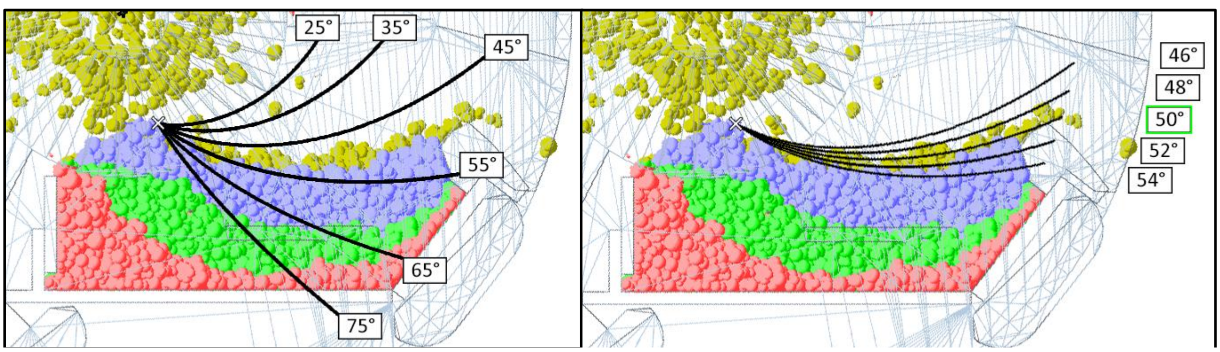


Figure 19. Depiction of one of the rotor exhaust ports and its particle bed. The black lines are Rychel curves with different angle values. The image to the left was the first rough analysis and the second one with a narrower spectrum. The angle was determined to be 50 degrees.

The resulting rotor designs can be seen in Figure 20, although the top has been cut off to make viewing of the insides possible. There are 8 different models to correspond to the

8 different simulations that will be run. They have different radii, exit angles and number of exhaust ports. These are listed in the figure.

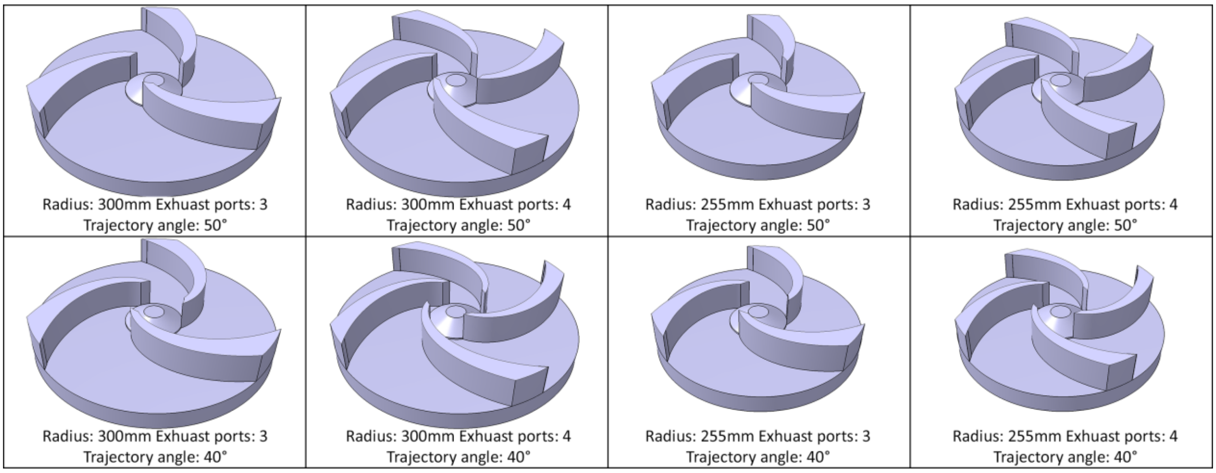


Figure 20. The 8 different rotor configurations that each corresponds to one of the DOE settings.

Now once the dead volume inside the rotor has been dealt with, a similar challenge inside the crushing chamber needed to be addressed. The chamber features large pockets in which material is accumulated to form the material bed. A simulation was run in order to try and fill this volume but it was never run to completion since the resources needed were proven to be too large.

The amount of particles needed to fill the space was too large and would require more storage space, computational power and time than was allotted for this project. Another approach was needed in order to reduce the complexity of the material bed in the crushing chamber. Having predicted that the material bed in the crushing chamber would pose some challenges, significant care was taken when photographing the components. Reference items, such as a ruler seen in Figure 21, were placed in the scene to get a sense of scale of the surrounding objects. An example of this can be seen in Figure 21.

Figure 21. Three different representations of the VSI crushing chamber material bed.The left-most image is a sketch of the material bed, the middle one is a photograph of a cross section of the material bed and the last image is of the CAD geometry made to represent the material bed and partially hidden to reveal to geometry underneath.

By using these images and the CAD geometry as a reference it was possible to create a solid material bed. The bed is rotationally symmetric which leads to a less realistic model and its impact on the results needs to be considered. The resulting crushing chamber can be seen in Figure 21where a section of the material bed has temporarily been removed in order to be able to see the crushing chamber underneath.

The differences from having a bed full of particles and a solid geometry will, similarly to the bed in the rotor, probably cause the results to be changed in some way. The scale of this is hard to determine but will be discussed in the conclusions chapter. With the VSI geometries made into more manageable entities it was now possible to proceed to the next stage of simulations, namely running the 8 simulation DOE test plan.

In order to capture the effects of a VSI as it is often run in operation, the crusher needs to be started,fed material through it and achieve a state where the number of particles inside the simulation is more or less constant. This is called a steady-state and this equilibrium is created when the flow into the system is equal to the flow out of the system. Once such a state is reached, data gathering from the simulations can be started.

While the number of particles is a good measure to use when establishing the steady-state of a VSI, there will always be a variation in this level since the material flow is regulated against a constant target mass while the particle sizes are normal distributed. So a decrease in the number of particles inside the crusher does not necessarily to a equate to a decrease in mass.

Since the data from the simulation prior to reaching steady-state won't be used, there is a desire to minimize the time each simulations needs outside of this state. By saving the position of all particles in the first simulation that was run and exporting it to the next run, a considerable amount of time is saved. Shown in Figure 22 is the number of particles in the simulation at any time in each simulation and it can be seen that every single simulation starts at around 6500 particles present in the simulation from the start while only one has to start at 0.

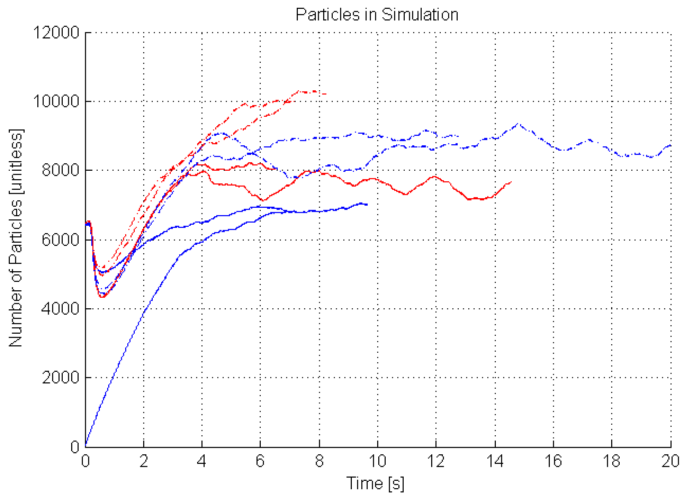


Figure 22. A graph showing the number of particles at any time for each simulation.

Given that each simulation will have the same feed and that they all have to reach steady state, it is shown that 6 seconds of simulation time per run has been saved this way. This equates to around 49 seconds of simulation time and although the start of a simulation with few particles will be the least computationally demanding parts of any simulation it is still a considerable amount of real time that has been shaved off from the resource demand of this project with little impact on the results. The first 6 seconds of simulation took 68.3 hours of computation time, which means that a total of 478 hours of computation time was reduced.

After a few weeks, the simulations had all been run through and the data export process was started. The first step was to retrieve all the sought data from EDEM with its built-in export tool. This produced a comma separated values file for each simulation with 3 properties for every single particle and 7 properties for each single collision event. The exact properties that were extracted can be seen in Table 5.

Table 5. A table of all the properties extracted from the simulations.

Entity	**Properties**
Particle	ID number, Volume and Mass
Collision event	ID number 1 and 2, X, Y & Z coordinates, Relative velocity magnitude and Total energy loss.

Due to the fact that the number of collisions and particles in a simulation is high, the resulting raw data files will be very large and makes manual post-processing impossible. So in order to handle the data, several scripts were written and deployed in Matlab.

The first script extracts the data from the originating file and splits it up into 16 different files that each have the one property stored in it and the individual time steps. This is a critical step since the amount of working memory is limited and cannot hold all the data simultaneously. By dividing up the data it is possible to select the data that is needed at any given time.

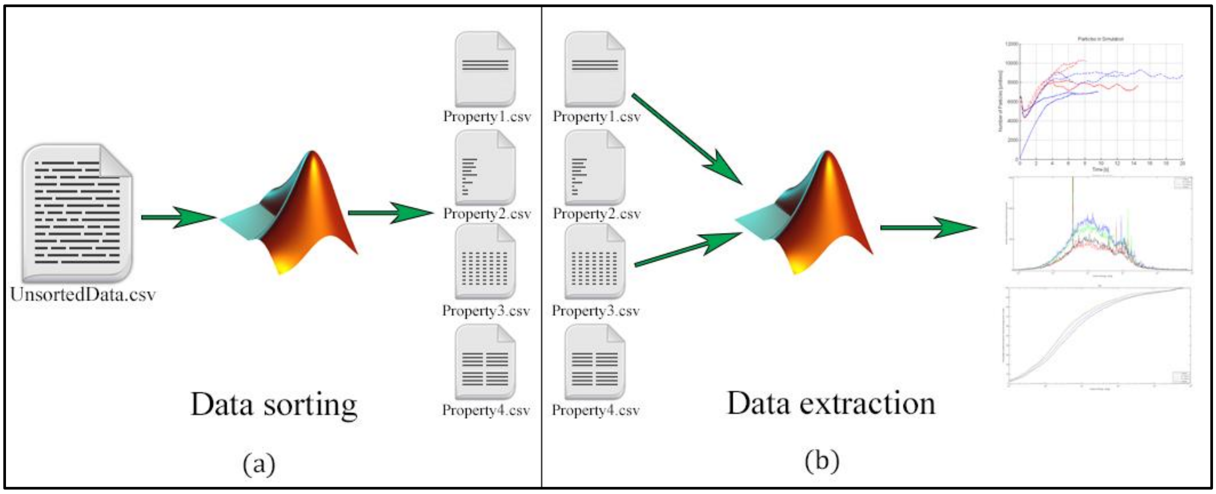


Figure 23. A visualization of (a) the datasorting and (b) dataextraction process.

The second scriptprocesses the data and creates a reference list of all the unique particles containing their ID, volume and mass. The script also assigns the size of each particle and the type of rock shape used.

The third script, similarly creates a list, but is instead of all the collision events that occur in the simulation. By having these lists created it is possible to filter out and investigate different particle groups or behaviors in the crusher. There were some particles that exhibited extreme values which resulted in an outlier analysis and data filtering. In Figure 24 the number of collisions for each unique particle can be seen both before and after the outliers have been removed.

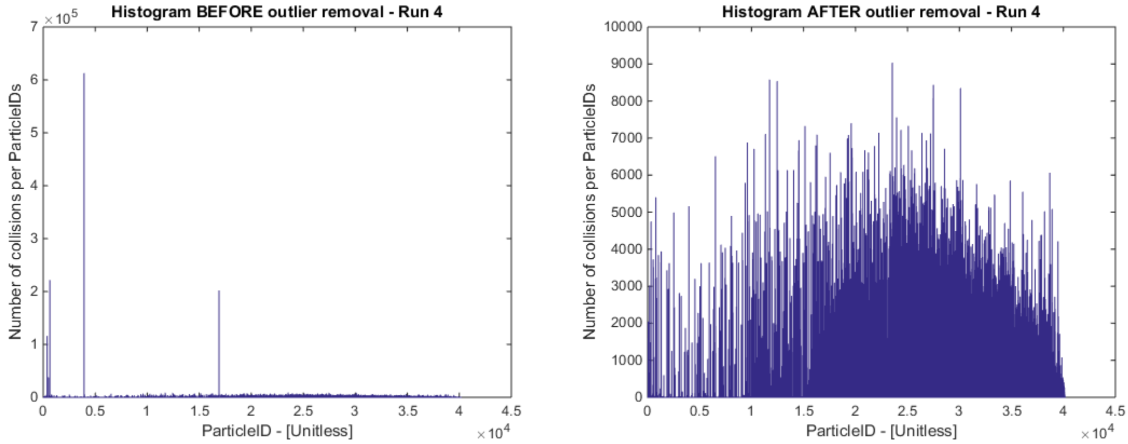


Figure 24 Left: The number of collisions for each unique particle before outliers. Right: The number of collisions for each unique particle after outliers have been removed.

During the initial stages of the project, several papers and articles were read to gain a better insight into common tools and presenting techniques used to display results from VSI crushing. One significant paper was that of Vogel and Peukert where they create mastercurves for probability of total breakage of particles at varying collision energies and particle size[18].

Two distinct graphs have been created for this work and their principal form can be seen in Figure 25. The first one displays the frequency of collision energy for a particle and the second one display the same data but in a cumulative manner similar to Vogel and Peukert.

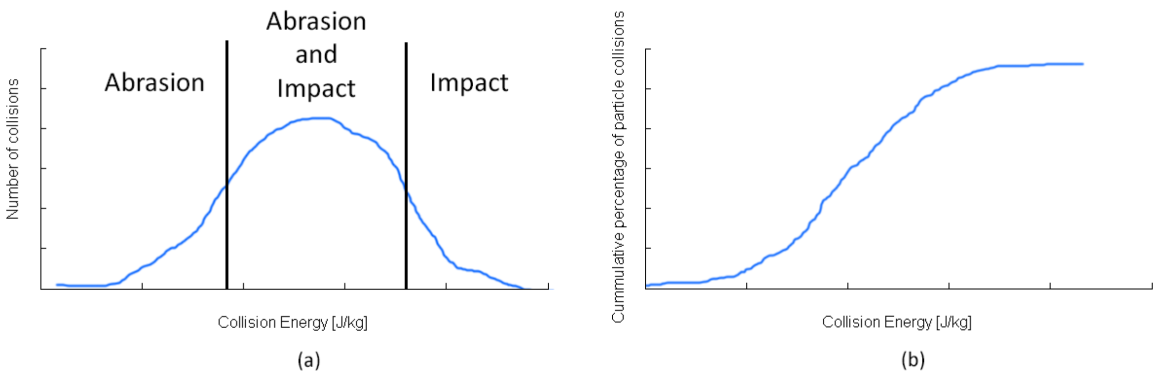


Figure 25. (a) A principle distribution of collision energies and what type of breakage they will result in. (b) A principle distribution of frequency of collision energy for a particle.

One important difference to point out is that Vogel and Peukert look at only one collision at a time while this thesis looks at all the collisions a particle goes through. As can be shown in the illustration in Figure 26, Vogel and Peukert's work only looks at single impacts and whether or not they lead to particle breakage while this work tracks the particles path through the crusher and its chamber recording every collision.

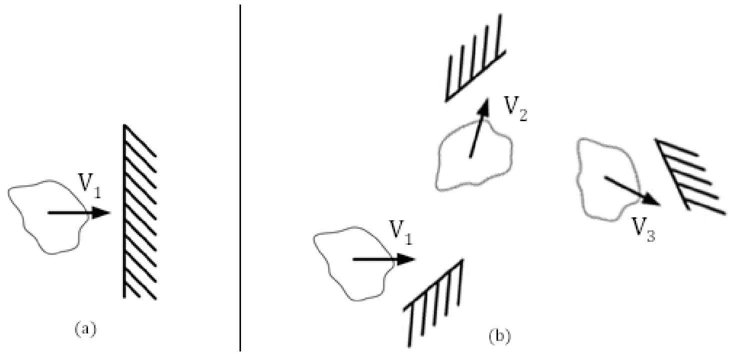


Figure 26. A particle being tracked and exposed to (a) a single impact and (b) several consecutive impacts.

For the different graphs there has also been a classification of particles with regards to size. Four size groups for the particles have been created and these are 8-10mm, 10-12mm, 12-14mm and 14-16mm with respect to the particles second largest dimension. The results from some selected simulations are shown in Figure 27, Figure 28and the rest of them can be found in the appendix.

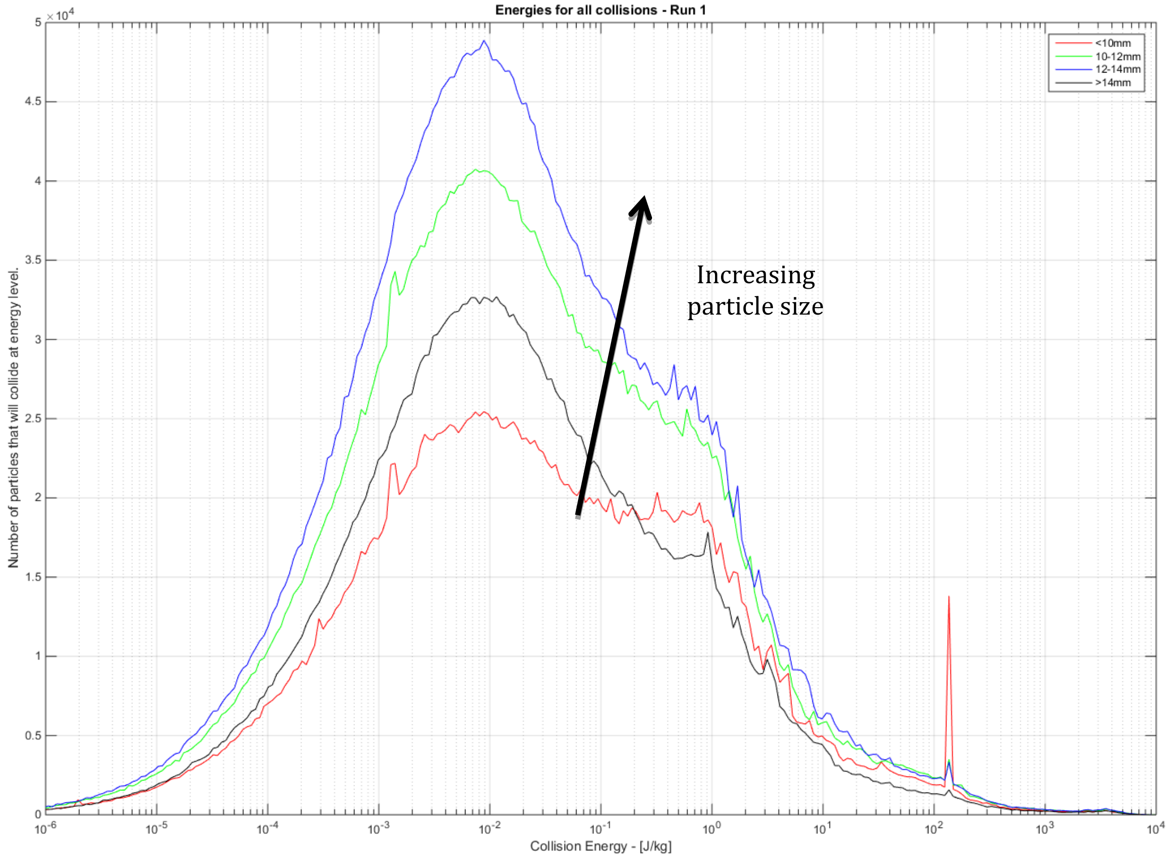


Figure 27. A frequency plot of collision energy for different sizes of particles.

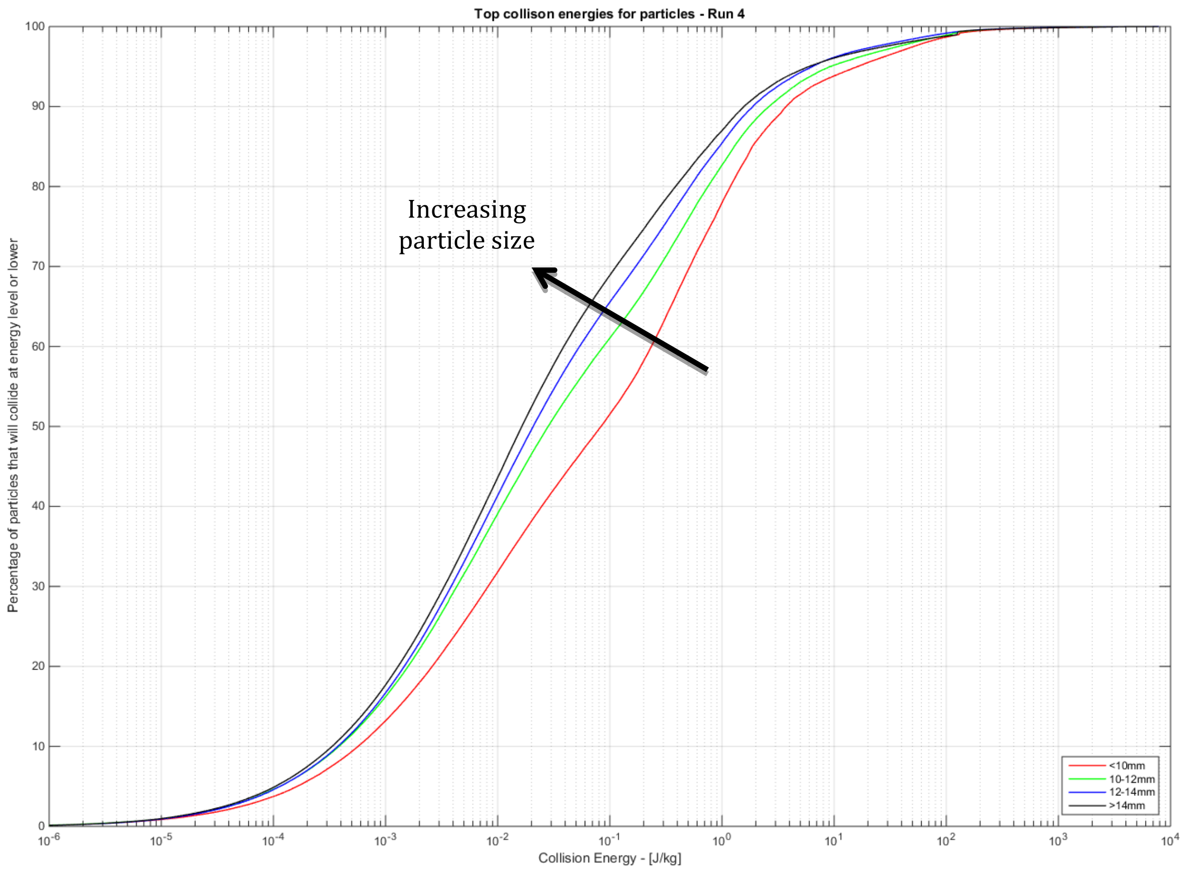


Figure 28. A cumulative plot of collision energy levels for different sizes of particles.

5. Conclusions

The start of this project was focused on investigating if the rotor design and its operating parameters could be changed in order to improve the particle breakage. As has been established in previous works, low energy that does not cause total particle breakage can still change the shape of the particle to a certain extent.

From the set of graphs that have been plotted, it is clear that the majority of collisions occur at low energies and if total breakage requires higher levels of energies, it can be concluded that the most dominant event in these areas is abrasion and chipping. This action will create particles that have a smoother and smaller area than when the particles first entered the crusher.

It is important to note that although low energies drastically reduce the chance for total particle breakage it is never impossible. A particle has a chance to collide at an optimal angle and thus making contact with a cross-section of low area and thus resulting in breakage despite low energy levels. This chance is low but is never the less always present.

5.1. Evaluation of Research questions

In the beginning of this study two research questions were asked in order to guide the process and these were the following:

RQ 1: How does the geometry of the rotor affect the particle breakage inside a Vertical Shaft Impact Crusher?

RQ 2: How do the operating parameters of a VSI affect the particle breakage and angle of impact inside a Vertical Shaft Impact Crusher?

From what can be seen from the graphs and the results, there is little to no effect from changing the number of exhaust ports. This makes sense, since the total flow of material remains constant and the particles are still flung out of the rotor.

While it seems that the number of exhaust ports is not critical to the collision events of the particles, it should be noted that more exhaust ports will mean that the maximum size of particles that can possibly pass through the rotor is reduced. More ports also carries with it an advantage, and that is that wear effects will take more time to present themselves since the same material is spread out over more ports.

By looking at the cumulative frequency of collision energy levels we see that smaller particles have a higher probability to occur at higher energy levels. This means that smaller particles have a greater chance to suffer total breakage while larger ones exhibit a lower chance for total breakage.

By designing the experiments in a screening manner, the aim was to be able to easily tell what parameters affect the particle breakage and the angle of impact inside the vertical shaft impact crusher. An issue that quickly became apparent is that the lack of a clear target or variable to be able to compare experiments with each other makes a parameters analysis challenging.

By checking several values from each experimental run a certain set of conclusions were drawn. The number of ports and the static friction seem to have little to no effect on number of collisions, while the most significant parameter seems to be the rotor tip speed followed by the radius of the rotor. When it comes to affecting the angle of impact, the most important parameters is to change the exit angle of the exhaust port.

5.2. Future work

There are a few things that were found during this thesis but that has been to demanding to solve at this juncture or simply outside of the scope. For instance, the impact of using a solid geometry with a fixed friction value for the entire surface might create some issues since a real material bed consists of an ever changing volume that is replaced with new particles as it is worn down.

Wear on components is another common phenomenon in crushing that could have significant effects on particle breakage but the differences between a brand new rotor and a worn out one will have to be studied at a later time. This also included the task of creating a predictive model for breakage of particles in a VSI and running verification experiments.

6. References

1. Norlin, L., et al. *Grus, sand och krossberg 2012*. 2014.
2. Langer, W.H., *Natural aggregates of the conterminous United States*. 1988: US Government Printing Office.
3. Bengtsson, M. and C.M. Evertsson, *Measuring characteristics of aggregate material from vertical shaft impact crushers.* Minerals Engineering, 2006. **19**(15): p. 1479-1486.
4. Quiroga, P.N. and D.W. Fowler, *The effects of aggregates characteristics on the performance of Portland cement concrete*. 2004, International Center for Aggregates Research, University of Texas at Austin.
5. Gonçalves, J.P., et al., *Comparison of natural and manufactured fine aggregates in cement mortars.* Cement and Concrete Research, 2007. **37**(6): p. 924-932.
6. Association, N.R.M.C., *Concrete CO2 Fact Sheet [Internet]*. 2012, National Ready Mixed Concrete Association: Silver Spring, MD.
7. Agency, S.E.P., *Sweden's environmental objectives – Are we getting there? De Facto 2004*. 2004. 101.
8. Government, S., *Swedish statute book - Environmental Code (1998:808)*, M.-o. energidepartementet, Editor. 1998.
9. Göransson, M., *Ersättningsmaterial för naturgrus.* 2011.
10. Lee, E., *Optimization of Compressive Crushing*. 2012: Chalmers University of Technology.
11. Rychel, R., *Modellierung des Betriebsverhaltens von Rotorschleuderbrechern.*2001.
12. Unland, G. and Y. Al-Khasawneh, *The influence of particle shape on parameters of impact crushing.* Minerals Engineering, 2009. **22**(3): p. 220-228.
13. Bengtsson, M. and C.M. Evertsson, *Modelling of output and power consumption in vertical shaft impact crushers.*International Journal of Mineral Processing, 2008. **88**(1): p. 18-23.
14. Quist, J. and M. Evertsson, *MinBaS II - Projekt 1.4.1 Krossteknik för produktion av fina ballastfraktioner till betong.*2010.
15. Unland, G., *The principles of single-particle crushing.* Handbook of Powder Technology, 2007. **12**: p. 117-225.
16. *1989-2007*. SAS Institute Inc.: Cary, NC.
17. Solutions, D., *EDEM 2.6 Theory Reference Guide.* 2014.
18. Vogel, L. and W. Peukert, *Breakage behaviour of different materials—construction of a mastercurve for the breakage probability.* Powder Technology, 2003. **129**(1): p. 101-110.

7. Appendix

This section will briefly introduce the work that Peukert and Vogel have done, describe the different equations used in the Hertz-Mindlin contact model and lastly it will detail all of the results from all the simulations.

Vogel and Peukert have created curves for breakage behavior for single particle breakage for different materials and have then, through experiments, retrieved data points for the different materials. These curves can be seen in Figure 29 underneath.

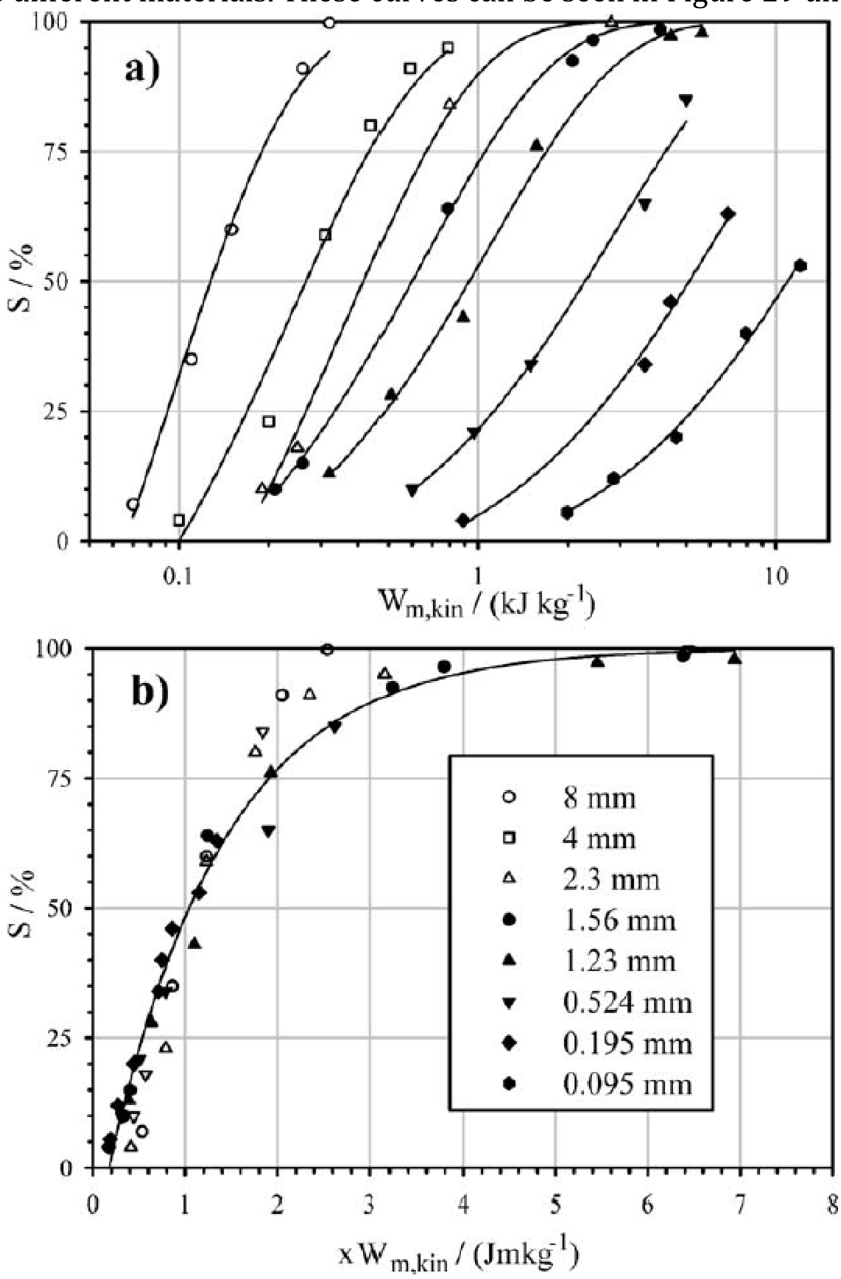


Figure 29.Breakage probability of glass spheres as a function of the impact energy and initial particle size.

Equations for the Hertz-Mindlin contact model

The normal force is directly related the normal overlap, δ_n, given by

$$F_n = \frac{4}{3} E^* \sqrt{R^*} \delta_n^{\frac{3}{2}}$$

And the normal dampening force is

$$F_n^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{S_n m^*} v_n^{\overline{rel}}$$

where the equivalent Young's modulus E^*, equivalent radius R^*, equivalent mass m^*, dampening coefficient β, and normal stiffness S_n are given by

$$\frac{1}{E^*} = \frac{\left(1-\nu_i^2\right)}{E_i} + \frac{\left(1-\nu_j^2\right)}{E_j}$$

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j}$$

$$m^* = \left(\frac{1}{m_1} + \frac{1}{m_2}\right)^{-1}$$

$$\beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}$$

$$S_n = 2E^* \sqrt{R^* \delta_n}$$

The letters *i* and *j* are indexes for the spheres that are in contact. The tangential force is directly related to the tangential overlap, δ_t, given by

$$F_t = -S_t \delta_t$$

And the tangential dampening force is

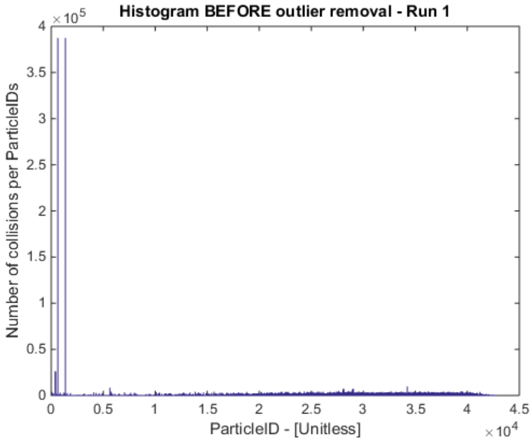
$$F_t^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{S_t m^*} v_t^{\overline{rel}}$$

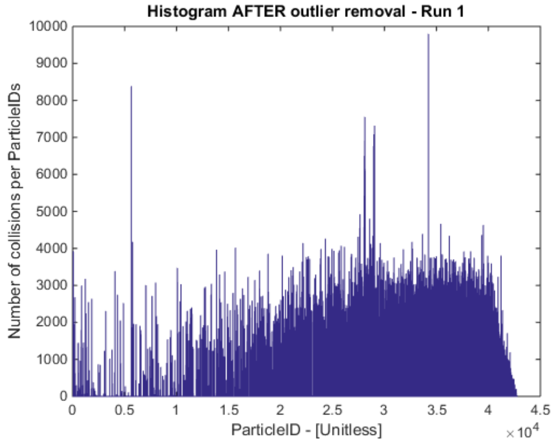
where the tangential stiffness, S_t, is given by

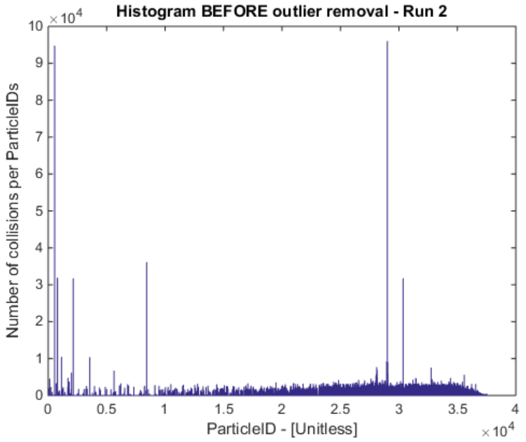
$$S_t = 8G^* \sqrt{R^* \delta_n}$$

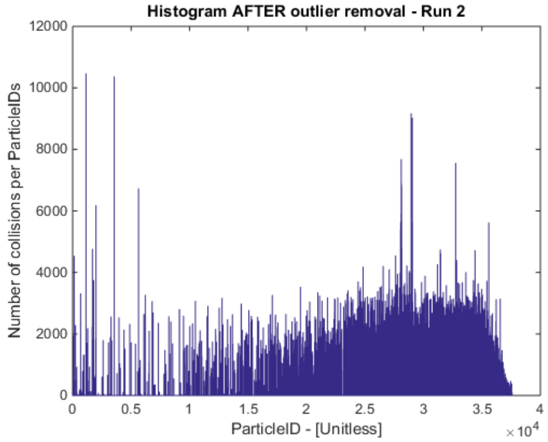
$$\tau_i = -\mu_r F_n R_i \omega_i$$

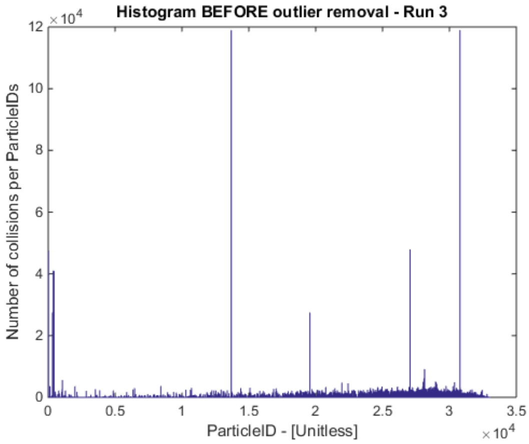
Outlier removal before and after analysis for Run 1 through 8

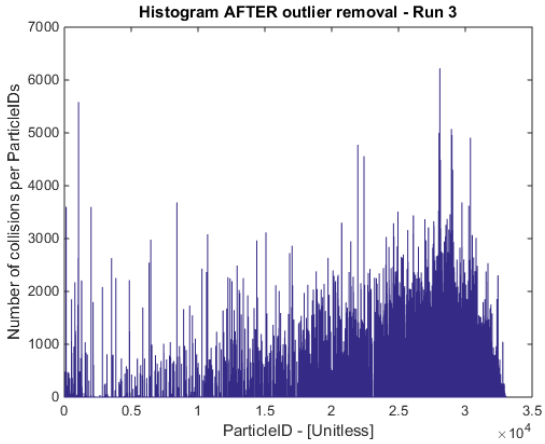


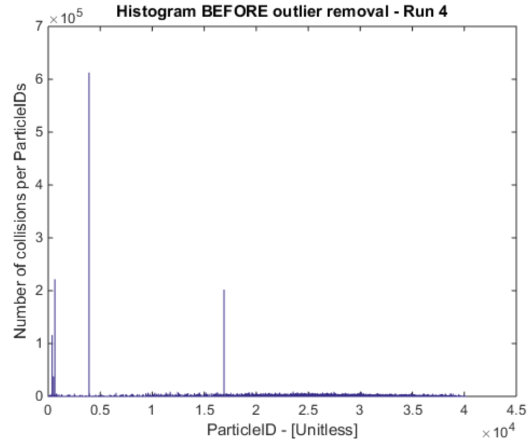








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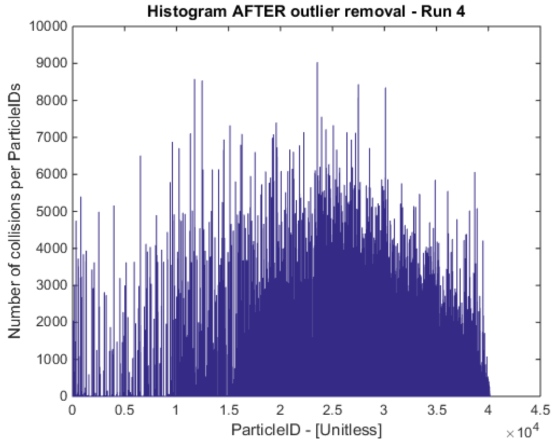
Number of collisions per ParticleIDs
ParticleID - [Unitless]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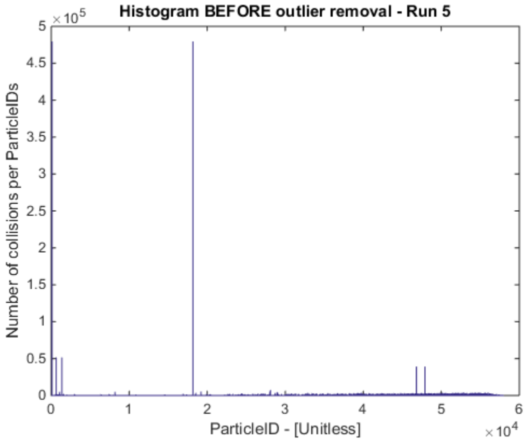
Number of collisions per ParticleIDs
ParticleID - [Unitless]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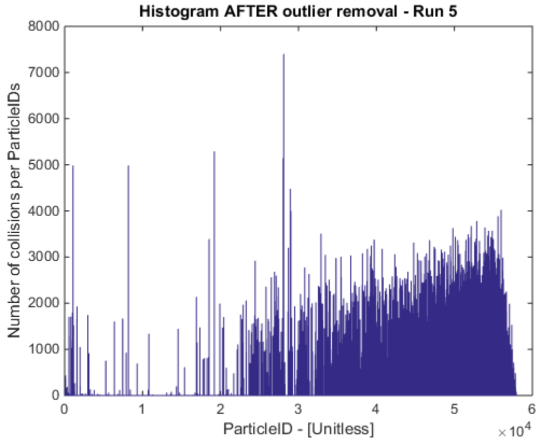
Number of collisions per ParticleIDs
ParticleID - [Unitless]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Number of collisions per ParticleIDs
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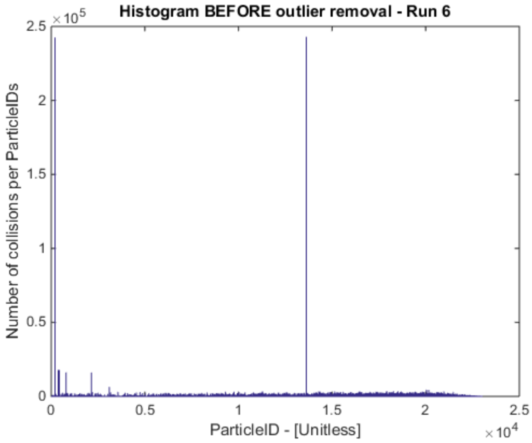
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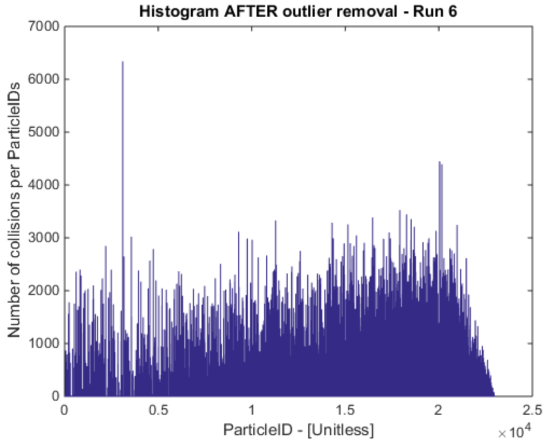
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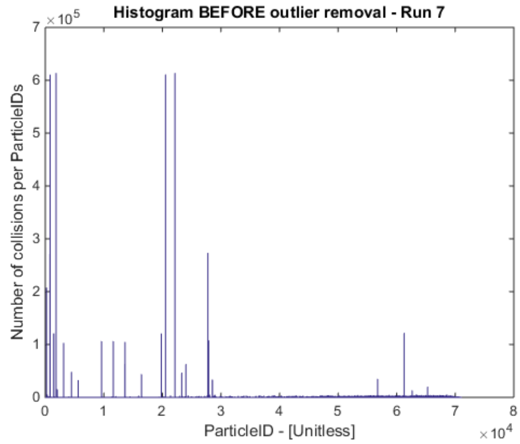
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Number of collisions per ParticleIDs
ParticleID - [Unitless]
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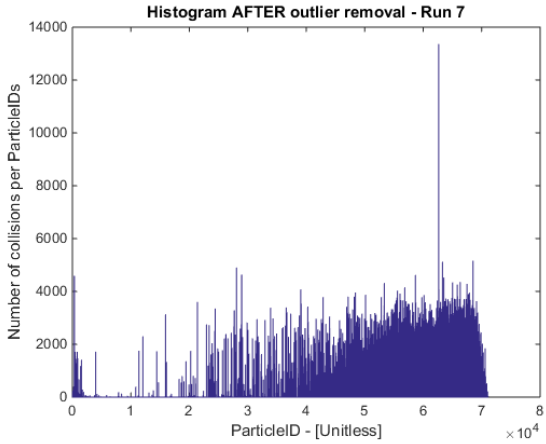
×10^4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Number of collisions per ParticleIDs
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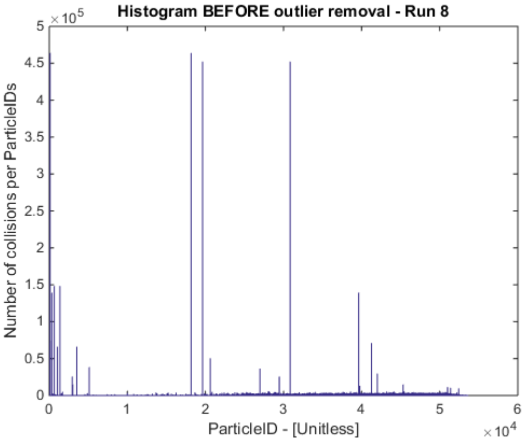
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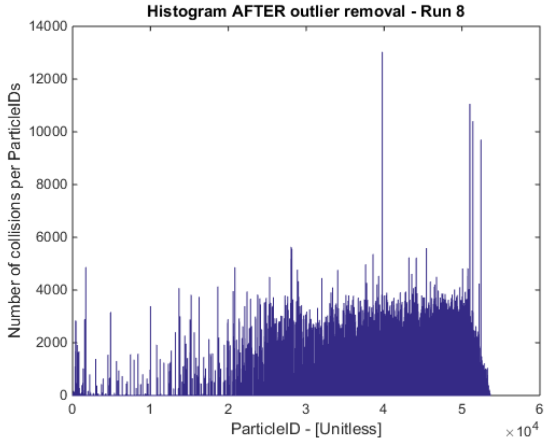
Histogram AFTER outlier removal - Run 8
Number of collisions per ParticleIDs
ParticleID - [Unitless]
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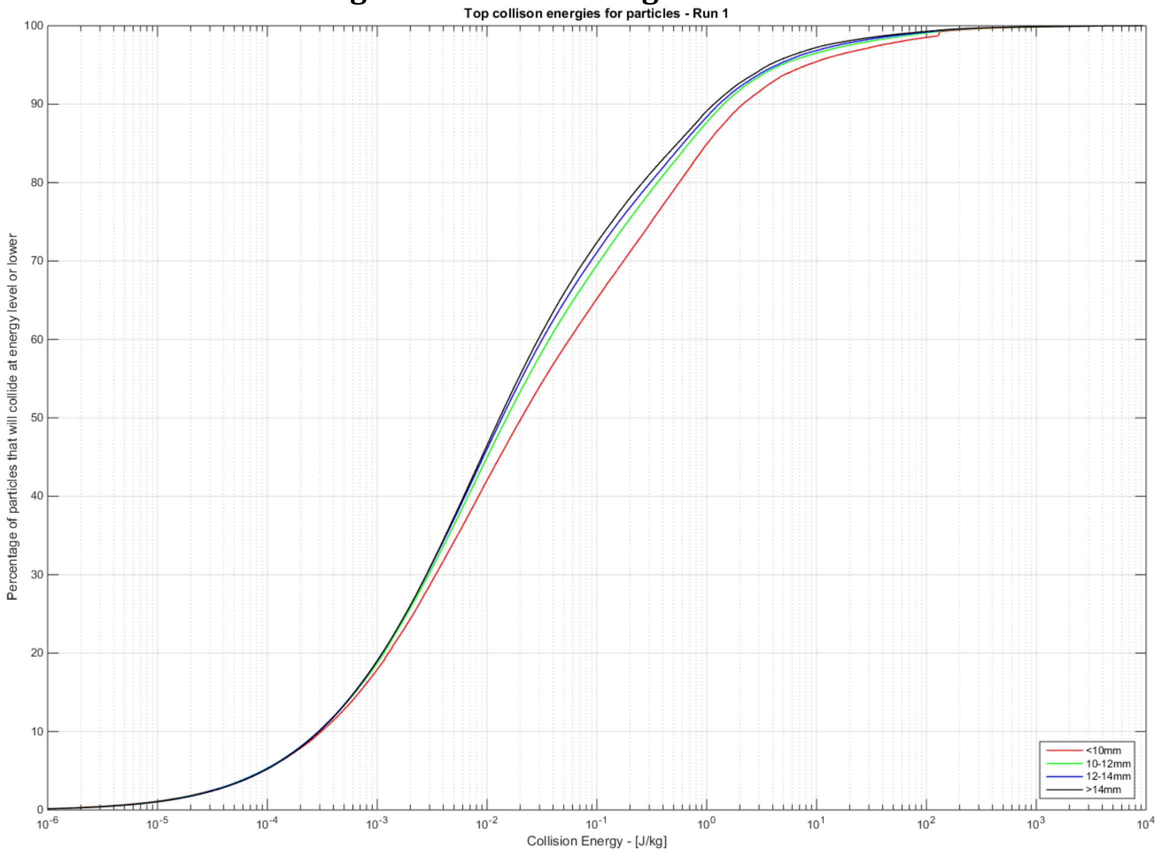
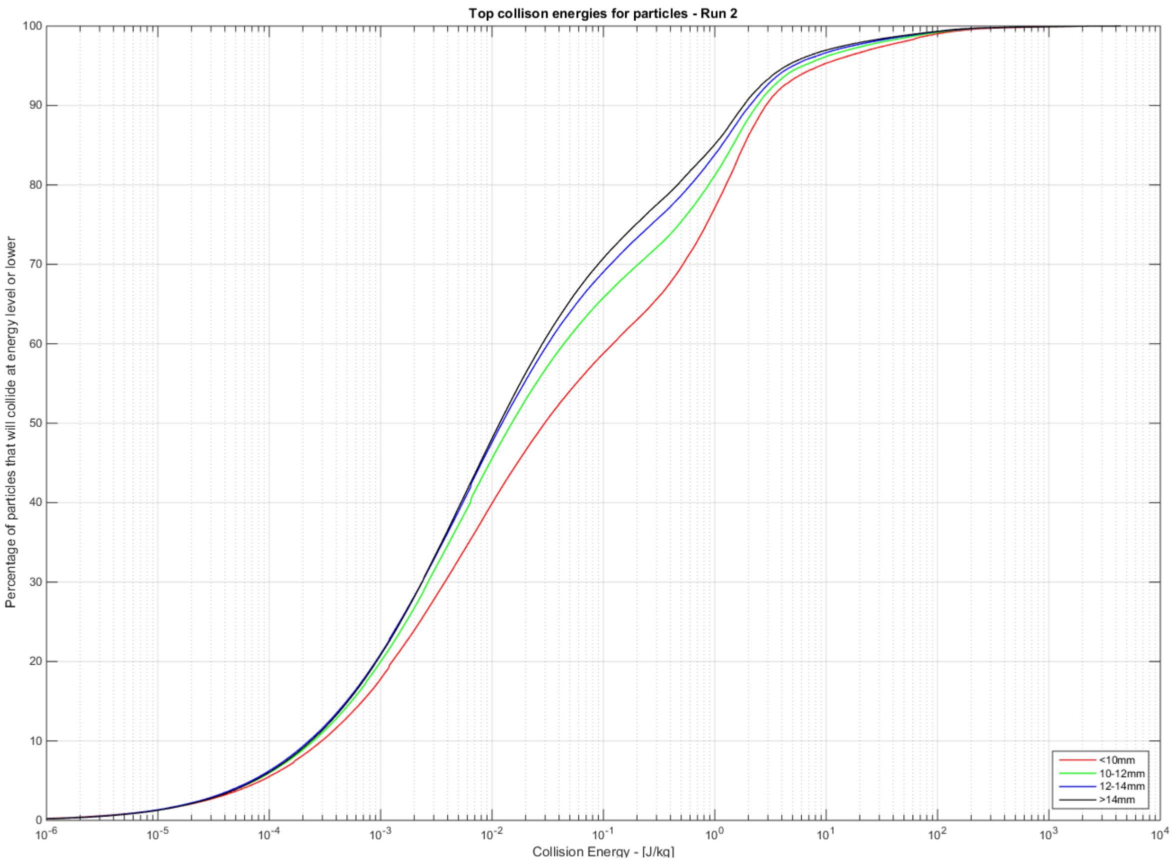
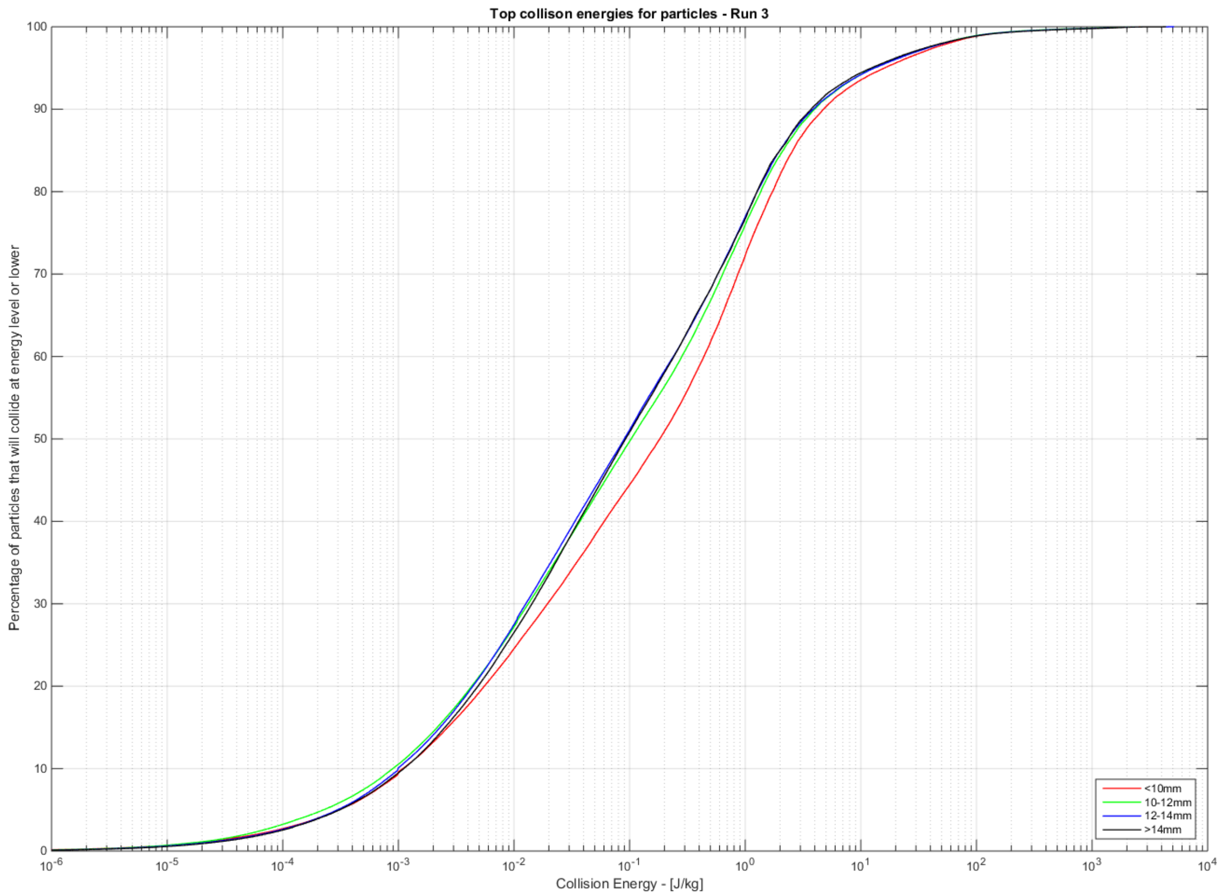
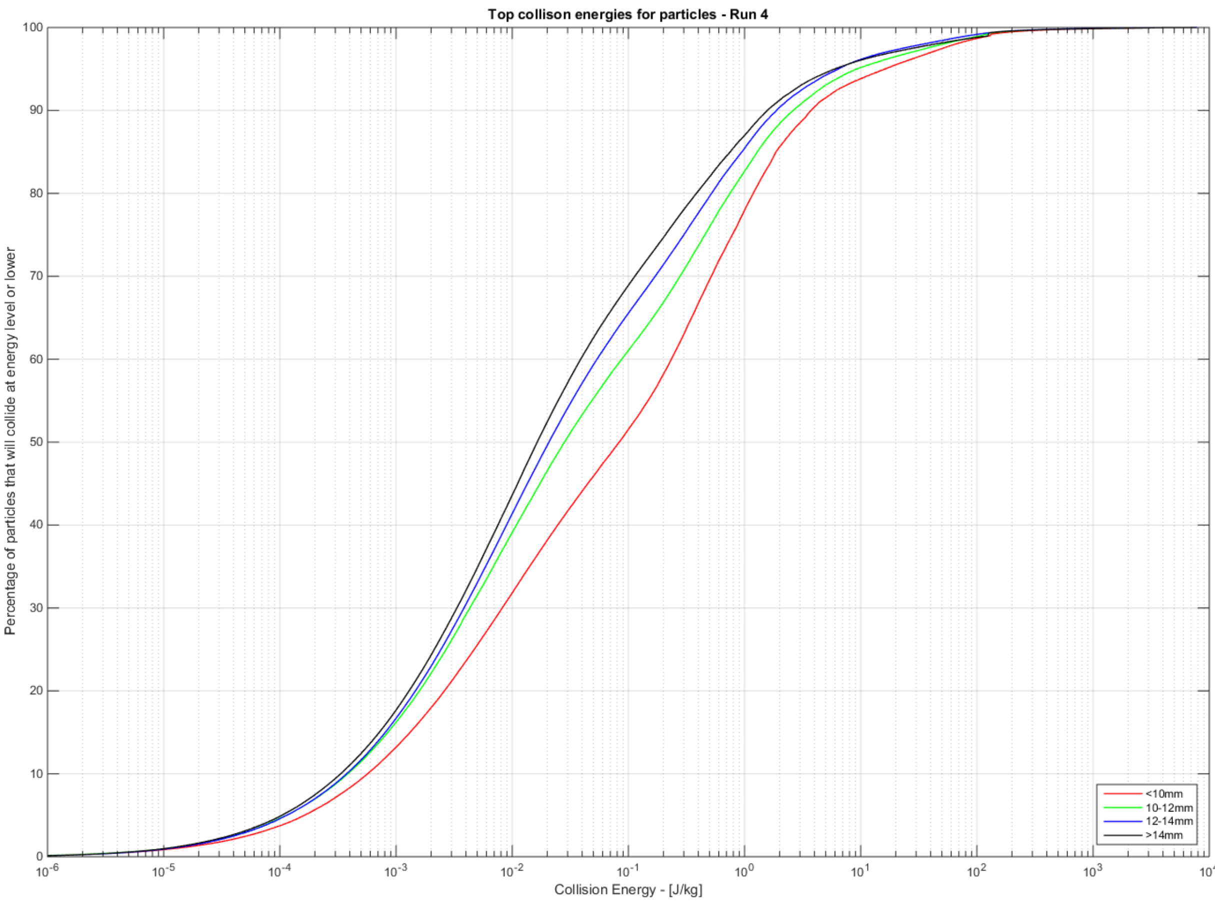
Cumulative collision energies for Run 1 through 8






Top collison energies for particles - Run 3
Percentage of particles that will collide at energy level or lower
Collision Energy - [J/kg]
<10mm
10-12mm
12-14mm
>14mm


Top collison energies for particles - Run 4
Percentage of particles that will collide at energy level or lower
Collision Energy - [J/kg]
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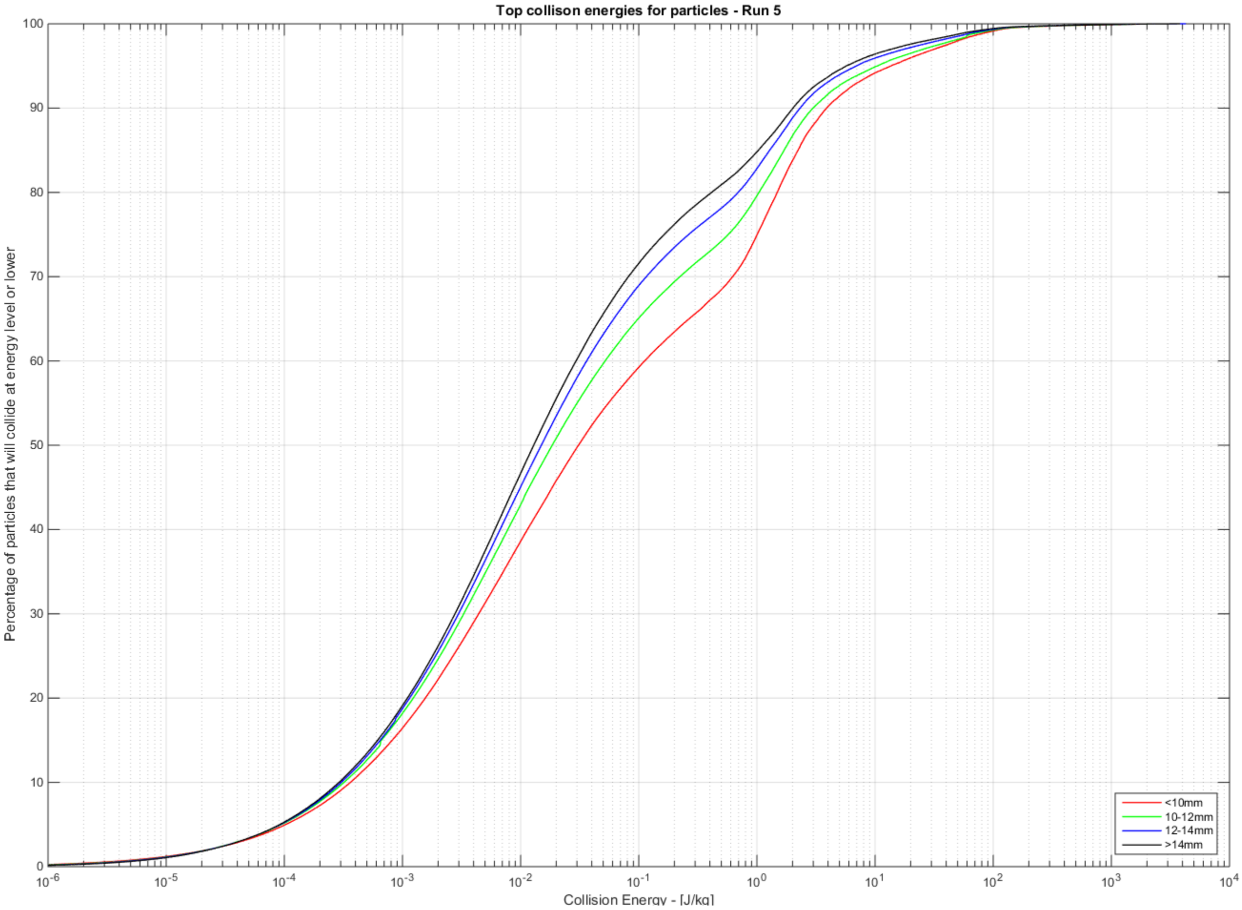
10-12mm
12-14mm
>14mm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Percentage of particles that will collide at energy level or lower
Collision Energy - [J/kg]
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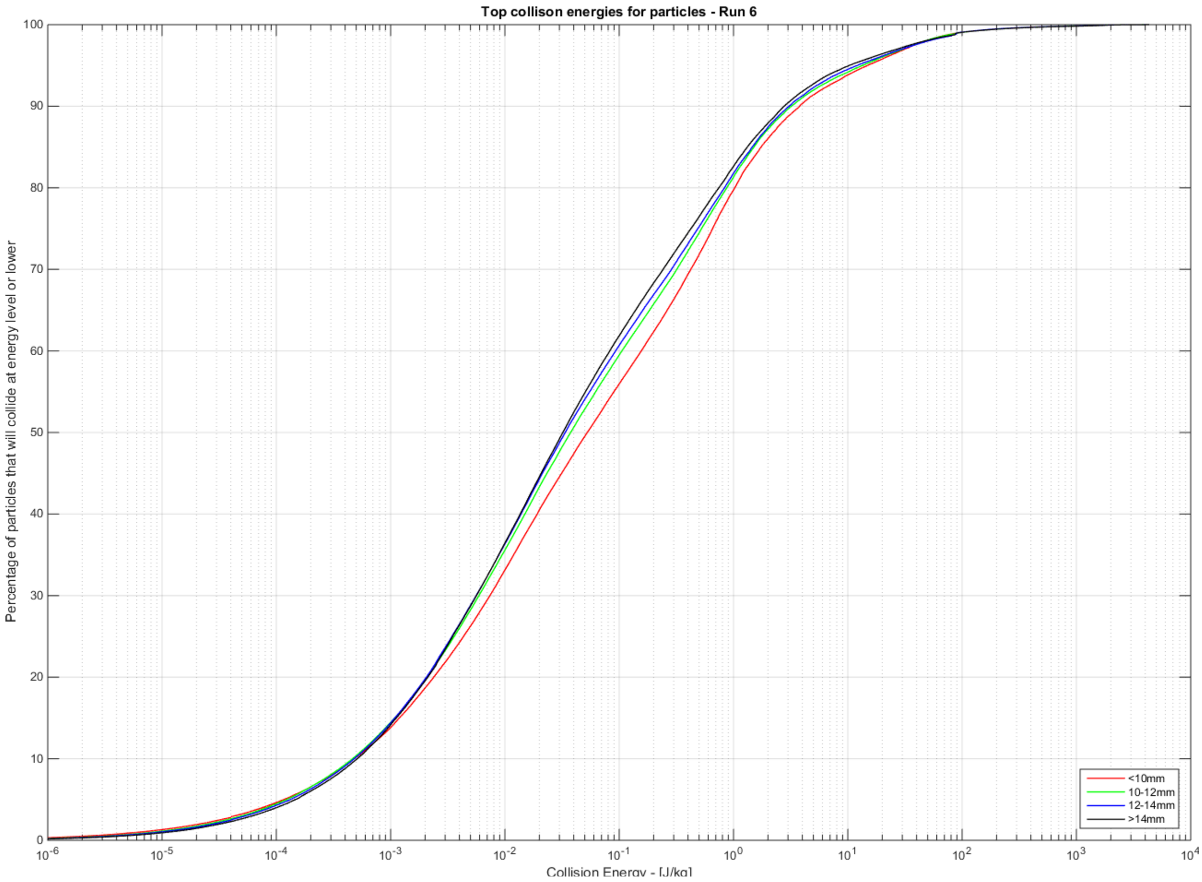
10-12mm
12-14mm
>14mm


Top collison energies for particles - Run 6
Percentage of particles that will collide at energy level or lower
Collision Energy - [J/kg]
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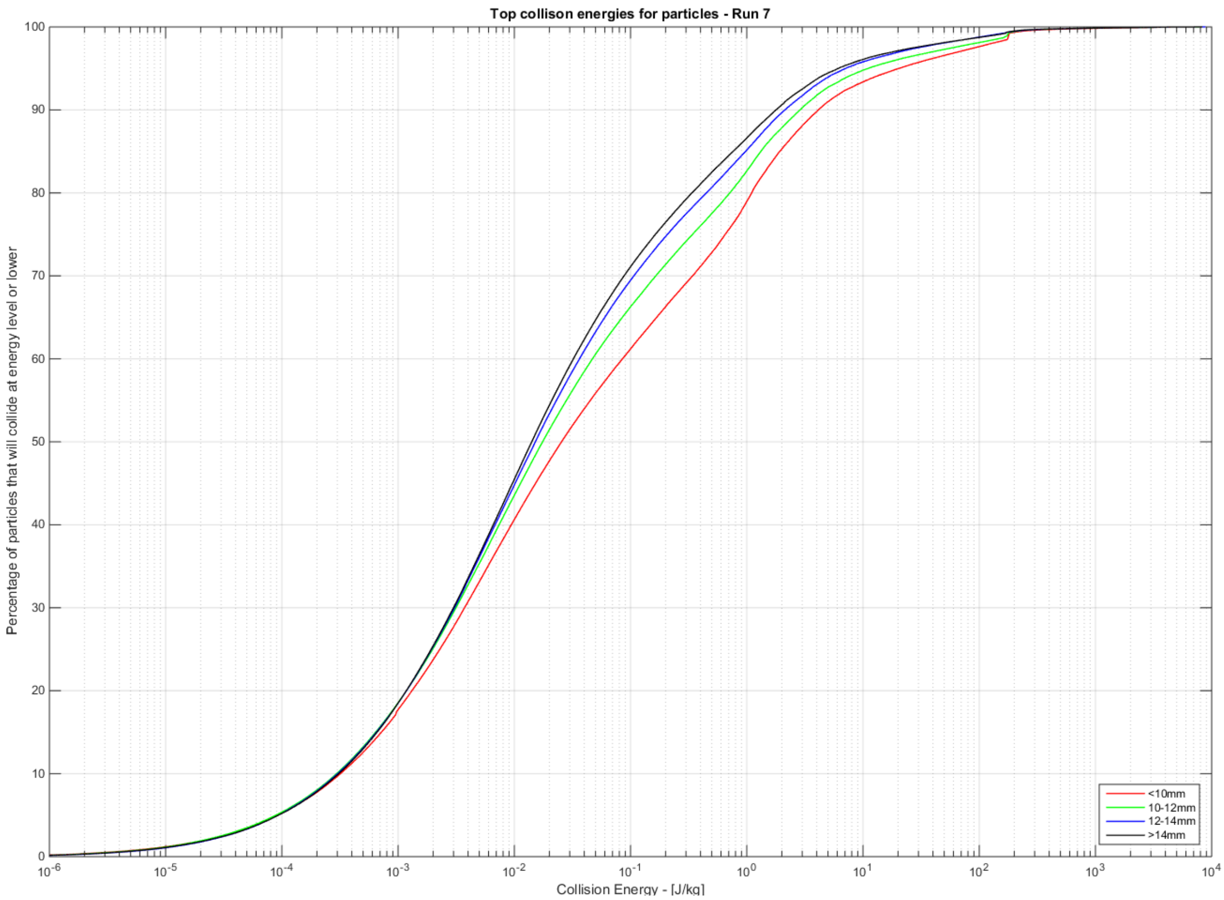
10-12mm
12-14mm
>14mm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Percentage of particles that will collide at energy level or lower
Collision Energy - [J/kg]
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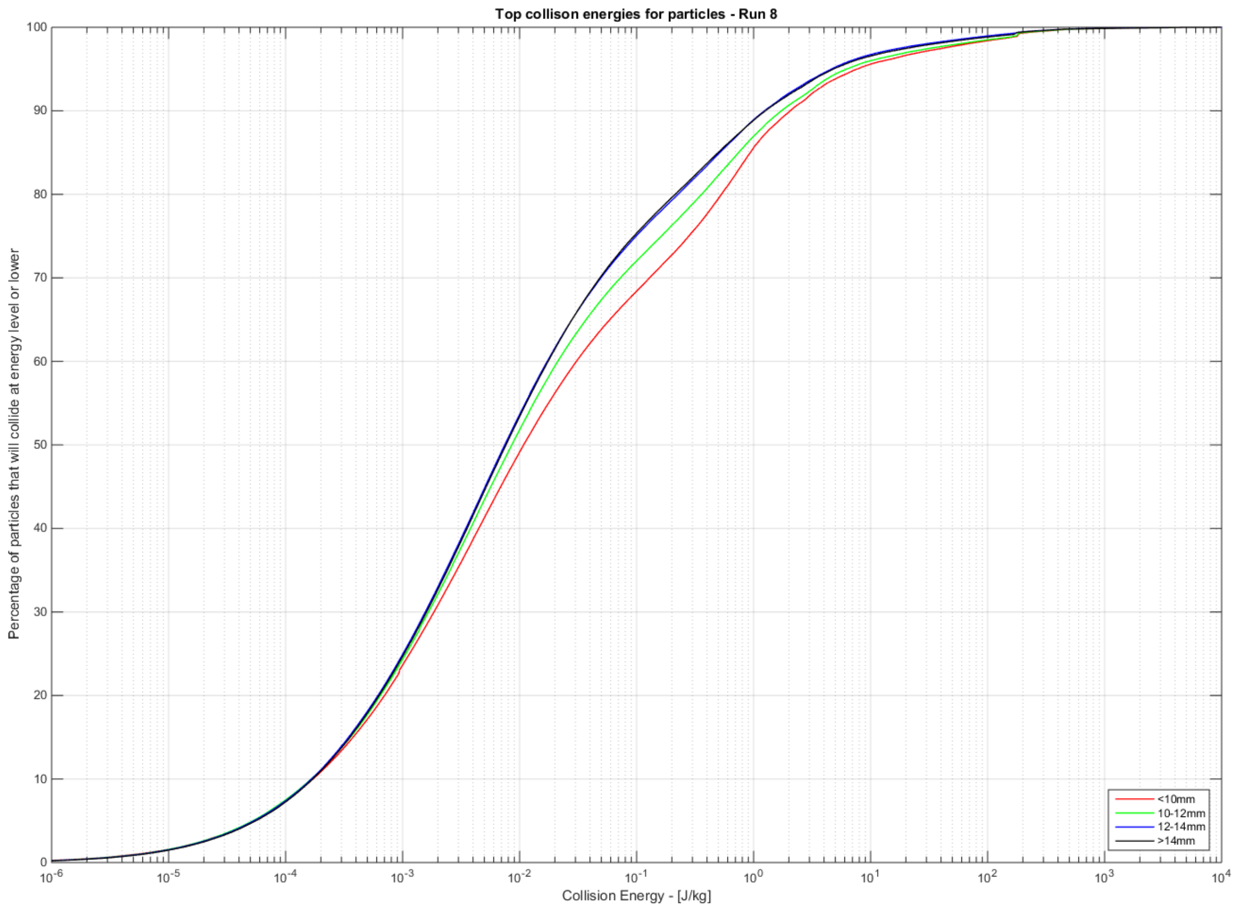
10-12mm
12-14mm
>14mm


Top collison energies for particles - Run 8
Percentage of particles that will collide at energy level or lower
Collision Energy - [J/kg]
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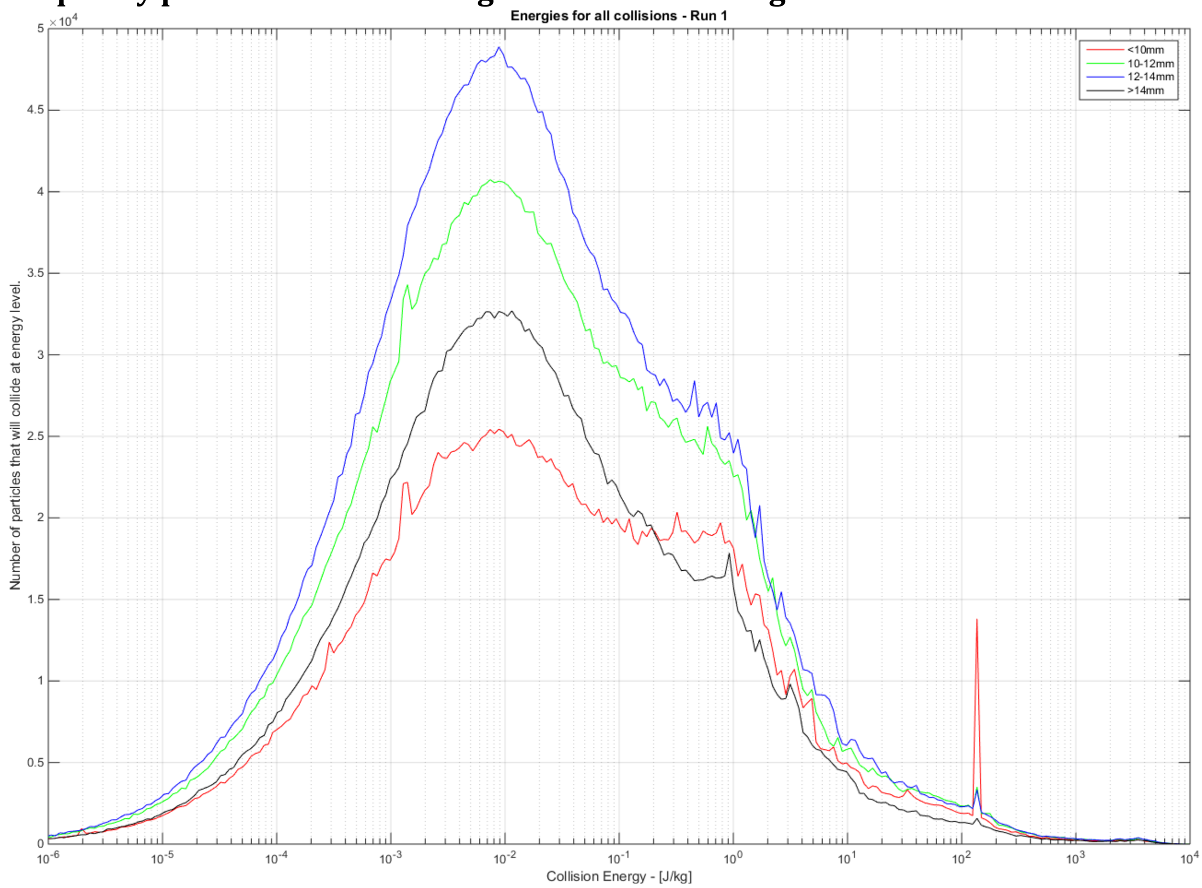
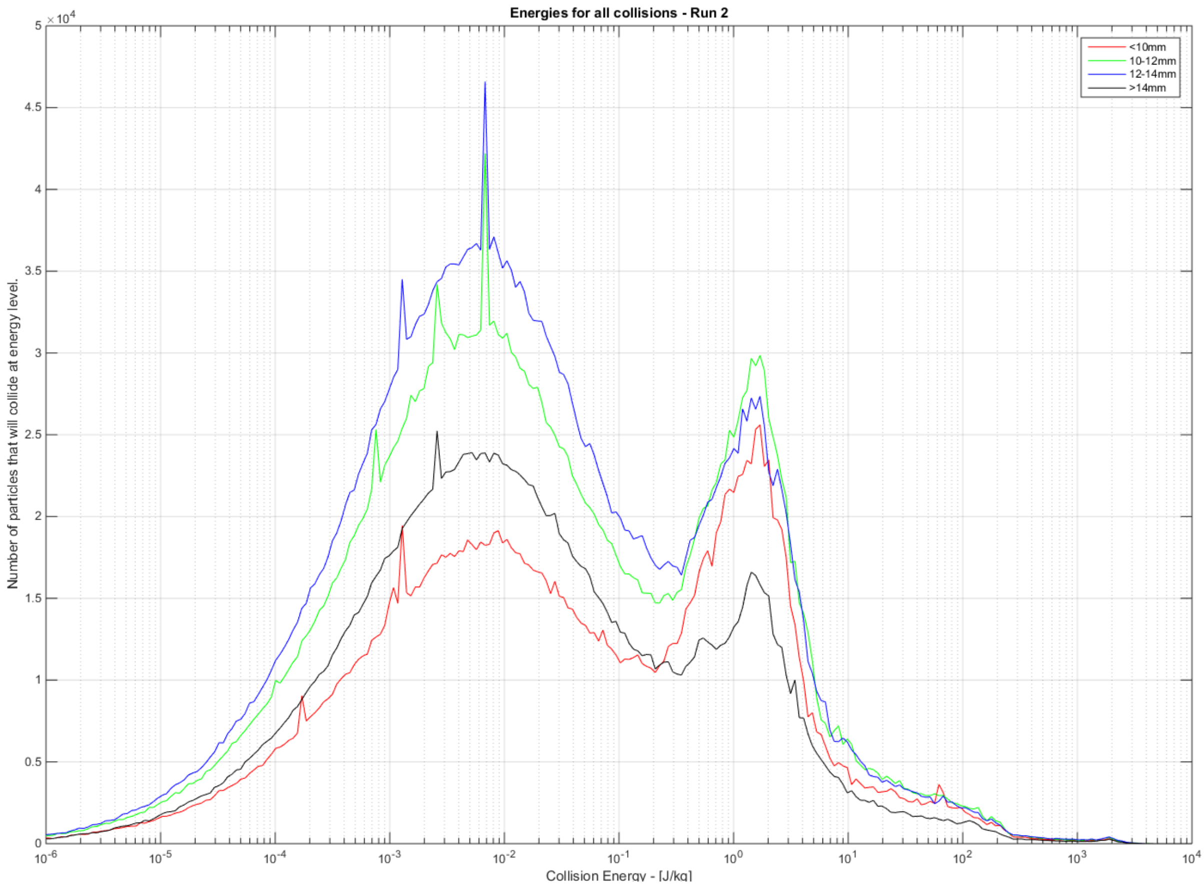
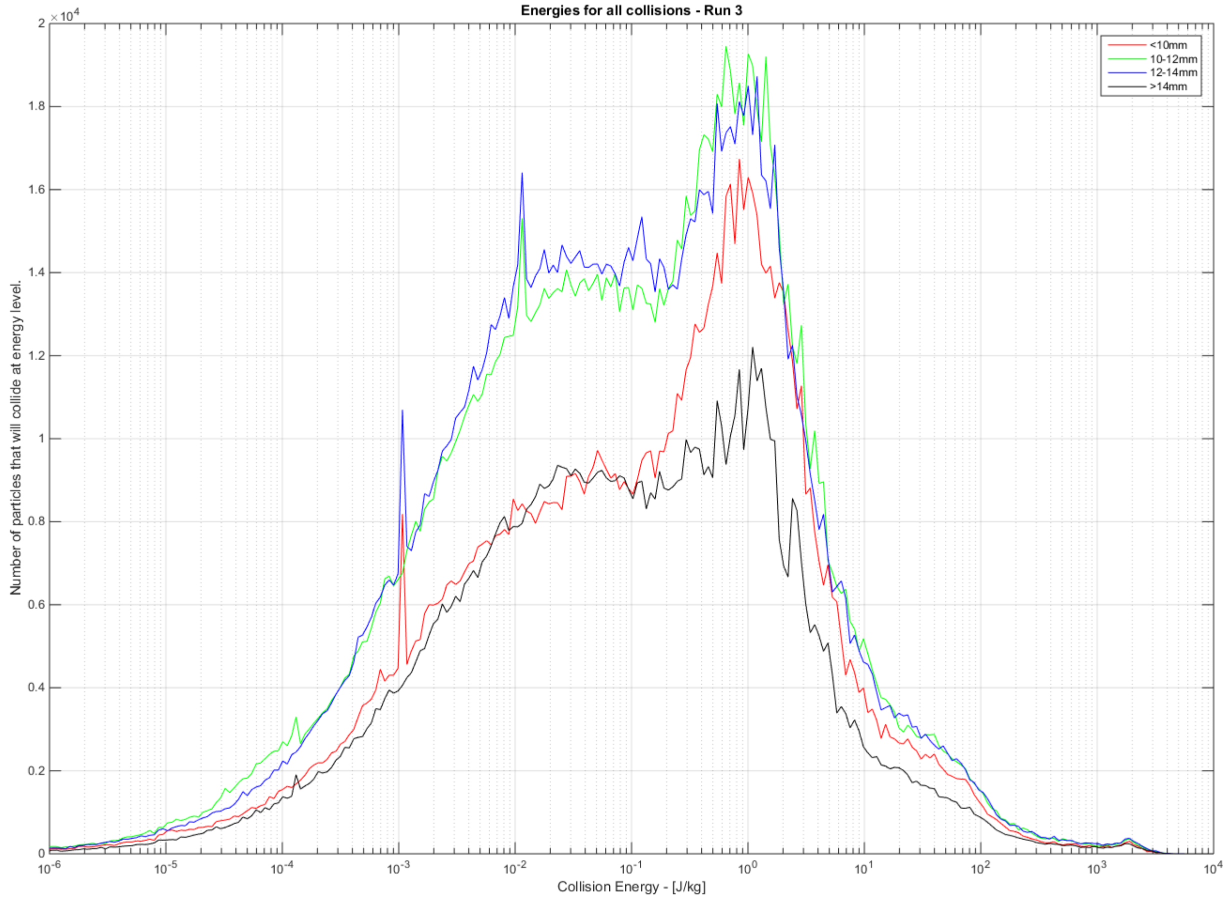
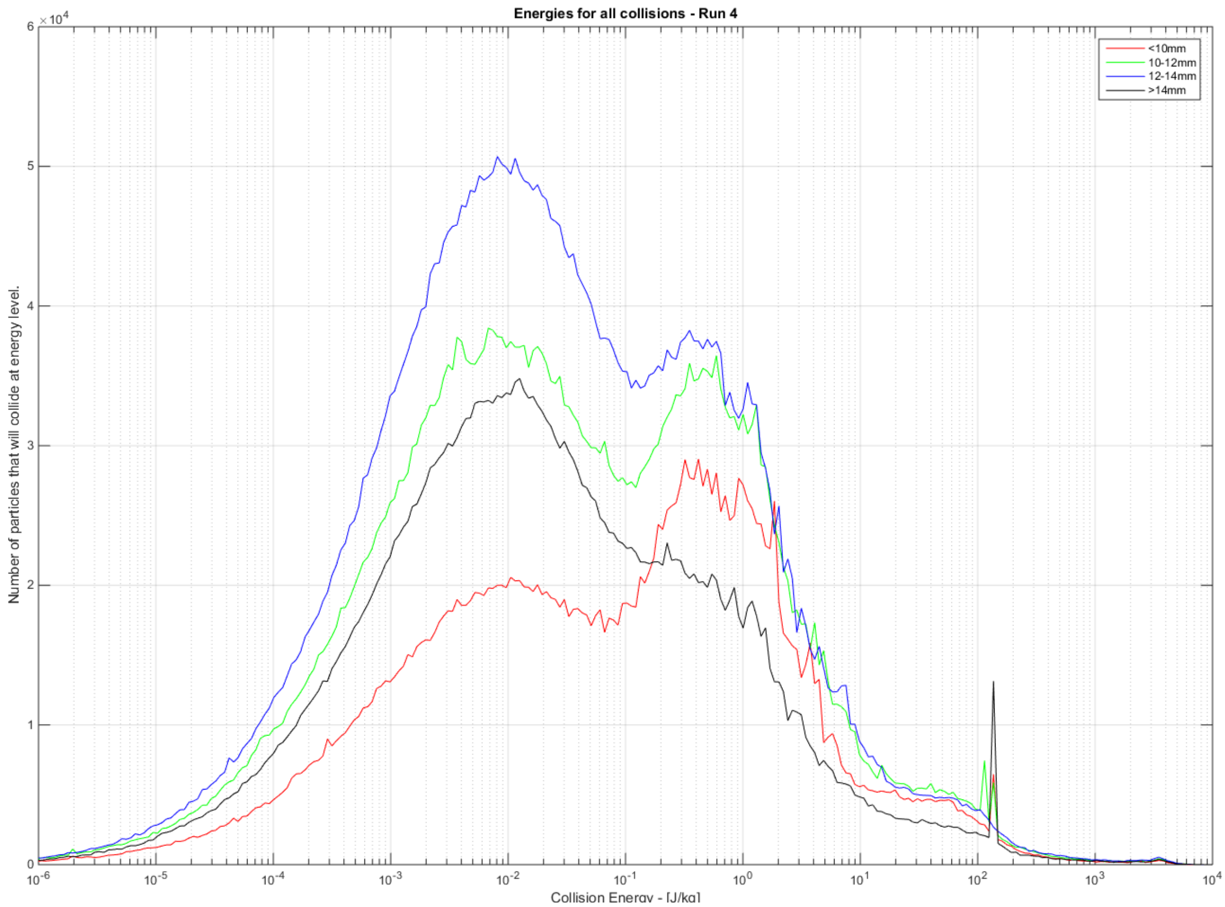
10-12mm
12-14mm
>14mm

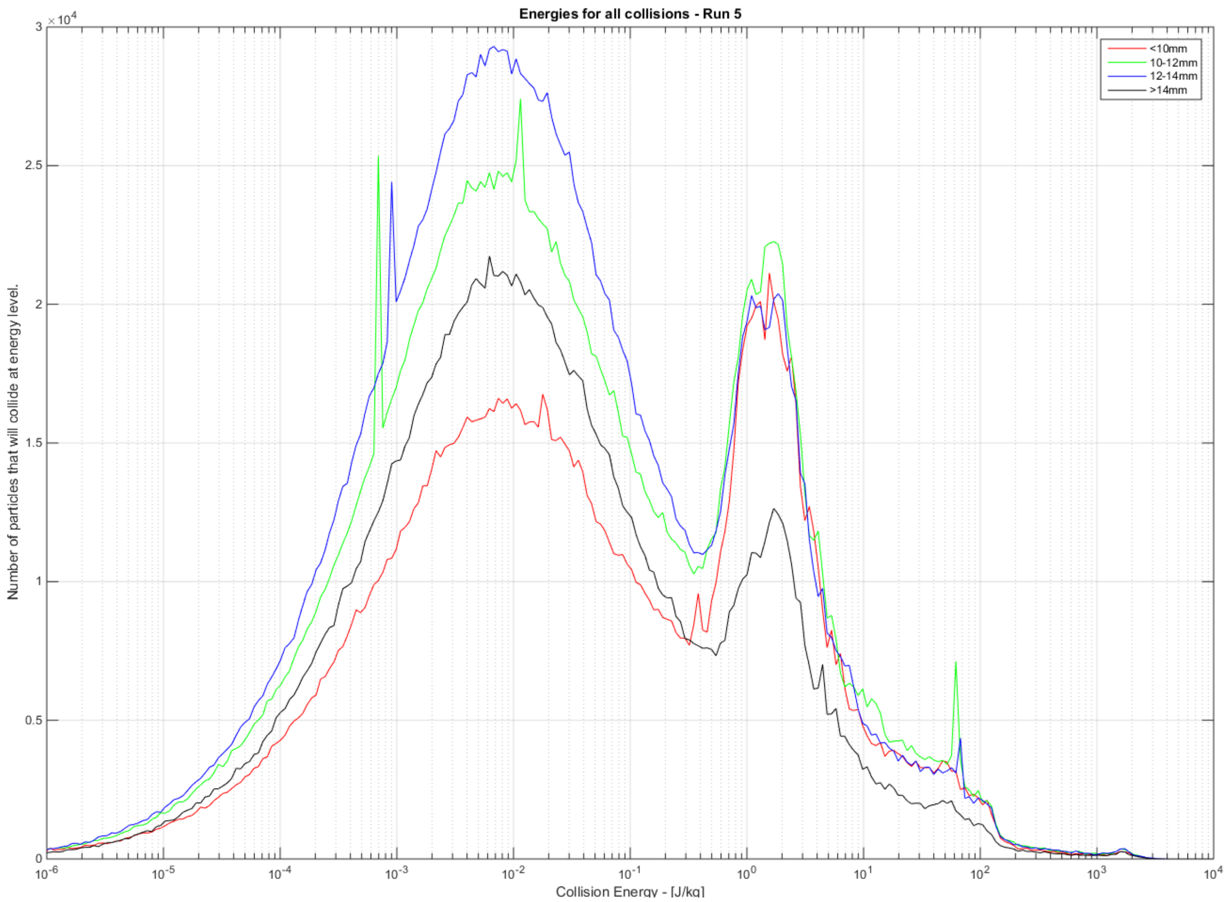
Frequency plots of collision energies for Run 1 through 8

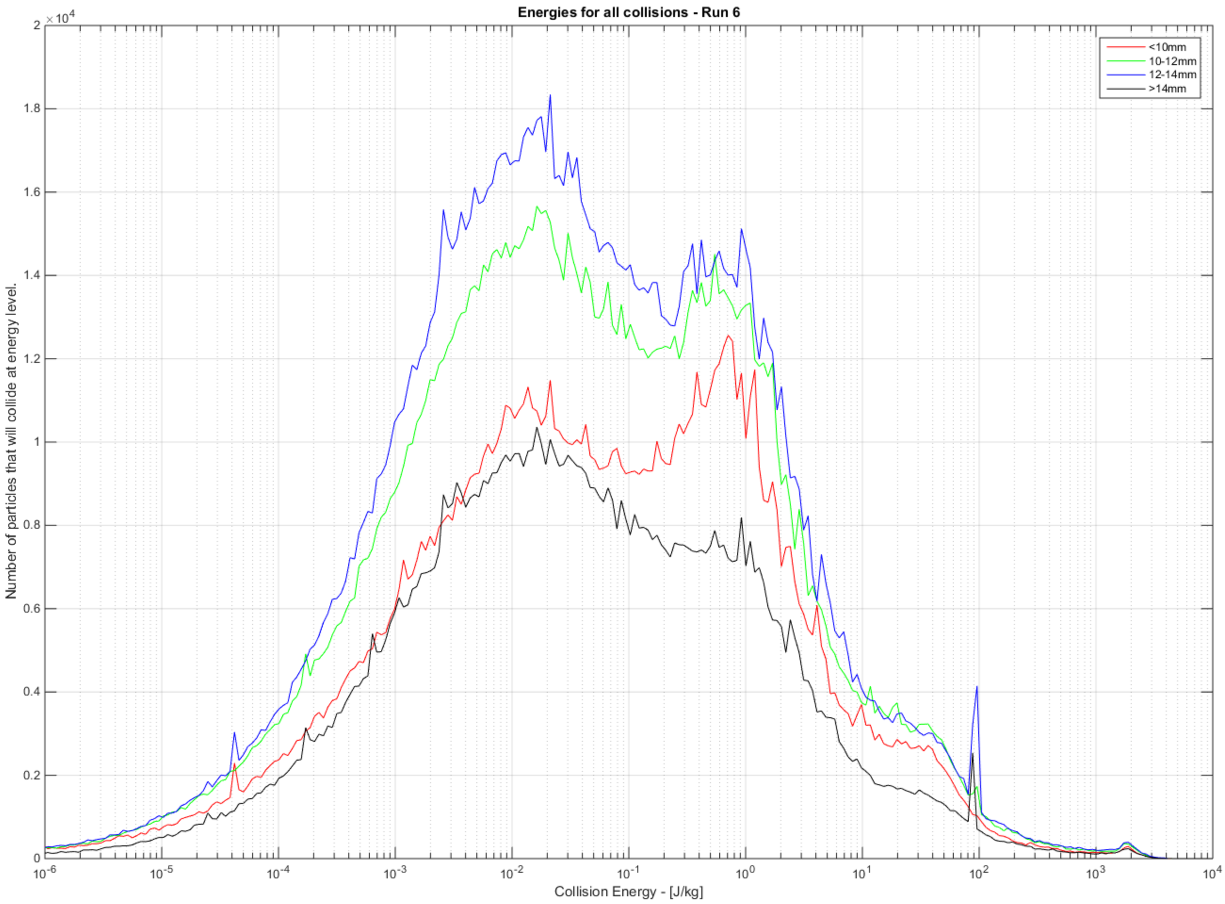


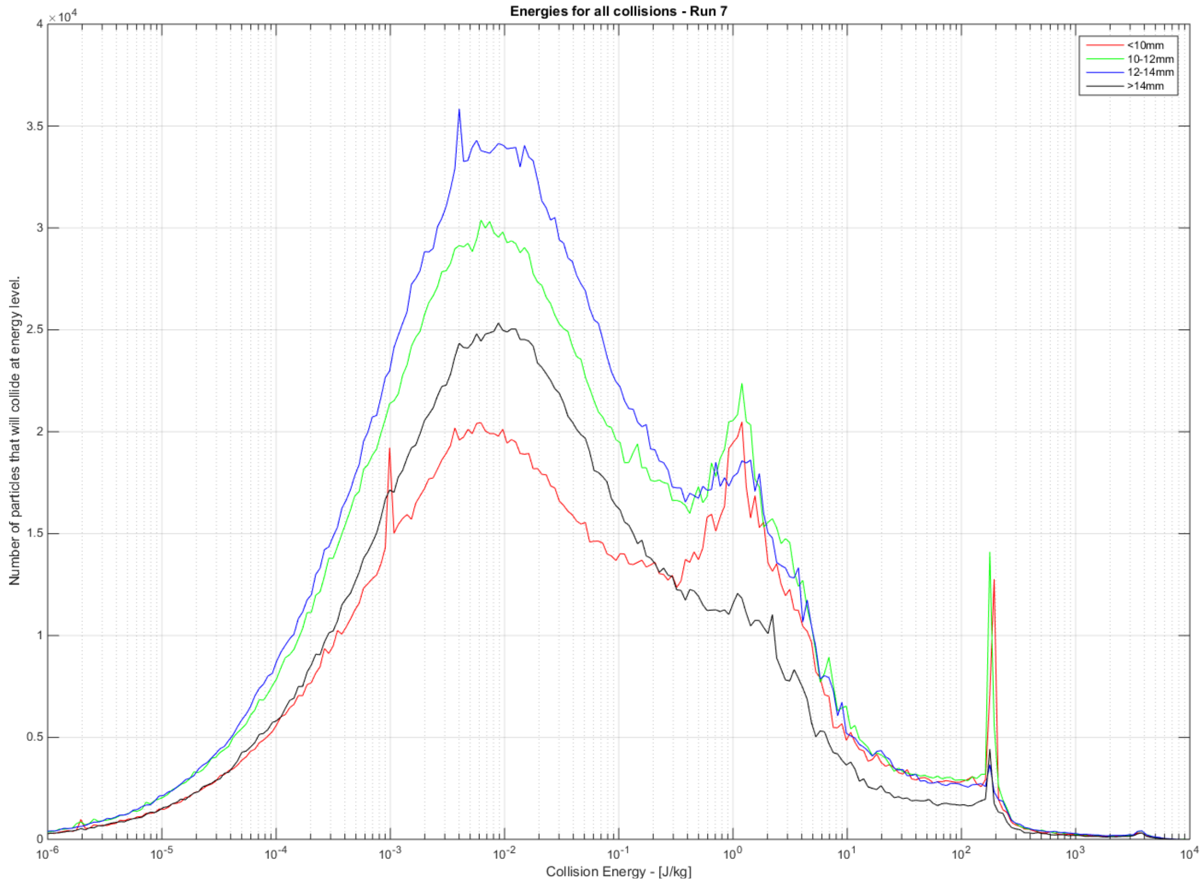


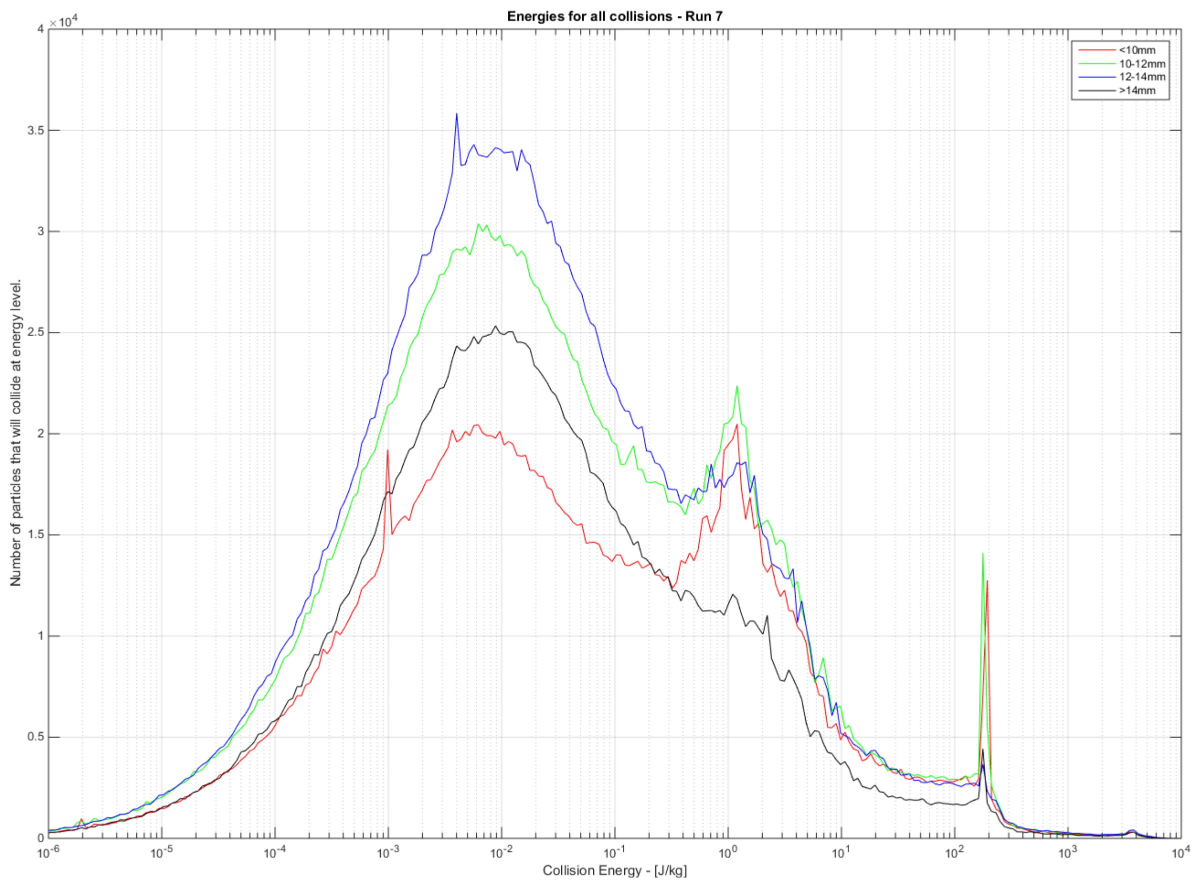

Energies for all collisions - Run 3
Number of particles that will collide at energy level.
Collision Energy - [J/kg]
<10mm
10-12mm
12-14mm
>14mm


Energies for all collisions - Run 4
Number of particles that will collide at energy level.
Collision Energy - [J/kg]
<10mm
10-12mm
12-14mm
>14mm


Energies for all collisions - Run 5
<10mm
10-12mm
12-14mm
>14mm
Number of particles that will collide at energy level.
Collision Energy - [J/kg]


Energies for all collisions - Run 6
<10mm
10-12mm
12-14mm
>14mm
Number of particles that will collide at energy level.
Collision Energy - [J/kg]


Energies for all collisions - Run 7
<10mm
10-12mm
12-14mm
>14mm
Number of particles that will collide at energy level.
Collision Energy - [J/kg]
×10^4


Energies for all collisions - Run 7
<10mm
10-12mm
12-14mm
>14mm
Number of particles that will collide at energy level.
Collision Energy - [J/kg]
×10^4