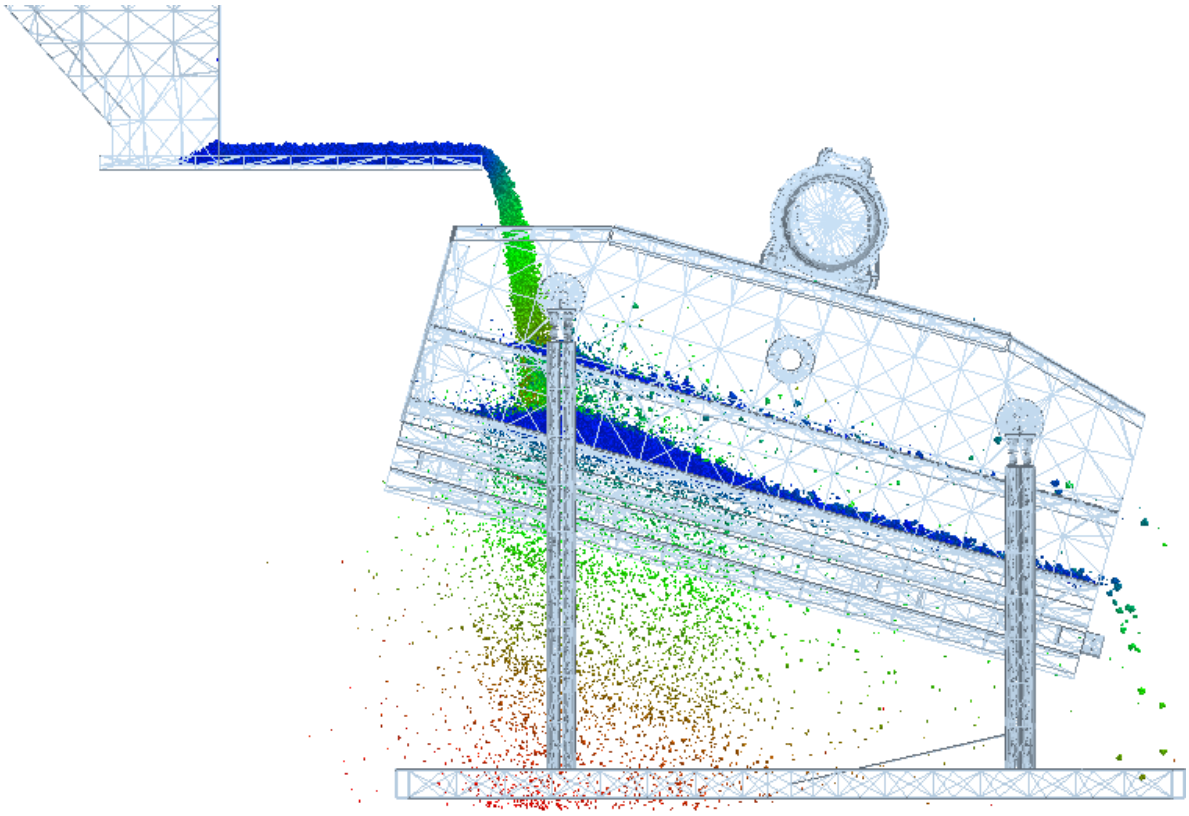

# DEM Modelling of Vibratory Screens

ALI DAVOODI

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020
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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Image from DEM simulation for laboratory vibratory screen, Page 47-49.

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# ABSTRACT

In Sweden, about 100 million tons of aggregate is used for road, railway, and concrete every year. Crushing is the main process for producing aggregate material in different size fractions. The production process is divided into two sub-processes: comminution or size reduction and classification. The vibratory screen is one of the separation machines used to make a final separation to produce the products based on a grade or a size range. In an industry where logistics plays an important role, the transport of unnecessary materials can be costly and it is therefore critical to screen these materials before transporting them. Industrial vibratory screens are costly and also have a substantial effect on the quality of the final product. Therefore, selecting the correct vibratory screen for the crushing plant at the outset results in a better return on investment and better quality products.

The main aim of this research is to understand the screening process in different conditions such as different particle size distribution (PSD) and different feed rates. The first step towards achieving the screening model is to understand the influence of different machine parameters and material properties in the screening performance. Some of these parameters have been studied in this research, such as the motion type, the material of the screen media, and the aperture shape. The Discrete Element Method (DEM) has been used to study these parameters with the idea that by using DEM simulation the particle-to-particle and particle-to-geometry interaction can be studied in a way that is impossible to achieve by real experiments.

The study results show that some of the factors have a greater influence on screening, such as the effect of the motion type for the different slope of the deck. Elliptical motion is more efficient compared to linear motion. Also, the aperture shape in different parts of the screen deck has a different effect when using a single-layer or multi-layer material in the feeding point. The result of this research needs further investigation to study the effect of the interaction between different factors before achieving the complete screen model. Another achievement of this research work is to investigate the validation of DEM modelling in screening performance by using a laboratory-scale vibratory screen.


*Keywords:* DEM simulation, Screen efficiency, Modelling, Validation.

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# ATTACHED PUBLICATIONS

| | |
|---|---|
| **Paper A** | Davoodi, A., Quist, J., Hulthén, E., Bengtsson, M., Evertsson, C.M., *DEM Modelling, and Simulation of Banana Screen Classification Efficiency,* 10th International Comminution Symposium (Comminution '16). 2016: Cape Town, South Africa<br><br>*Distribution of work:*<br>Davoodi wrote the paper, performed data collection, and analysis. Quist, Hulthén, Bengtsson, Evertsson contributed as a reviewer. |
| **Paper B** | Davoodi, A., Hulthén, E., Bengtsson, M., Evertsson, C.M, Eriksson, A., Analysis *of Screening Performance Using Discrete Element Modelling,* Minerals Engineering Symposium (Minerals Engineering '17). 2017: Luleå, Sweden<br><br>*Distribution of work:*<br>Davoodi wrote the paper, performed data collection, and analysis. Eriksson, Hulthén, Bengtsson, Evertsson contributed as a reviewer. |
| **Paper C** | Davoodi, A., Hulthén, E., Bengtsson, M., Evertsson, C.M., *The Effect of Different Aperture Shape and Material of Screen Deck on Screening Efficiency,* Journal of Minerals Engineering 2018.<br><br>*Distribution of work:*<br>Davoodi wrote the paper, performed data collection, and analysis. Hulthén, Bengtsson, Evertsson contributed as a reviewer. |
| **Paper D** | Davoodi, A., Asbjörnsson, G., Hulthén, E., Evertsson, C.M., *Application of the Discrete Element Method to Study the Effects of Stream Characteristics on Screening Performance,* Journal of Minerals 2019, 9(12), 788.<br><br>*Distribution of work:*<br>Davoodi wrote the paper, performed data collection, and analysis. Hulthén, Asbjörnsson, Evertsson contributed as a reviewer. |
| **Paper E** | Davoodi, A., Asbjörnsson, G., Hulthén, E., Evertsson, C.M., *Investigating the effect of the feeding arrangement on screen media wear and screening efficiency by using DEM,* submitted to Journal of Minerals Engineering 2020.<br><br>*Distribution of work:*<br>Davoodi wrote the paper, performed data collection, and analysis. Hulthén, Asbjörnsson, Evertsson contributed as a reviewer. |
| **Paper F** | Davoodi, A., Asbjörnsson, G., Hulthén, E., Evertsson, C.M., *Validation of a DEM model of screening,* submitted to Journal of Minerals Engineering 2020.<br><br>*Distribution of work:*<br>Davoodi wrote the paper, performed data collection, and analysis. Hulthén, Asbjörnsson, Evertsson, contributed as a reviewer. |

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# 1. INTRODUCTION

*The aim of this chapter is to:*

- *Introduce the general usage of rock processing.*
- *Describe different stages in the crushing plant.*
- *Define the comminution and classification process.*

## 1.1. GENERAL

Construction aggregate or aggregate is a granular material used in construction. The most common aggregates of mineral origin are sand, gravel and crushed rock. Aggregates are used as base material under foundations, roads, and railroads. Today, significant growth in housing construction and infrastructure means that more construction aggregates are required. In Sweden, construction aggregates are the largest raw material extracted, as it constitutes the main component of asphalt and concrete, and is also used as a filling material and railway ballast. A total of 8.5 tonnes of construction aggregates per citizen was consumed in Sweden in 2018 (SGU, 2019).

Three are two sources of construction aggregate, those produced from natural sources extracted from quarries and gravel pits, and recycled aggregates derived from the reprocessing of materials previously used in construction. Because the transportation of material is costly and not environmentally friendly, large quarry and gravel operations often exist near to population centres.

The aggregate is divided into coarse and fine categories. The type of aggregate varies in shape and size based on the application where it will be used. The aggregate's quality is measured during production based on product characteristics. The most important characteristics are the shape, size, and strength of the product.

One example is the aggregate types used in the cement industry, where fine and coarse aggregates generally occupy 60% to 75% of the concrete volume and strongly influence the concrete's hardened properties, mixture proportions, and economy. Fine aggregates generally consist of natural sand or crushed stone, with most particles smaller than 5 mm (Poon and Lam, 2008).

Another example is asphalt aggregate, some research and development have been undertaken into creating the right mix of asphalt aggregates for a given application. Aggregates are sorted and classified by size, and the amounts and sizes used in an asphalt mix can vary. The shapes of the particles affect the asphalt mixture's overall strength and workability, as well as the density achieved during compaction (Mills-Beale and You, 2010).

## 1.2. CRUSHING PLANT

A crushing plant is used to crush different types of rocks from large size to small in many quarries or at construction sites. Crushing plants be made of different machines that can be configured according to the purpose of the site. For example, the plant might be used for rock crushing for construction or mining, or for recycling. It is often classified as either a mobile or stationary type and mainly includes a feeder, jaw crusher, cone crusher, impact crusher, vibrating screen, conveyors and bins. Figure 1 shows an example of two stage crushing plant. A crushing plant has different stations for primary, secondary, and tertiary crushing, where selection and transport cycles are done to achieve different particle sizes. A crushing plant is based on the following main elements:

1. Feeders: used to feed the material to crushers, mainly the primary crusher.
2. Crushers: the first stage in most operations is size transformation by crushing.
3. Conveyor belts: used to transport the material between different machines.
4. Vibratory screens: one of the common separation devices, suitable for particle size over 2 mm.
5. Control system: to control the operation of the equipment.
6. Storage: stockpiles and bins, used to accumulate material in order to suppress variations.

Figure 1. Two stage crushing plant. (Swerock, Vändle Bergtäkt)

The crushing performance from the start to the final product is divided into two main processes, namely comminution and classification. Figure 2 shows a typical layout of a crushing plant which comprises three crushing and screening stages.

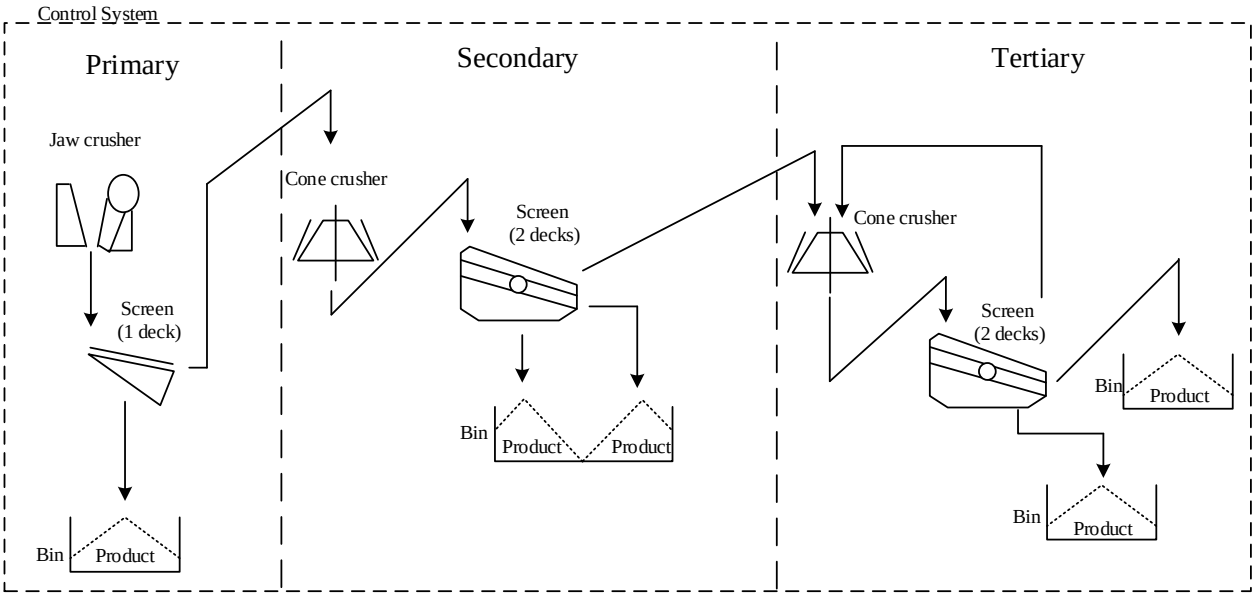



Figure 2. Example layout of three-stage crushing plant, including crushers and screens.

### 1.2.1. COMMINUTION

The comminution process reduces the particle size by using different types of crushers or grinding machines. Depending on the average size of the particle at the start and the expected final product size, different machines will be used. The first step is to reduce large fragments of rock to a size that can be transferred to the secondary stage crusher on conveyors. Gyratory crushers and jaw crushers are mostly used for this primary crushing. The working principle of the gyratory crusher and jaw crusher can be seen in Figure 3. The secondary stage is used to reclaim the primary crusher product, and to produce coarser types of products. In the tertiary crushing stage, the rock material is further crushed to a range of final products.

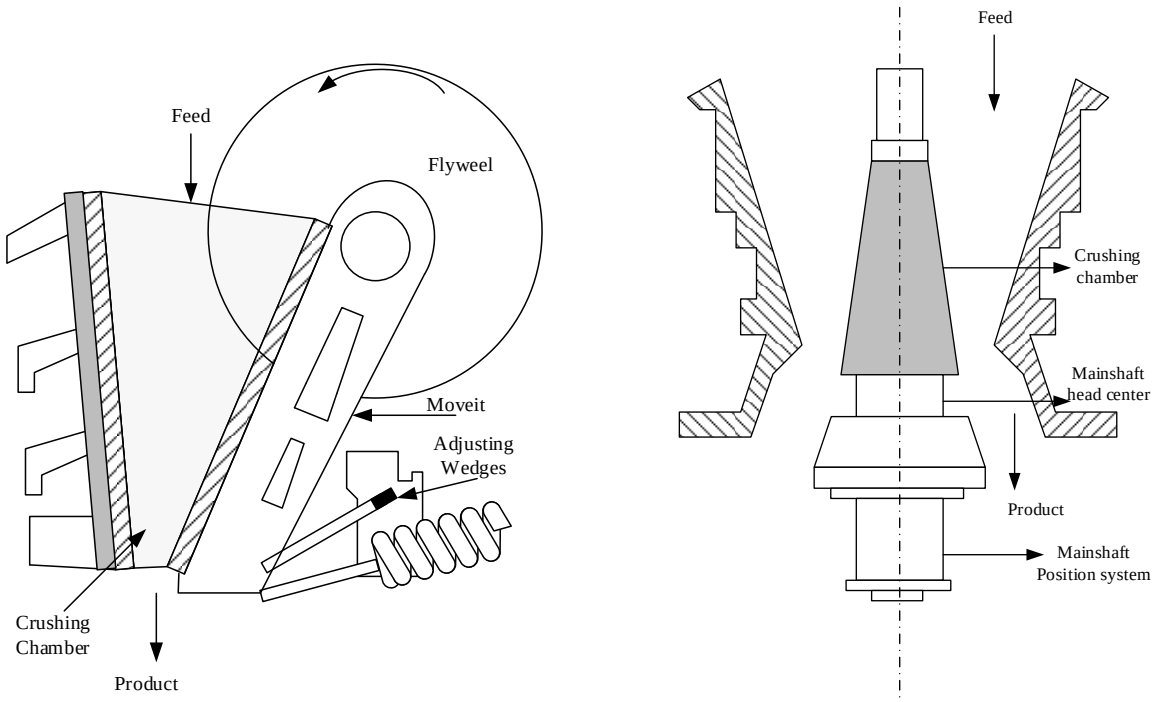



Figure 3. Working principle of the gyratory crusher (right) and the jaw crusher (left).

The most common crusher used in the secondary and tertiary crushing stages is a cone crusher. As the mechanisms of crushing in the cone crusher are similar to gyratory crushers, their designs are similar, but the spindle is supported at the bottom of the gyrating cone instead of being suspended as in larger gyratory crushers.

The crushing process in the cone crusher starts when rock is fed into a large opening at the top of the crusher, where it is compressed between the mantle and the cone. As the size of the rock decreases, pieces fall into lower levels of the crusher, where they continue to be broken down further, depending on the chamber geometry, crusher dynamics, and material characteristics (Evertsson, 2000). Figure 4 presents a schematic diagram of a cone crusher.

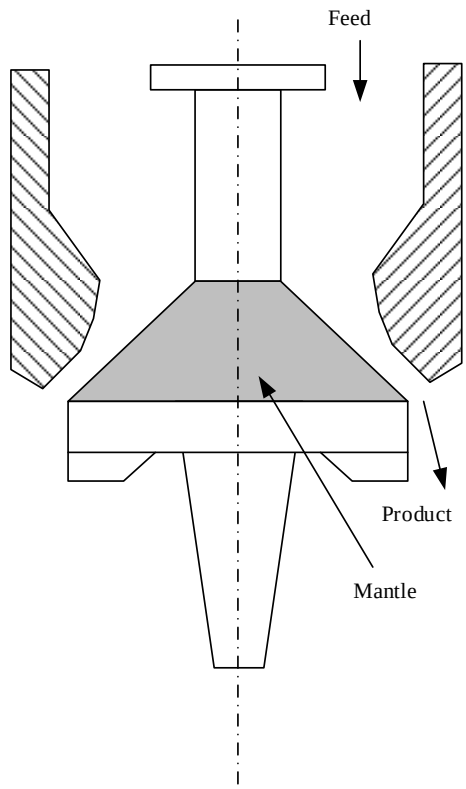



Figure 4. Schematic diagram and working principle of a cone crusher.

### 1.2.2. CLASSIFICATION

Classification is the process of the separation of particles based on their size and shape. The most common classification process in the aggregate and mining industry in the coarse comminution is screening or passing the particles to be sized through a screen or a deck with a number of screens. There are different types of vibratory screens which vary according to their different configuration such as size and the number of decks. The selection of vibratory screens used also depends on the fraction of particles and on whether it is a wet or dry screening process. Figure 5 shows the schematic diagram of different designs of vibratory screens.

One example of a high capacity vibratory screen is the banana screen, named because of the shape of the screen. The banana screen is a multi-slope screen and is popular when the capacity and efficiency of the screening process are in focus. The size of the screen and the slope of the first deck cause the feed material to flow rapidly along the screen deck and the size of the screen causes the formation of a single layer of particles, which gives the particles more chance of passing through the screen deck, thus increasing the efficiency.

Other examples of vibratory screens are inclined and horizontal vibratory screens, the difference between these machines being that in the horizontal or near-horizontal screen deck the vibration of the screen is the only external force supporting the material transportation along the screen deck, which means that the screen has a lower capacity than the inclined screen, where gravity also assists the material flow to the discharge point. The normal slope of the inclined screen is between $15^{\circ}$ and $25^{\circ}$.

A multi-deck vibratory screen is also used for classifying several fractions based on having different numbers of layers of screen decks. The number of decks is usually between 4 and 6. The screen capacity is not as great as the banana and inclined screens based on the size of the screen. There are also other classification machines, such as the Grizzly and Trommel, but these are not as common as vibratory screens in the mining and aggregate industry.

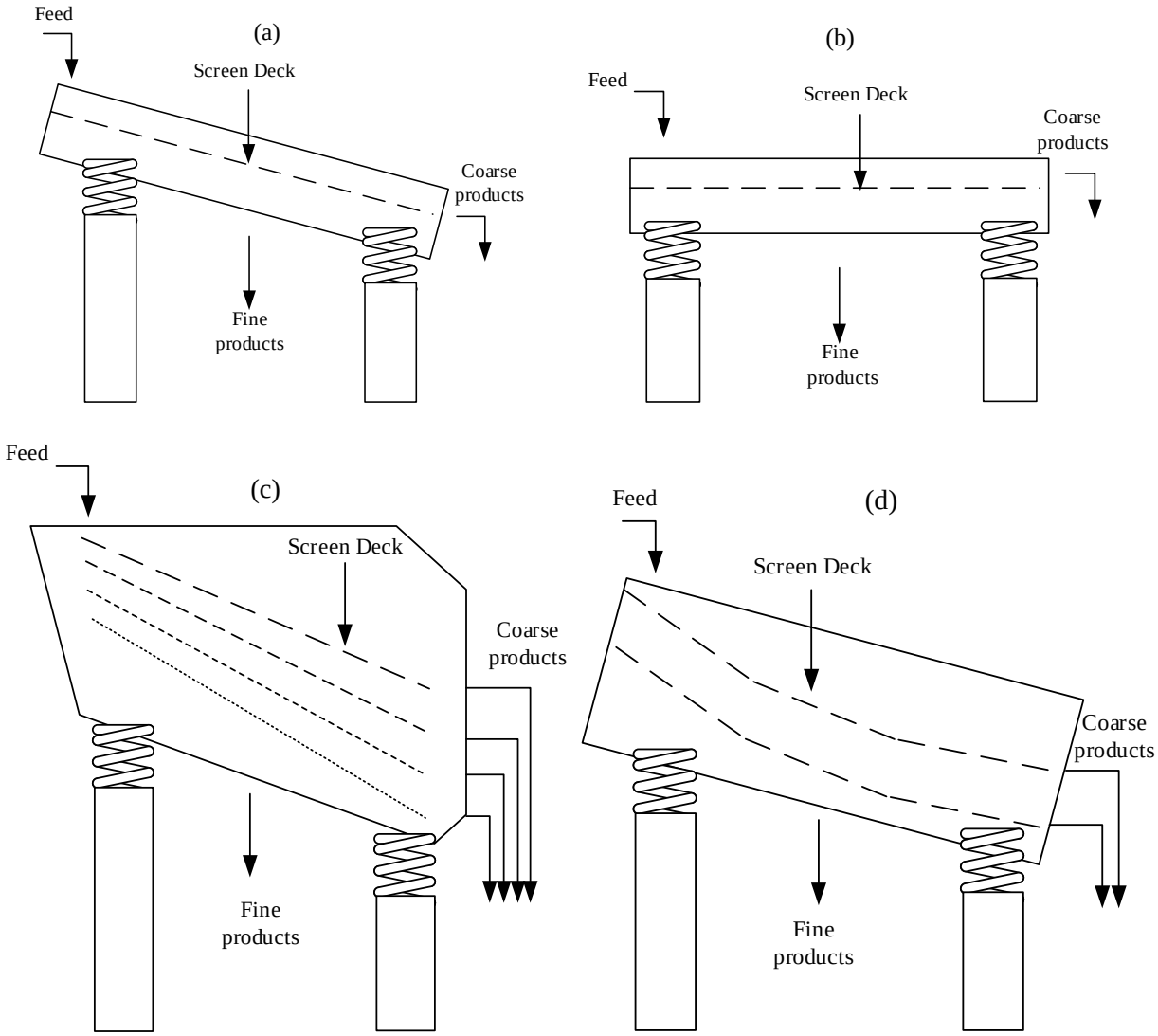



Figure 5. Schematic diagram of four different types of vibratory screens a) inclined vibratory screen, b) horizontal vibratory screens, c) multi-deck vibratory screen, d) banana screen.

# 2. OBJECTIVES

*The aim of this chapter is to:*

- *Describe the aim of this research.*
- *Formulate the research questions.*
- *Define the delimitation of this research.*

## 2.1. RESEARCH SUMMARY

The screening process is complex because of the numbers of parameters that affect it. The highest possible quality of the final product and efficiency of the screening performance is always the main goal for both machine manufacturers and users.

The aim of this work is to study the influence of different parameters on the screening performance and to investigate how these parameters affect the screening efficiency. The goal of this study is to understand the screening performance for each process and to adjust the parameters to achieve the best product quality while also maximising efficiency. In order to simulate the screening performance, the Discrete Element Method (DEM) has been used for different screening conditions and analyse the performance of the screening process. To determine whether the outputs of the simulation model are acceptable, a laboratory-scale vibratory screen has been designed and build in order to validate the simulations.

## 2.2. RESEARCH QUESTIONS

Considering the aim of this research, a set of research questions has been formulated.

RQ1. How do selected screening parameters influence the screening efficiency?

> *Studying the effect of different parameters is a first step to understand the screening process, this would make both process improvement and machine development less complicated.*

RQ2. How should DEM simulation be used to model and simulate screening with adequate accuracy?

> *The DEM simulation used to study the behaviour of the particles and tracking particles movement. The simulation conditions need to be calibrated to have acceptable accuracy. The calibration includes particle size and shape, feed rate and also material properties for both particles and geometry.*

RQ3. How can DEM simulation be used for industrial purposes?

> *The most important output from simulations and the experiments are the improvement of the screening process in the real scale industry screen. Using a DEM simulations platform is a sustainable way to analyze the screen process behaviour.*

RQ4. How should a vibratory screen be designed based on the parameters and process requirements?

> *Based on numbers of different machine parameters the design of the vibratory screen is challenging, due to feed rate and expected product quality for the final product the design is very critical.*

RQ5. What are the limitations of using simulations compared to real experiments?

> *It is important to consider the limitations in order to place research findings in perspective, to interpret the significance of scientific work and to attribute a degree of validity to the results of published research.*

## 2.3. DELIMITATION

In this research the design principle of one factor at a time (OFAT) has been considered, meaning that the interactions between factors cannot be completely estimated and also requiring more simulations for the same precision. The most important advantage of using OFAT is that the simulation error is not large compared to the factor effects. Another delimitation of this research is the exclusion of wet screening, which is complex to achieve with DEM simulations. All the simulations and studies have therefore been done for a dry screening process. DEM simulation can be very time-consuming given all the data from the interactions both between all particles and also between the particles and geometry, and for that reason, some of the simulations have been done on a laboratory scale screen to save simulation time.

# 3. BACKGROUND

*The aim of this chapter is to:*

- *Present the background of the vibratory screen.*
- *Define different elements of screening performance.*
- *Describe the numbers of different screening simulation models based on the literature review.*

## 3.1. VIBRATORY SCREEN

In the aggregate and mining industry, the screening process takes place both between crushing stages and also as the final stage of the process of classifying the final product. This makes the process very important for the quality of the final product and also for the efficiency of the entire operation.

The main components of the vibratory screen are the screen deck, the frame, the vibratory motor, or drive assembly and springs. The feeding distributor is also part of the screening process which has an important effect on the efficiency, and the most common feeding machine for screening is a conveyor belt. Based on all these components, the working principle of the vibratory screen is a frame that is mounted on springs, with the vibration transferred to the frame generated from an unbalanced mass or vibrator motors.

Several different parameters affect the screening performance efficiency and these are divided into machine and process parameters. Process parameters include the product characteristics and material feed. Figure 6 shows the overall view of the main elements of screening.

MAIN ELEMENTS OF SCREENING

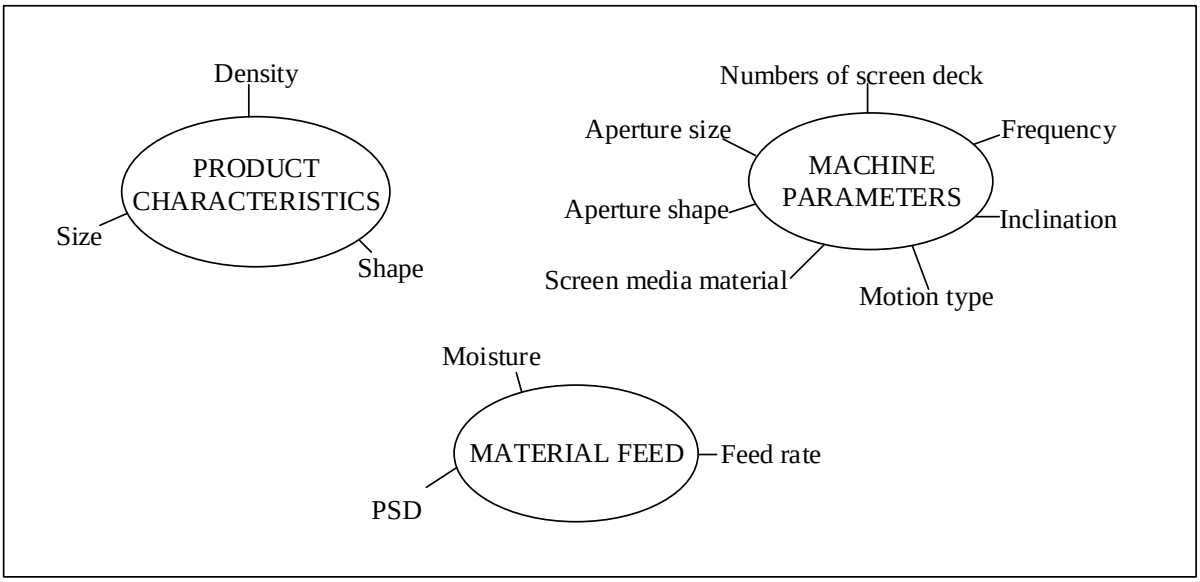



Figure 6. The main elements of screening.

*Type of motion*

The vibratory screens have different motion types based on the inclination of the screen deck; a circular motion along with the incline of the screen tends to tumble the material as it moves over the screen deck. Tumbling helps to keep material from hanging in the openings and makes it possible for smaller material to move from the upper layer of the material bed to the deck surface. The stratification works better if there is an inclination in the screen so that the material is assisted by gravity along the screen deck.

In the horizontal vibratory screen, there is little or no inclination. A linear motion imparts a back and forth action with some amplitude at some positive angle to the vertical. Therefore, the screen deck boosts the material and then drops away from it, and this action carries the material down the screen.

Another type of motion is elliptical motion, which is a combination of both circular and linear motion. Elliptical motion can be used in both horizontal screens and screens with a higher degree of inclination. Different types of screen motion are illustrated in Figure 7.

The feed rate of the material and size of the vibratory screen are two other parameters that affect choice of the screen motion type. The combination of these two parameters makes the material bed thickness. This means that if it is a mono-layer bed then the material doesn't need to be tumbled, so even a vibratory screen with a higher degree of inclination can have a linear motion.

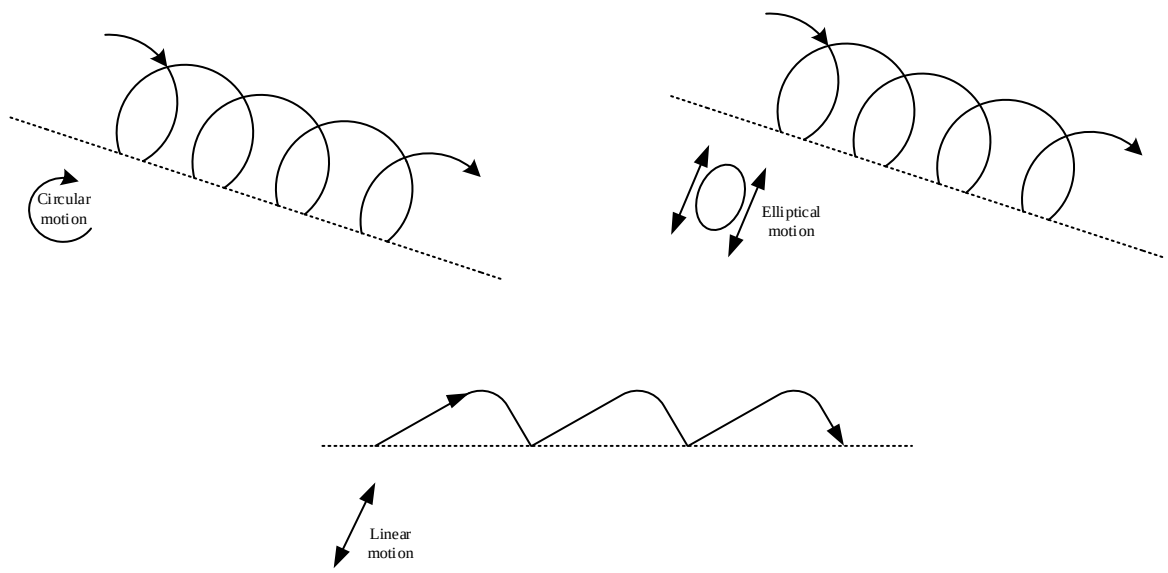



Figure 7. Schematic view of different motion types.

*Screen deck*

The number of screen decks in a vibratory screen depends on the requirements for the final products. A vibratory screen with two screen decks has three different final products as an output: the discharge of the product from the upper deck and the lower deck, and the product passing through the lower deck.

The size and shape of the aperture and the material of the screen panels that form the deck vary in different screens and applications. It is even possible for the same screen to use different types of screen deck. Selecting the right screen deck for each screening performance is one of the key factors in maximising the screening efficiency. There are mainly two types of screen deck: one is a panel which is manufactured of rubber or polyurethane material and the other is wire mesh, which is commonly made of steel.

For screening performance with high feed rates, panel screen decks are very popular. Both rubber and polyurethane materials offer excellent abrasion resistance, although rubber is used mostly for dry screening applications and polyurethane is generally preferred for wet applications. For the installation, the panels will be assembled to the sub-frame in each screen deck, which makes it possible to use different panels in the same screen deck. There are variations in the aperture shape in the panel deck, the most common shapes being rectangular and square, while others are circles, octagons, and hexagons.

Wire mesh is the cheapest type of screening deck, with the advantage of having a high proportion of open area, and it is relatively light compared to the panel deck. The large open area generally allows the screen to be smaller than a screen with modular panels for the same expected capacity. Increasing the wire thickness increases the strength, but decreases the open area and hence the capacity. Figure 8 and Figure 9 shows different categories of screen deck.

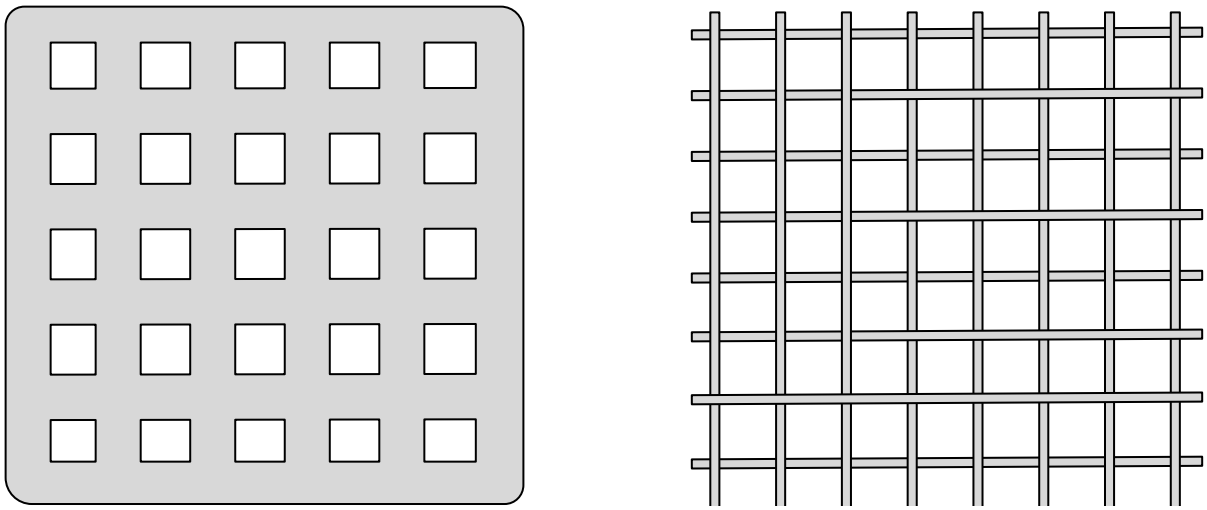


Figure 8. Illustration of a schematic view of a panel screen (left) and wire mesh (right).

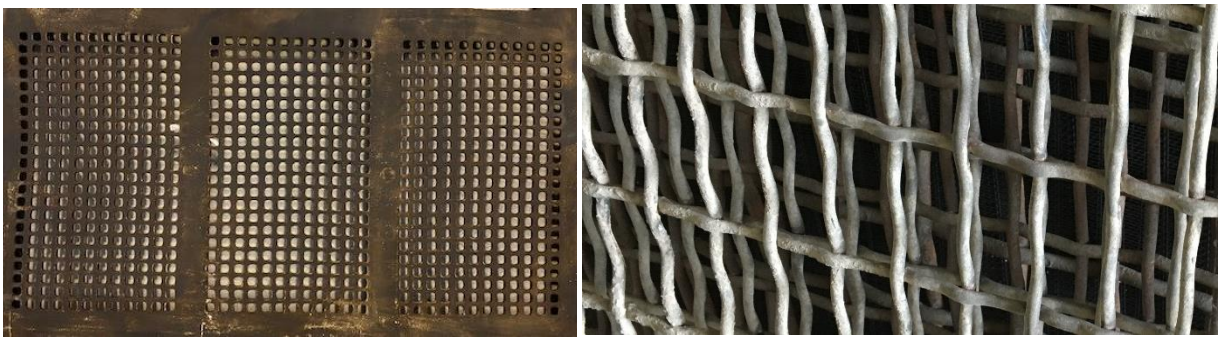


Figure 9. Illustration of rubber panel screen (left) and wire mesh (right).

The vibratory motor or drive assembly provides the vibration for the screen. Based on the stiffness of the spring, mass of the screen frame and decks the frequency is typically between 12-20 Hz. A typical amplitude is between 10 mm and 14 mm in vibratory screens.

## 3.2.VIBRATORY SCREEN MODELLING

Several studies have investigated the modelling of screening performance, aiming to predict the screening model to provide a better understanding of the screening process and improve the efficiency of the screening.

There are different definitions of screening efficiency, the simplest definition being how effectively steady-state screening produces variation in the mass of particles falling through the screen deck along its length. According to Wills and Finch (2016), the most common method for calculating the efficiency is to define the recovery of the finished product to fine stream. This means that the screening efficiency is the ratio of undersized material in the feed that actually passes from the screening media to the undersized material that should pass from the screening media. The efficiency is defined by Equation (1) present the efficiency for fine particles, where *e* is the undersized percentage in the feed and *v* is the undersized percentage in the overflow. If the coarse particle is more concern, then the recovery of oversize to overflow will be calculated as shown in Equation (2) where *O* is the mass flow rate of the coarse product stream and *F* is the mass flow rate of feed material to the screen.

$$E_U = \frac{e - v}{e(1 - v)} \tag{1}$$

$$E_O = \frac{O(1 - v)}{F(1 - e)} \tag{2}$$

### 3.2.1. EMPIRICAL MODELLING

There are several screening calculation methods available to predict screening performance. Many studies in the past have led to the development of empirical screening models to predict the classification functions corresponding to size fractions. One of these methods is the Karra method, which is only valid for cut apertures larger than 1 mm (Karra, 1979). The Karra model describes how a screen may be expected to perform during operation with different conditions. The model is based on the capacity of the screen, which is affected by the proportion of undersized material in the feed. The factors that affect the capacity of the screen are the standard conditions of the screen and the feed material. According to Karra (1979), the theoretical amount of undersized material that can be transmitted by the screen can be calculated by:

$$K = ABCDEFG \times screen\ area \tag{3}$$

In the Equation (3), the factors A, B, and C are the capacity, which is defined as the amount of undersize, oversize, and half size in the feed, respectively, and D is the location of the screen deck. Factor E is the wet

screening factor and F is the material density. The factor G is a near-size capacity factor which has a significant effect on the screening performance. If the value of *K* is almost equal to the quantity of undersized material in the feed, this means that the screen is good or well designed.

One of the studies in which the Karra model was adopted as a screen model was presented by Cotabarren et al. (2009), who showed that the output of the Karra model as an empirical approach has a great simplicity and high efficiency, since it manages to predict all the experimental data. This study applied the Karra model to a large-scale double-deck vibrating screen.

### 3.2.2. ANALYTICAL MODELLING

According to Soldinger (2000), two main processes occur during screening. One is the stratification process by which fine particles pass through spaces between other particles and come into contact with the screen deck. The other is the passage, which is the process of particles passing through the apertures in the screen deck.

The stratification process is dependent on the proportion of fine particles and the thickness of the material layer. The stratification rate is low when the proportion of fine particles is high and also a thicker material layer reduces the stratification rate because it increases the distance particles are transported through other particles. On the other hand, increasing the thickness of the screen bed material increases the transportation velocity over the screen deck, which means more time for particles to pass through the apertures (Soldinger, 2000).

According to Davoodi (2016), the proportion of different sizes of particles is the same in different layers at the beginning of the screen, but along the screen length, due to the stratification process, this proportion will change, which means that the smaller particles move to the bottom layer and larger particles move to the layers above. This process continues until all the fine material has moved to the bottom layer and is in contact with the screen media surface.

In work presented by Djokovic et al. (2017), the effect of some key factors such as the length and inclination of the screen deck on the screening, efficiency was analysed by using an analytical model, as a result of which one can see that the screening efficiency increases with the vibration amplitude and increase of the screen length.

### 3.2.3. NUMERICAL MODELLING

*DISCRETE ELEMENT METHOD (DEM)*

Initially, the theory of the discrete element method was introduced for studies of molecular dynamics. The principles of the discrete element method, also called the distinct element method, were then developed by Cundall and Strack (1979). DEM simulation has relatively recently been increasingly applied to the mineral and aggregate industry, from the simulation of the conveyer belt to the crushing process, such as for cone crusher and screen size classification. The reason that DEM has gained popularity is that it requires less resources than real test experiments. The disadvantage of full-scale experiments is that they require the process to be stopped, which costs production time and money and is also not as energy-efficient as simulation.

The DEM itself is an analytical tool that saves a lot of time compared to a full-scale experiment. One example which is common in analysing the output of the experiment is when sieving the material. The DEM makes it possible to track each fraction of the particle size distribution in the simulation.

In contrast to the continuum approach, discrete approaches model every single particle as a distinct entity and represent granular material as an idealised assembly of particles. The overall (macroscopic) system behaviour results from individual particle interactions. This makes the discrete approach very good for investigating phenomena occurring at the length scale of the particle diameter and simulating the bulk behaviour of particles.

There are some calibration challenges that arise in using DEM compared to real test experiments, one of these being the particle shape and the effect that it has in the stratification and passage processes. The most popular method for modelling the particle shape is the use of clumps (clusters or multi-spheres), and no convincing evidence that other shape representations outperform clumps in modelling natural materials such as crushed rock, soil, and seed grains was found in the work by Aghlmandi Harzanagh et al. (2018), where a simple procedure was developed to generate clumps which better resemble real aggregate particles than spheres. The influence of the clump shape on the heterogeneous stresses within an aggregate was investigated, and it was found that more angular clumps lead to a higher degree of homogeneity.

The effect of using spherical particles instead of the real shape of particles was investigated in different research by Plassiard et al. (2009), who showed that, when using spherical particles in simulation, the bulk friction or shear strength of the assembly is usually too low compared to real granular material.

The advantage of using clumps is that efficient algorithms can still be used for contact detection and determining the contact point used for spherical particles. However, to accurately model both sharp edges and smooth surfaces, a large number of spheres would be required, which will increase the computation effort. It is also possible that multiple contacts can occur between clumps, which are not necessarily true for the same natural particles.

### *NUMERICAL MODELLING FOR SCREENING MODEL*

Due to several different factors that affect screening, it is a complex process, which makes it difficult to have an effective and simple calculation procedure when designing the machine or choosing a screen for a crushing plant. One of the models that have been used recently to make it easier to understand the process is a numerical model using the Discrete Element Method (DEM) (Li et al., 2015). The advantage of this kind of method is the possibility of starting the number of simulations with different process conditions, which are truly time-effective.

Several studies have been done to validate using DEM simulation to simulate screening behaviour. According to Jahani et al. (2015), the industrial and laboratory banana screen shows different behaviour when the design parameters are changed. One important parameter which has been studied to validate the DEM simulation is the particle shape, and Delaney et al. (2012) carried out experiments and simulations to test the validity of the spherical particles in their DEM model simulating real granular screening processes. The spherical particles in the lower feed rate for simulations are more realistic than real experiments with non-spherical particles. On the other hand, with a higher feed rate and a thicker particle layer, there are significant deviations between real experiments and simulations (Delaney et al., 2012).

Some screen factors and design parameters have been studied in previous works. Dong et al. (2009) showed that when the inclination of the discharge end is too small or too big the screening efficiency decreases

because of the particle velocity. This means that there is an optimum inclination which is typically around 5°. The vibration amplitude was also studied by Dong et al. (2009), who found that by decreasing the vibration amplitude and frequency the screening performance can be improved. The increased passing percentage of small undersized particles was mainly at the feeding point on the first deck (Dong et al., 2009). Some other studies analysed the frequency, which shows the same result, that the screening efficiency does not increase with an increase in vibration frequency (Chen and Tong, 2009).

There are some other screening conditions applied in real experiments such as airflow and wet screening which are not covered by DEM. Li et al. (2012) studied the effect of the airflow velocity in terms of grains and short straws by linking Computational Fluid Dynamics (CFD) to DEM. Similar work was done by Fernandez et al. (2011) to analyse the effect of water flow in a wet screening process.

# 4. RESEARCH APPROACH

*The aim of this chapter is to:*

- *Introduce the research methodology used in this thesis.*
- *Describe the Discrete Element Method.*
- *Discuss research validation.*

## 4.1. RESEARCH METHODOLOGY

This work was carried out at Chalmers Rock Processing System (CRPS) in the Machine Elements group. The focus of the group is on machines and systems for the production of crushed rock materials in both aggregate production and minerals processing. The research methodology which has been followed in this thesis is based on the methodology described by Evertsson (2000) and illustrated in Figure 10.

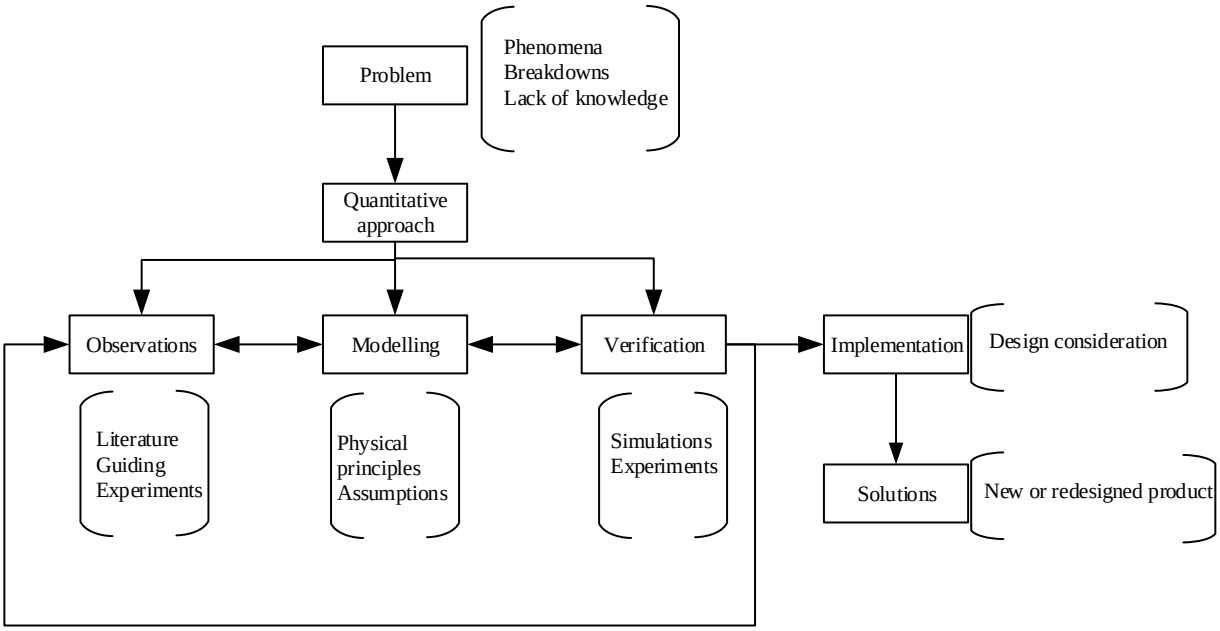



Figure 10. Problem-oriented research methodology.

The process of applying a quantitative study begins with a researcher selecting a topic. Quantitative researchers typically start with a general area of study or an issue of professional importance. This must be narrowed down to a specific research question that can be addressed in the study, and the final step is the collection and analysis of numerical data (Choy, 2014).

Observation is a technique that involves systematically selecting, watching, listening, reading, touching, and recording the behaviour and characteristics of objects or phenomena. Observation is used as a method for collecting data about people, processes, and cultures (Kawulich, 2012).

The first step is to define the system that is to be modelled and the goals for the model, so defining the system generally involves drawing the boundaries around what you want to model, and then determining the key variables and the relationships between those variables based on assumptions and physical principles.

Validation of the research methodology and its results is a fundamental element of the process of research. This can be done by using tools such as a simulation platform or experimental data. The following two sections describe the methodology that has been used for verification of the research in this thesis.

## 4.2. DISCRETE ELEMENT METHOD (DEM)

The development process of engineering products and systems often includes testing to evaluate their reliability. In many cases, products and systems may be designed for long service lives and high reliability, and the experiments might be expensive for complicated systems. One strategy that can be pursued is to accelerate the development process and reduce product development costs is the use of computer simulation models.

The Discrete Element Method (DEM) is a special class of numerical schemes for simulating the behaviour of particles and interacting bodies. The analysis process consists of three main computational steps: internal force evaluation, in which contact forces are calculated; integration of equations of motion, in which element displacements are computed; and contact detection, where new contacts are identified and broken contacts are removed. In a DEM analysis, the interaction of the elements is treated as a dynamic process that alternates between the application of Newton's second law and the evaluation of a force–displacement law at the contacts (Tavarez and Plesha, 2007).

The main principle of DEM is based on contact detection algorithms and applying a suitable contact model based on the requirements. Three different elements are considered in the contact detection algorithm: acceleration, velocity, and position. For the contact model, force and contact are the main elements. The relation between these elements is shown in Figure 11.

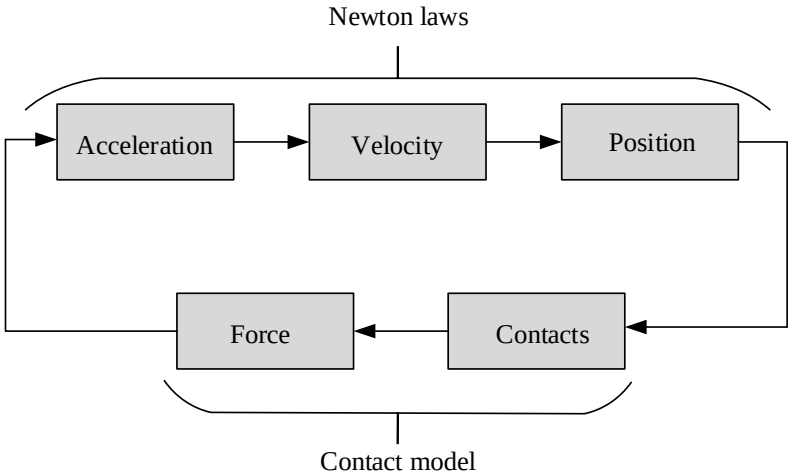



Figure 11. The main principle of DEM.

Particles can have a variety of shapes, although most often they are considered as circular or spherical due to the simplicity and speed of the contact detection algorithm. An important part of DEM simulation is to define the particles, which can be done in two different ways. One option is to define the particles by importing the model from the DEM library, where the particles are grouped by the numbers of spheres and shapes. A second way to define the particles is by customising their shape and size by using a coordinate system.

After defining the particles, the next step is to choose the contact model for particle-to-particle and particle-to-geometry interaction. The necessary steps in DEM for defining the particles set-up for simulation are shown in Figure 12.

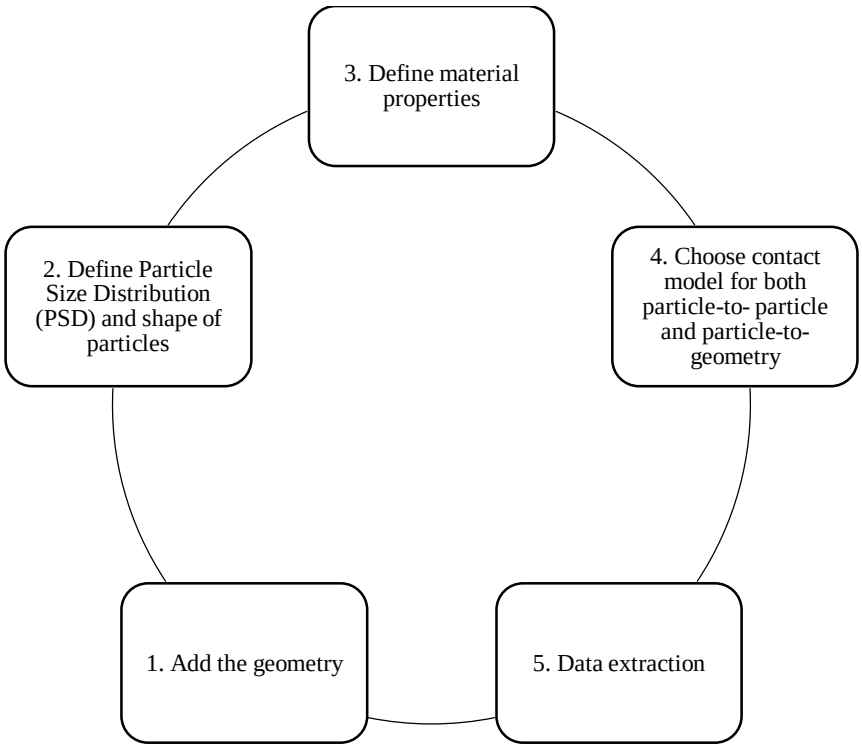



Figure 12. Five steps to generate the particles for simulation.

There are two types of basic contact models in DEM simulation: the linear elastic model and the nonlinear elastic model. Linear elastic models can just be simplified as a spring, while the non-linear normal elastic model usually refers to the Hertz model, which is more complicated. The disadvantage of the linear contact model is that the shape of the particles is not accurate enough in the calculations.

The simple linear contact model contains force and displacement, where the increase of the contact force linearly connects with the increment of the displacement. The contact force can be calculated by Equation (4).

$$\vec{F}_i^n = -K^n \vec{U}^n \tag{4}$$

where $K^n$ is the normal stiffness, $U^n$ is the normal overlap displacement, and $n_i$ is the unit vector whose direction is the same as the overlap displacement. The linear elastic contact model is a simple, effective contact model with fairly high efficiency, and it is more commonly used than the Hertz–Mindlin model. This is because in most simulations the elastic property is the main factor that should be considered. But in a simulation where the shape of the particles has a big impact on the validity of the simulation the Hertz–Mindlin model is a better option.

The Hertz–Mindlin contact model is a non-slip model that uses a linear spring dashpot model (Just et al., 2013). Figure 13 shows the interaction between two particles with a frictional element between the normal force and the tangential force.

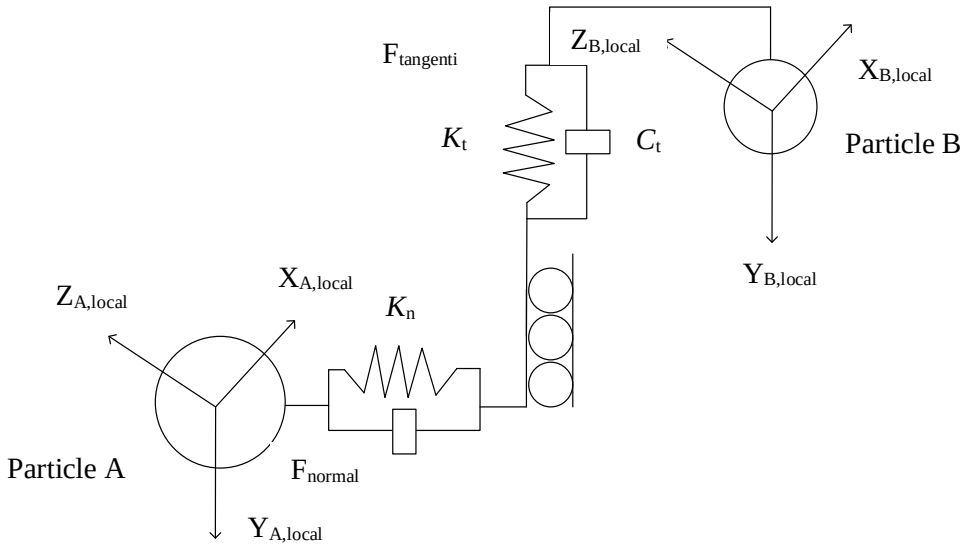



Figure 13. Graphic illustration of the Hertz–Mindlin contact model.

The Hertz–Mindlin contact force model is based on the normal force and the tangential force between particles. The normal force is based on Hertz's contact theory and the tangential force is based on Mindlin–Deresiewicz (Keer et al., 1991).

The normal force $F_n$ has two terms: a spring force and a damping force. The tangential force $F_t$ also has two terms: a shear force and a damping force (Just et al., 2013; Maw et al., 1976). The normal and tangential force can be calculated by Equations (5) and (6).

$$F_n = -K_n \Delta x + C_n V_n \tag{5}$$

where $K_n$ is the elastic constant for normal contact, $\Delta x$ is the distance between the two particles, $C_n$ is the viscoelastic damping constant for normal contact, and $V_n$ is the normal velocity of the particles.

$$F_t = -K_t \Delta x + C_t V_t \tag{6}$$

where $K_t$ is the elastic constant for tangential contact, $\Delta x$ is the tangential displacement vector between the two spherical particles, $C_t$ is the viscoelastic damping constant for normal contact, and $V_t$ is the tangential particle velocity.

In the Hertz–Mindlin contact model, the elastic constants $K_n$ and $K_t$ are calculated based on material properties and are given by Equations (7) and (8).

$$K_n = 2E^* \sqrt{R^* U_n} \tag{7}$$

$$K_t = 8G^* \sqrt{R^* U_n} \tag{8}$$

where Young's modulus $E^*$, the equivalent radius $R^*$, normal overlap $U_n$, equivalent shear modulus $G^*$, equivalent mass $m^*$, the viscoelastic damping constant for normal contact $C$, particle radius $R_1$ and $R_2$ and $m_1$ and $m_2$ as a particle masses are given by

$$\frac{1}{E^*} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \tag{9}$$

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2} \tag{10}$$

$$\frac{1}{m^*} = \frac{1}{m_1} + \frac{1}{m_2} \tag{11}$$

$$C = \frac{1}{\sqrt{\ln^2(e) + \pi^2}} \tag{12}$$

Defining particles is an important step for DEM simulation due to the effect of properties such as a particle shape and density on screening efficiency. Based on the objective of each paper, particles with user-defined diameters were employed to match the planned simulations. All of the particles were non-spherical in shape, as very different results are obtained using one spherical particle in the simulations versus multi-sphere particles. Multi-sphere particles produce more realistic results because these particle shapes are closer to those of real particles. Figure 14 shows the example of some particle shape that was used in the simulations where all spheres had the same material properties.

The characteristic of particles varies in different simulations, as long as particles used for the classification process and not for breakage is not critical to have the breakable particles, this saves calculation time.

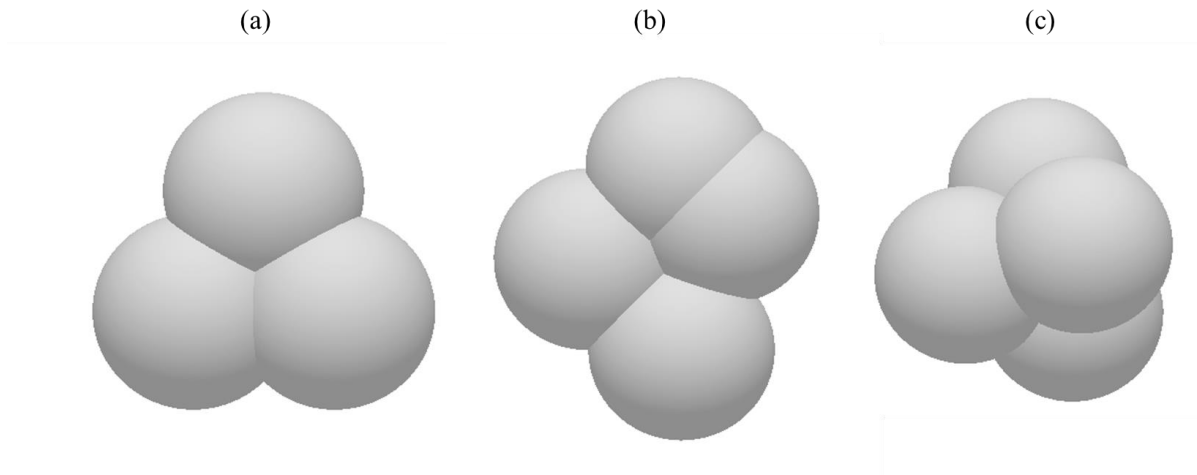



Figure 14. Example of (a) three spheres, (b) four spheres and (c) five spheres modelling particle shape.

Regarding the particle characteristics, some parameters need to be modified for each simulation, these parameters affecting the frictions between the particles and also the contact model parameters. Table 1 shows the summary of these parameters which have been used for all simulations. The coefficient of restitution between particle-particle is 0.2 and between particle and screen is 0,6 and the and the coefficient of static Friction is 0,6 for the particle-particle collision. (Atkins, 2013)

The shear modulus for a particle is 24 Mpa and for the screen is 79 GPa. The Poisson's Ratio is 0.3 and 0.2 for particles and screen. (Oxford, 2020)

Table 1. Summary of simulation parameters.

| **Material Properties** | **Poisson's Ratio** | **Shear Modulus** | **Density** |
|---|---|---|---|
| Particles | 0.3 | 24 MPa | 2500 kg/m$^3$ |
| Screen (Steel) | 0.2 | 79 GPa | 7800 kg/m$^3$ |
| **Collision Properties** | **Coefficient of Restitution** | **Coefficient of Static Friction** | **Coefficient of Rolling Friction** |
| Particle-particle | 0.2 | 0.6 | 0.01 |
| Particle-screen (Steel) | 0.6 | 0.45 | 0.01 |

## 4.3. EXPERIMENTS

Model validation is the process of quantifying the agreement between the model prediction and experimental data in order to guarantee that the prediction model can represent the actual physical system well. To achieve acceptable validity, a number of experiments need to be done.

Laboratory experiments provide cost-effective means of quantifying processes and evaluating the boundaries of the validity of the theory. Studying different parameters in full-scale experiments is usually costly and mostly difficult to achieve because of the non-adjustability of industrial full-scale machines. Therefore, a specially designed laboratory-scale vibrating screen was designed and built, allowing for observation of the motion of particles during the screening process and precise control of the screening parameters. Figure 15 shows the laboratory-scale screen model used in the experiment and schematics of the model used in the simulations and Figure 16 shows a photo of the laboratory-scale screen model used in experiments.

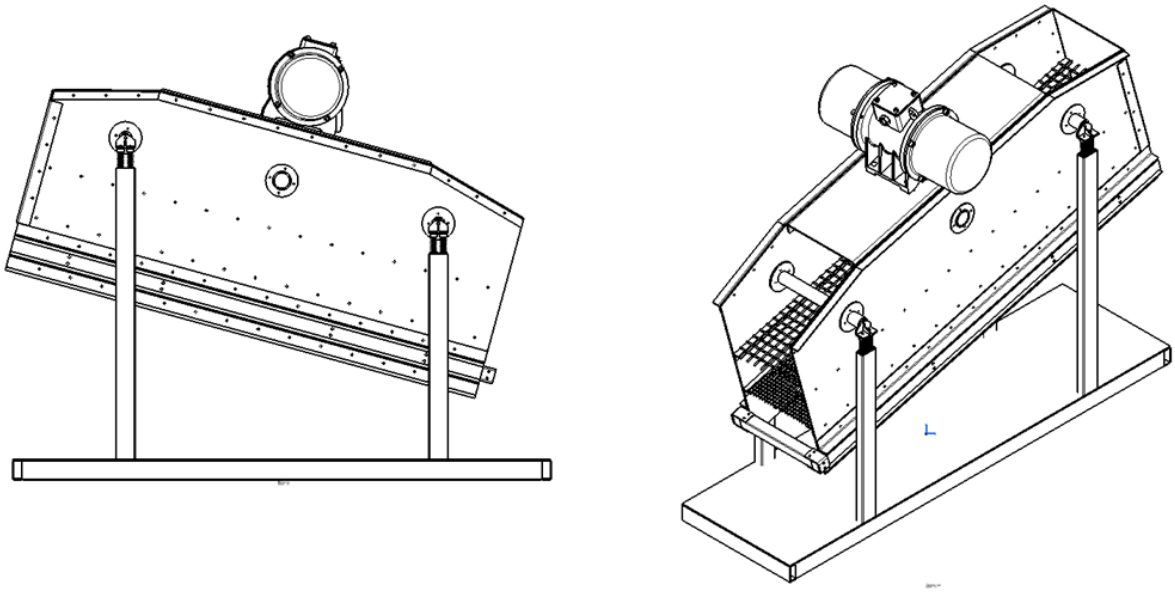


Figure 15. View of CAD model of laboratory screen.

Figure 16. A photo of the laboratory-scale screen model used in experiments.

The screen has two decks, allowing particles to be separated into an oversize product discharged from the end of the upper and lower deck and an undersized product passing through the aperture by the upper and lower deck. Figure 17 shows the screen deck aperture shape and scale size for both the upper and lower decks.

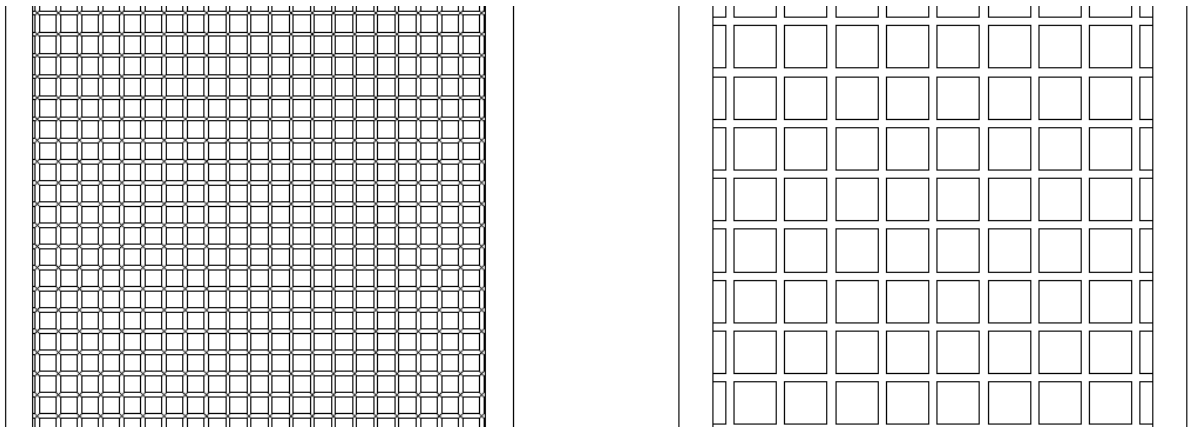


Figure 17. The aperture shape for the upper deck (right) and lower deck (left).

A summary of the operational and geometrical parameters is shown in Table 2. The type of motion is linear and the amplitude of the screen can be adjusted by changing the angle between the two eccentric unbalanced blocks in the vibratory motor or by changing the frequency of the motors by using a frequency converter. Other parameters that can be adjusted are the screen aperture size and shape by changing the screen deck. The feed can be adjusted by the bed thickness and velocity of the feed conveyor.

Table 2. Geometrical and operational parameters for laboratory screen.

| Parameters | Value |
|---|---|
| Screen length | 1500 mm |
| Screen width | 300 mm |
| Aperture size | 10 x 10 – 25 x 25 mm |
| Wire diameter | 2.5 mm |
| Deck material | Steel |
| Inclination | 15° |
| Amplitude | 1.5 to 9.5 mm |
| Vibration motion | Linear |

# 5. RESULTS AND DISCUSSION

*The aim of this chapter is to:*

- *Discuss the general ideas from all papers.*
- *Discuss the result of the papers based on different screening elements.*
- *Define the verification and validation process.*

## 5.1. GENERAL

During this research work, different screening parameters have been selected for investigation by using DEM to analyse the screening behaviour. For the material characteristics, the particle density has been studied to understand the effect of density on stratification and the passage rate.

Some machine parameters such as the motion type of the screen deck have been investigated to understand how the way that the particle moves along the screen deck is affected by changing the motion type. Also, three different screen deck materials have been studied: rubber, polyurethane, and wire mesh. The main purpose of this study is to examine the effect of the open area on the passage and the material of the screen media on particle movement.

One problem that arises during the screening process is wear on the screen deck. The wear will change the aperture size and geometry, this will reduce the product quality and also often decrease the utilisation of the screen, causing a loss of production because of the need to stop the whole process to replace the screen deck. Different calculations have been made by using the various models for wear on the surface.

For validating the DEM model for the screening process, a laboratory-scale vibratory screen has been constructed. The main purpose is to determine how accurate the simulations are compared to real tests. The same condition has been set up in the simulations and experiments. DEM is the simulation platform with the main purpose of tracking the particles and their interactions and makes the platform suitable for simulating the screening behaviour in different conditions.

## 5.2. MODELLING OF SCREENING KEY FACTORS

### 5.2.1. DIFFERENT MOTION TYPES

Paper A, DEM is used to analyse different types of motions by focusing on the factor of the amplitude in elliptical motion. By reducing the amplitude of the elliptical motion, the sections in the banana screen are differently affected depending on the process of screening. The motion type has less effect in the sections that have passage or a free-fall process as the main effect. In the sections with a larger thickness of bed material, stratification becomes an important effect, and in these sections elliptical motion has a stronger impact on the stratification process.

Three different motions are simulated in this paper. The first simulation was elliptical motion with a 6 mm amplitude. The second simulation used elliptical motion with a 3 mm amplitude, and the third simulation used a 1 mm amplitude. All three motions have the same amplitude in the orthogonal direction which is 14

mm. The purpose of minimising the amplitude is to approach linear motion, while simultaneously studying the amplitude effect on the screening efficiency. Figure 18 shows the amplitudes used in the simulations.

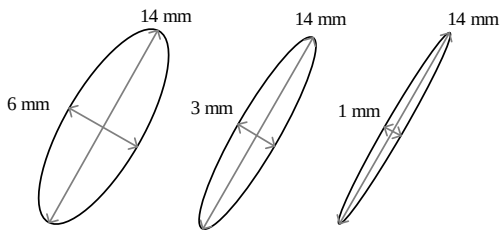



Figure 18. Images of different amplitudes used in simulations with elliptical motion. From left to right, 6 mm, 3 mm and 1 mm.

Three simulations of a banana screen were performed in this work. In these simulations, the efficiency of the screen was analysed by changing the motion type as one of the conditions of the simulation. Geometric bins were generated for the simulations to make it possible to export the data. Each section had one geometric bin. A schematic illustration of the screen decks and bins is shown in Figure 19.

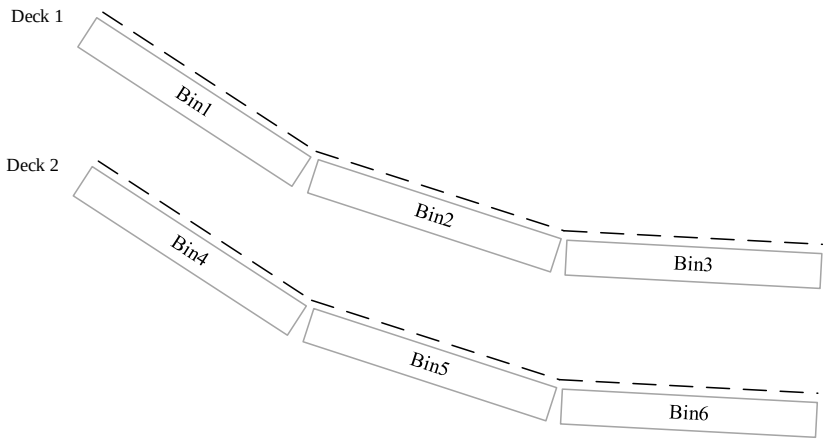



Figure 19. Schematic illustration of the geometric bins.

The particles are stored in the simulation until the process reaches steady-state (Cleary, Sinnott et al., 2009). This means that the number of particles in the simulation is stable. In this work, steady-state conditions were reached in all three simulations after 10 s.

The total number of particles was studied by comparing the number of particles that passed through each bin for all three simulations. The results show that the number of particles is very similar in Bin 1 in all simulations. Bin 1 and Bin 4 are located under the feeding point of the screen deck; hence, gravity was an important factor that affected the passage of particles, which meant that the effect of passage was greater than the effect of stratification in Section 1.

The number of particles that passed Section 2 in all simulations was greater than that in Section 1 because the stratification became a more important effect in Section 2 of Deck 1. The results show that minimising the amplitude of the elliptical motion had a negative effect on the screening efficiency. Bin 5 in Section 2 had the same effect as Bin 1 and Bin 4; the effect of passage was greater than the effect of stratification

because of free fall. Because of the smaller angle of the deck in Bins 3 and 6, the material accumulated, and the process of stratification became more important.

The results from Bin 3 and 6 show that an elliptical motion with a 6 mm amplitude is more efficient than a 3 mm and 1 mm amplitude. Figure 20 shows the images of the simulation after 12 s, illustrating that the material bed thickness in Section 3 increased by minimising the transverse amplitude of the elliptical motion.

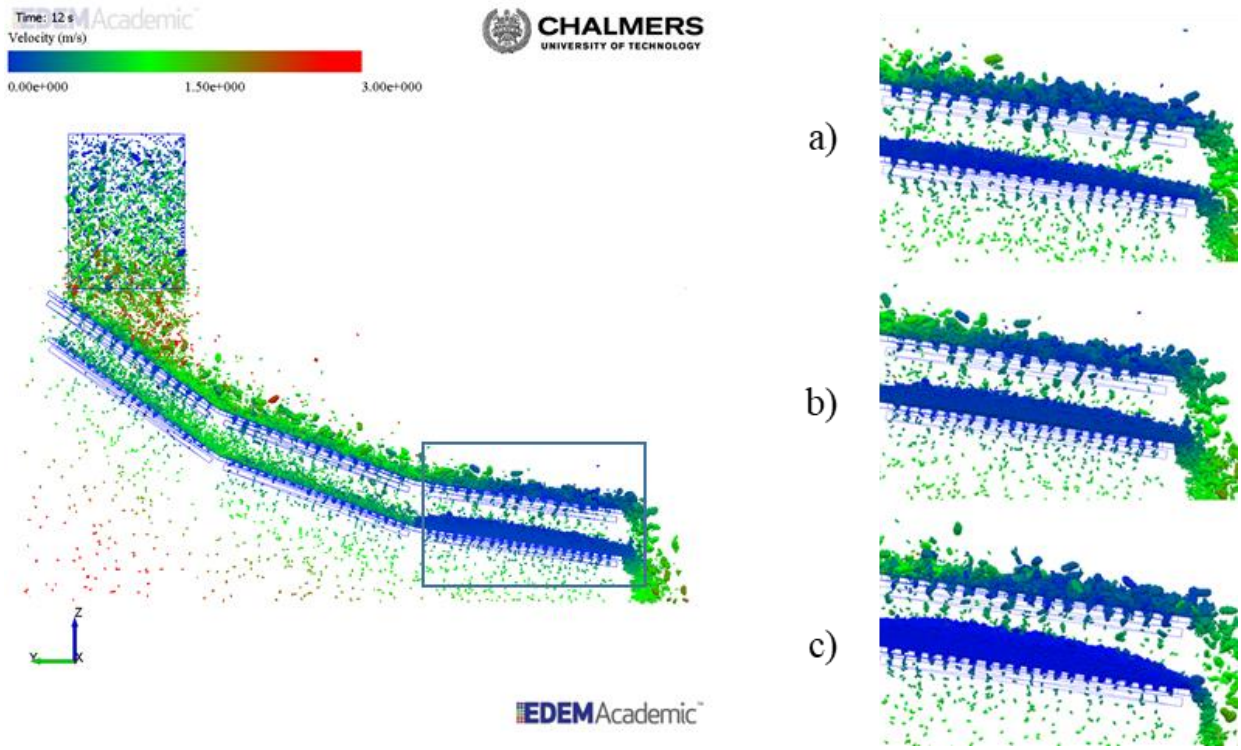



Figure 20. Illustration of simulation after 12s: a) elliptical motion with 6 mm amplitude; b) elliptical motion with 3 mm amplitude; c) elliptical motion with 1 mm amplitude.

The total number of particles and the particle size distribution generated in all three simulations were the same. Better passage efficiency was achieved by using elliptical motion with a higher transverse amplitude. In this case, the first simulation had a 6-mm amplitude, and the second and third simulations had a 3-mm and a 1-mm amplitude, respectively. Figure 21 shows the percentage of particles that passed through each section in relation to the total number of particles.

The results of the simulations show that the movement velocity in two coordinates has a positive effect on the particle passage, which causes the material bed to be thin because the particles have a higher chance of contacting the screen deck, causing the screening efficiency to increase. Different deck slopes also affected the efficiency of the banana screen.

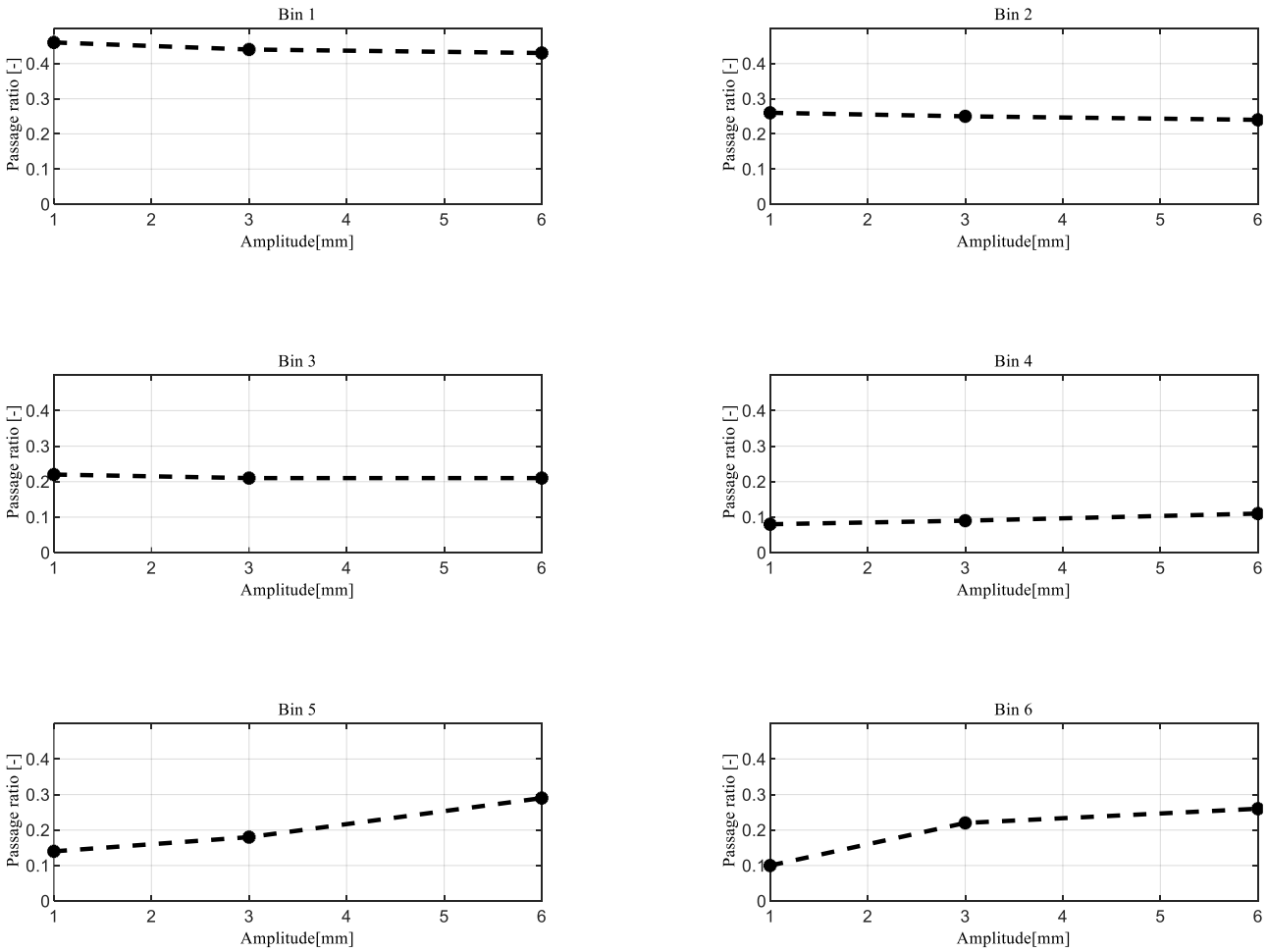



Figure 21. The ratio of particles that passed through each section.

### 5.2.2. SCREEN DECKS' APERTURE SHAPES AND MATERIALS

In Paper C, the simulation results show that the number of particles that pass through the screen deck varies depending on the configuration of the screen media. The number of holes in the wire screen deck is more than in the rubber and polyurethane decks and thus has a larger effect, especially in the feeding point before building up the particle bed. When the feed rate is low, there will be a difference in the screening performance. By increasing the feed rate, the material bed will start to build up, and the stratification process starts, which affects the efficiency of screening.

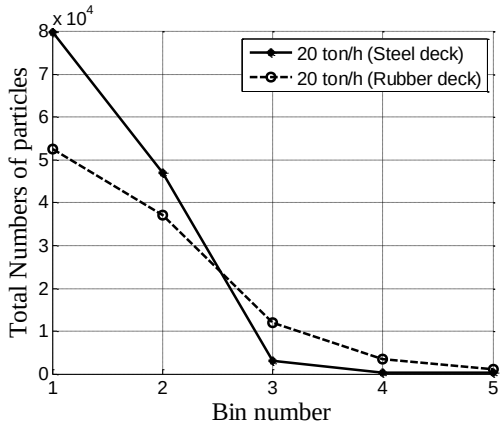
The number of particles that bounce on the steel screen deck is less compared to the values for the rubber and polyurethane decks, but the difference is not excessive and only affects the single-layer particles.

The simulation shows that the effect of the aperture shape on the screening efficiency is not significant, but different sections on the screen deck have different passage rates based on the aperture shape.

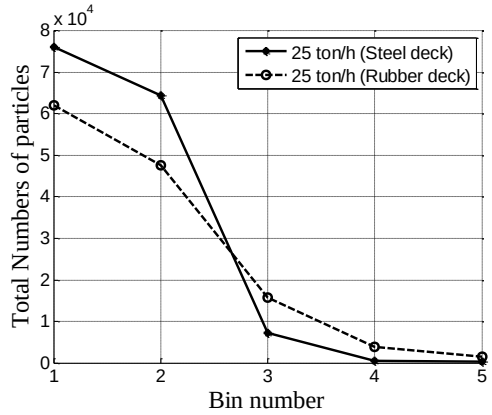
*Effect of the aperture on screening efficiency along screen length*

Further analysis was carried out to examine the number of particles passing through the screen at different sections along the whole screen length during a time period. This was done by using geometrical bins and by recording particle coordinates when they pass through the bins in the model. Figure 22 shows the relative number of particles passing through at different sections of the screen, at a longer interval of 1500 mm, for a period of 15-s simulations.

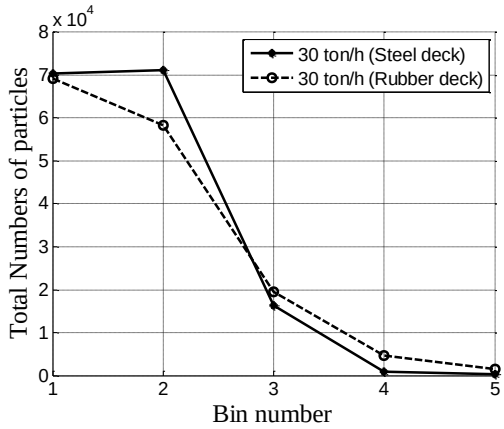
The amount of the particles passing through Bin 1 is higher in the screening process with wire mesh when the feeding rate is 20 tons/h and 25 ton/h. By increasing the feed rate to 30 tons/h, the number of particles in both the panel and wire mesh deck in Bin 1 is almost the same. Once the feed rate increases to 35 tons/h and 40 tons/h, however, the panel deck is more efficient. The reason for this is that the number of holes in the wire mesh deck is higher compared to the panel deck because of the thinner wire, which means that the particles have more chance of passing through the deck before building up on the material bed. As more material is fed onto the screen, the accumulation of particles spreads onto the whole feeding region, and a material heap forms, as seen in Figure 23 for low and high feeding rates.



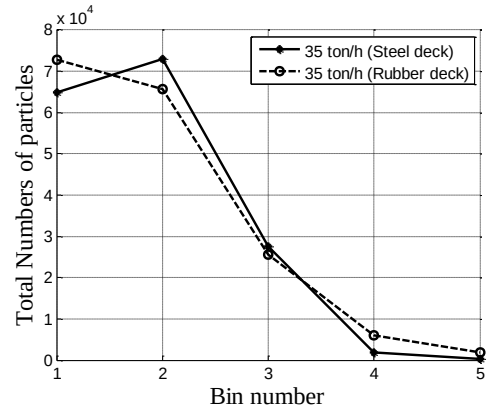

(a)



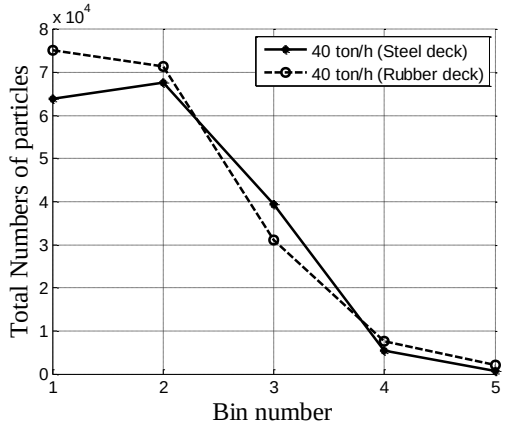

(b)




(c)



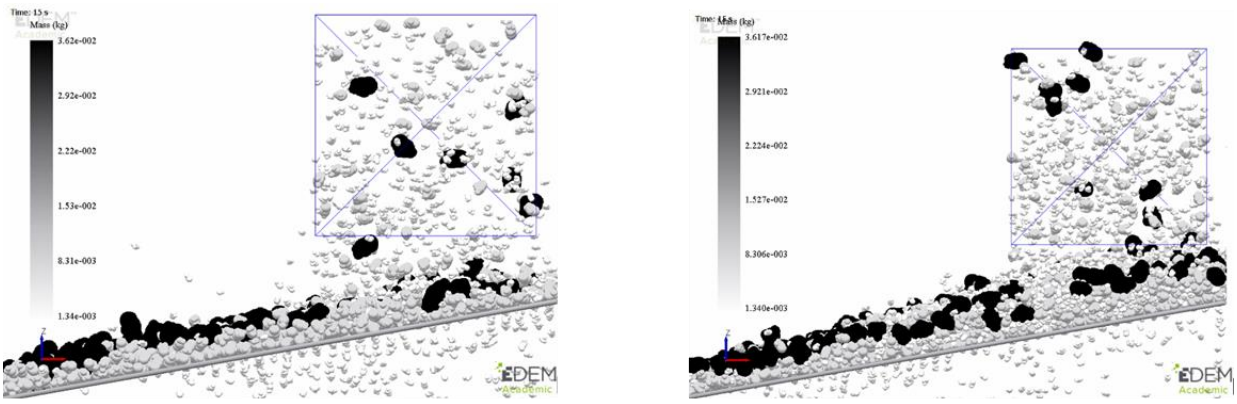

(d)




(e)

Figure 22. Analysis of screening performance along the screen length.

When the material bed on the screen deck has built up, then the stratification process will affect the screening, which means that small particles still have a chance to travel across the interstitial gaps between large particles near the screen and thus pass through the apertures in the feeding region. The reason that more particles pass through Bin 1 in the panel deck compared to the wire mesh at a higher feed rate is that the particle velocity along the screen deck is less when using the rubber panel deck. Therefore, there is more time for the stratification process to take place, and the particles have more chances to reach the screen deck. The average velocity for particles along the panel deck is 0.56 m/s, whereas in the steel deck it is 0.68 m/s in the simulations. Figure 24 shows the average particle velocity in both the panel and the steel deck at different feed rates. By increasing the feed rate, the particle velocity will decrease because of the number of collisions between the particles increases due to more material on the screen deck.




(a) (b)

Figure 23. (a) The particle bed in 20 ton/h feeding and (b) in 40 ton/h feeding.

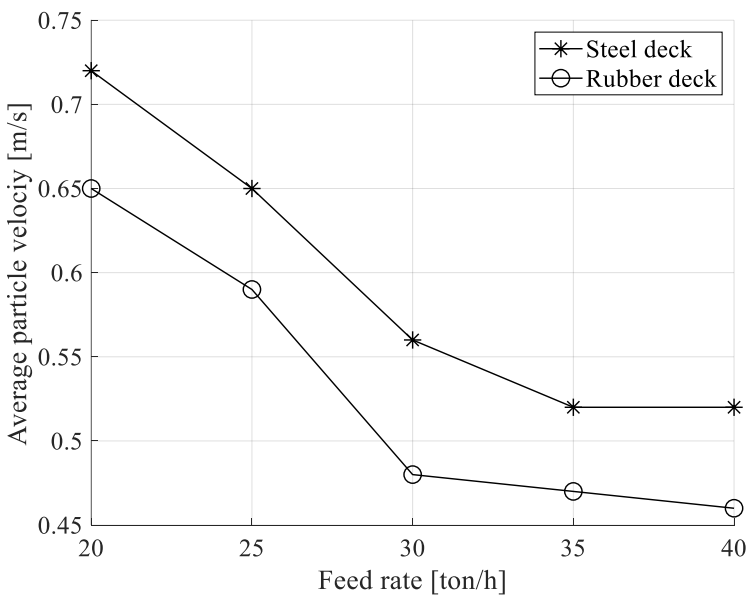



Figure 24. Average particle velocity at different feed rates.

As seen in Figure 22 for Bin 2, the scenario is the same as Bin 1, which means that the material bed still has the same effect on screening in this section. By decreasing the thickness of the material, the layer particles have more chance to reach the screen deck and pass through. As the particles travel along the screen surface, more and more undersized particles pass through the apertures.

The stratification process depends on the difference in the particle size, which means that an increase in the difference in particle size will increase the stratification (Soldinger Stafhammar, 1999). The particle size distribution (PSD) in all of the simulations is the same; this is because the simulation conditions are the same for the stratification process. A large number of fine particles will slow down the material transfer during the stratification; this can be seen in Figure 23(a) and Figure 23(b). When the proportion of fine particles is low, the interaction with other particles is less, which means that it is easier for small particles to pass through spaces between larger particles. Since the feed rate is low, the undersized material will be included in the bottom layer, which has a higher probability of passage. As shown in Figure 22(c) to Figure 22(e), by increasing the feed rate, the total numbers of particles that pass through Bin 1 increase in both the panel and wire mesh decks. This is because more fine material feeds to the screen. However, it causes a thicker layer of material, which will result in more time needed for the undersized material to stratify in the space between the oversized materials.

The passage process depends on the number of fine particles that have contact with the screen surface, i.e., the more particles that come into contact with the screen surface, the higher the probability of passage.
The rate of passage will decrease when the smallest particles have passed through the screen deck in the first two sections. In the simulation with 20 and 25 ton/h feed rates, the number of particles that pass through Bin 4 and Bin 5 is almost zero. Next, by increasing the feed rate, more fine particles travel along the screen deck, as the probability that they have contact with the screen deck decreases due to a thicker material bed layer building up. They therefore continue to move along the screen deck, passing through the deck in Bins 4 and 5, as can be seen in Figure 22(d) and Figure 22(e).

The mathematical model from Soldinger (1999) shows the relationship between the number of material layers and the passage probability, which proves that the probability of passage will increase when the screen surface is covered by one layer of fine particles. The rate of passage for fine particles through the apertures is calculated by the mass of a single-particle layer of fine material that covers the entire screen surface and the parameters that determine the rate of passage.

To track the fine particles on different screen deck materials, particles with the same size and same amount has been generated. Figure 25 shows that the amount of particles of type 2 that passes through Bin 1 in the wire mesh deck is higher compared to the panel deck because of the greater number of holes in the wire mesh screen deck. This causes more material to pass through the screen deck by free fall in the feeding point. In the other sections of the screen, a material bed has been formed, and the number of type 2 particles that pass the screen deck is almost the same because the stratification process has occurred.

To be able to fully analyse the different types of screen decks, the effect of the material for both wire mesh and rubber panels screening media should be studied as well. Beside the shape of the aperture, the material is also different; for the wire mesh the material is steel and the panel is rubber or polyurethane. Both steel and polyurethane are stiff enough that the aperture size is not affected by the load of material. On the other

hand, rubber has a different elastic behaviour; when calculating the maximum load from the simulation in one area of the screen deck, the bending of that area has been calculated, but is very relatively small and does not affect the aperture size.

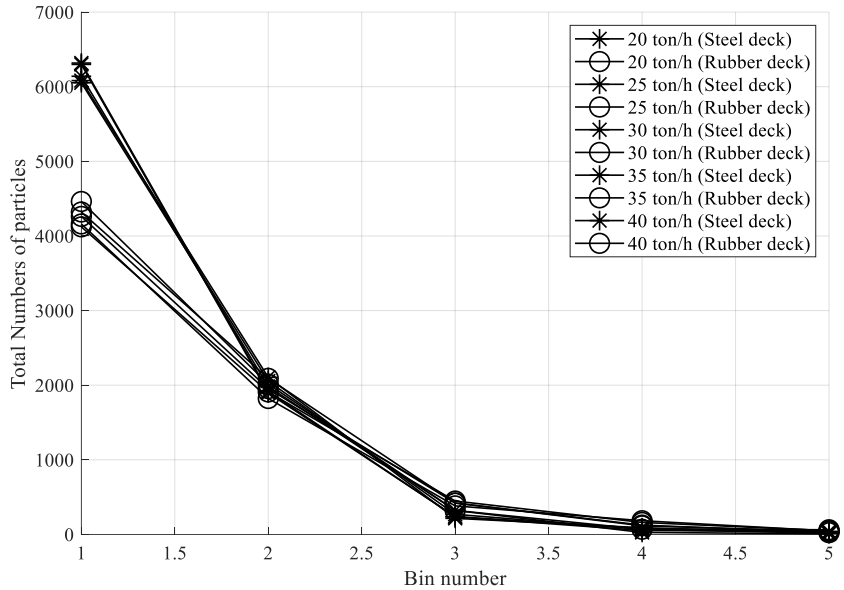



Figure 25. Tracking the passage of particle type 2 along the screen deck.

Furthermore, the effect of different screen media materials on the number of bounces for one single particle moving over the deck was analysed. The reason for this analysis was that increasing the number of particle bounces increases the number of interactions with the screen deck, which in turn increases the probability of passage. This was done by running the simulations with a single particle, which was big enough not to pass through the apertures. The study was done in two different ways. First, the total number of particle contacts with the screen deck by time step was analysed. For each screen deck material type, three simulations were done with the same particle but with different starting positions based on the position of creating the particle. Figure 26 shows the number of particle bounces for the different screen deck materials. The number of contacts on the steel screen deck was marginally lower compared to the rubber and polyurethane decks. The reason for this was that the damping ratio is greater on the steel deck.

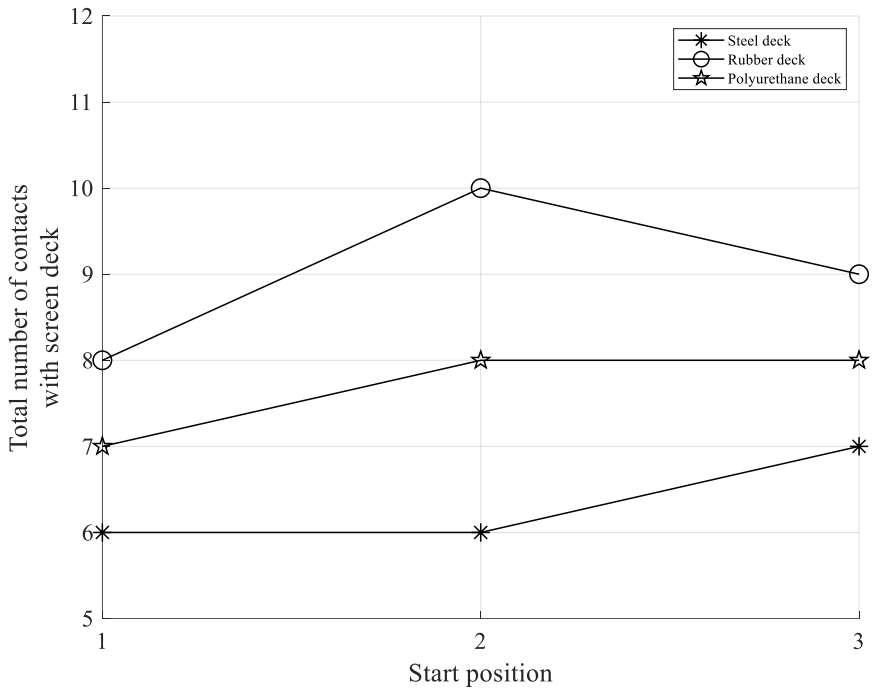



Figure 26. Number of bounces on different screen deck materials.

This analysis is for a single particle and can be compared to a single-particle layer. However, when the material bed builds up, interaction between particles will appear, which affects the number of bounces and the time required for particles to travel along the screen deck.

There are a number of models that define the screening performance in different process conditions. In this paper, the mass balance model presented by Soldinger (2002) was analysed by using MATLAB to study the passage rate along the screen deck.

A comparison was made between the steel wire mesh and panel deck media. The feed rate and size distributions were fixed. The model presented by Soldinger (2002) allows a wider size distribution since it is designed to simulate a population of particles subjected to screening. The size distribution was chosen to be in the same size range as for the DEM simulation. In Figure 27 the simulation result shows that the steel deck is more efficient than the panel deck in the feeding point; this result is very similar to the DEM model presented in Figure 25.

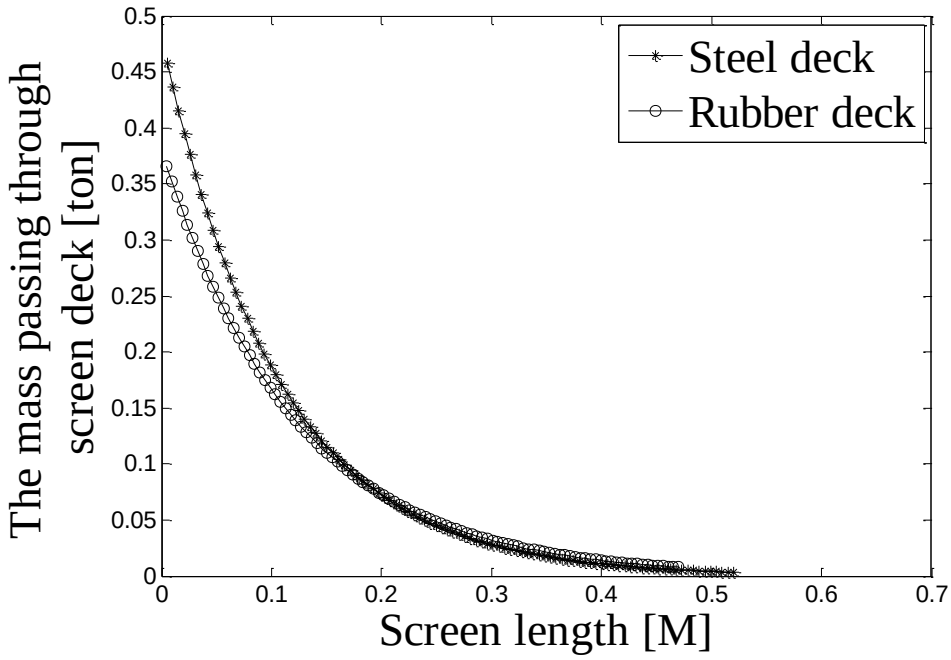


Figure 27. Total mass passing through the screen deck.

In work by Asbjörnsson et al. (2015), a theoretical model for the geometry was introduced that could be used for modelling the panel decks. However, the model used the same velocity for different types of screen deck material. The equation for determining the particle velocity, shown in Equation (13), consists of several empirical parameters that suggest the velocity function can be modified to handle more process variables in the future. The velocity model shown in Equation (13), is a function of stroke $R$ and frequency $f$ and the slope of the screen deck $\alpha$. The empirical model does not cover the effect of the particle size distribution or different feed rates to calculate the passage rate. However, the DEM model can cover this. The main reason for analysing different feed rates and particle size distributions is that the interaction between the particles will change and this affects the particle velocity along the screen deck. A lower particle velocity in the screening process provides the particle with a higher chance of stratifying earlier in the process and thus passing through the screening deck.

$$v = (0.064\alpha + 0.2)(380R - 0.18)(0.095 f \alpha^{(-0.5)} + 0.018\alpha - 0.38) \tag{13}$$

One other parameter that is not covered by the empirical model is friction. Friction between particles and between particles and the screen deck is different based on the different rock materials used and screen deck material. In the case of the DEM model, this is covered by the Hertz–Mindlin contact model.

### 5.2.3. DENSITY OF FEED MATERIAL

In the simulations, the passage rate for the low-density material was lower than for the high-density material, since the low-density material had a lower stratification rate than the high-density material. In the stratification of materials with various densities, it is easier for the high-density material to move vertically through the particle bed. Thus, the high-density material has a higher probability of passage.

The increase in the passing percentage of small undersized particles mainly occurred at the upper deck, and as a result, the particle bed was thicker at the lower deck, which means that the stratification process mainly affects the screening efficiency in the lower deck.

The DEM simulation results for the vibratory screening process are shown in Figure 28, for which the feed rate increased from 4 to 6 kg/s. As the feed rate increased, a thicker and approximately constant thickness material layer built up on the screen deck.

The stratification process is different for various bed thicknesses. The stratification process that occurs during the screening process is expected to proceed in the vertical direction; thus, a thicker material bed requires more time for stratification. One way to adjust the stratification time is to control the particle velocity during the screening process by adjusting the inclination and frequency of the vibratory screen.

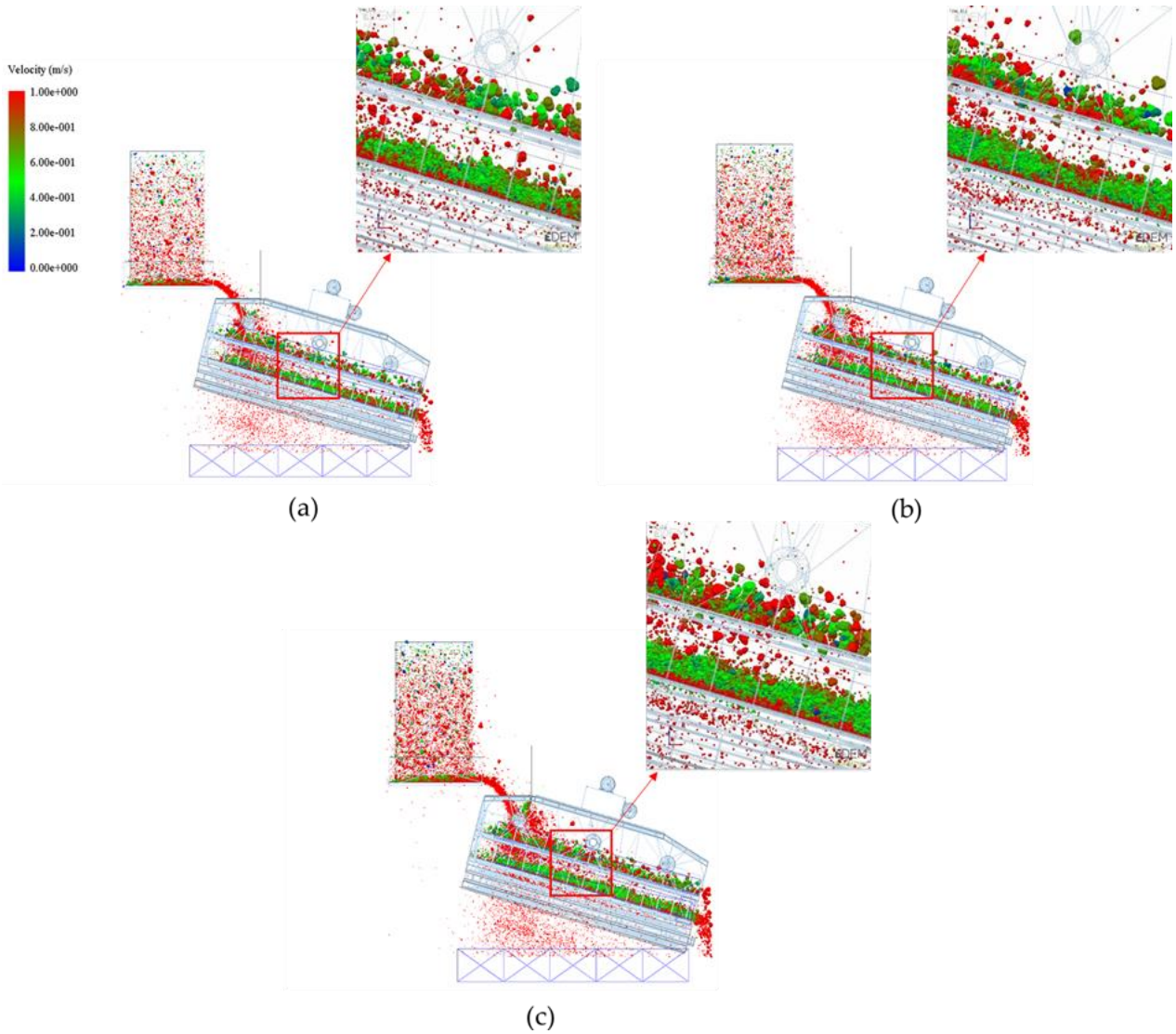



Figure 28. Discrete element method (DEM) simulation results for the vibratory screening process with three different feed rates: (a) 4 kg/s; (b) 5 kg/s; and (**c**) 6 kg/s.

Stratification has the largest impact on screening efficiency, and can be affected by different factors, such as material segregation, which itself depends on the physical particle characteristics, such as the particle size, shape, density, and surface texture. The particle size has a significant effect on segregation and stratification. Smaller particles can move towards the screen through the gaps between large particles, and this is a key factor in screening efficiency.

The different sections of the vibratory screen were analysed by using the bin to separate the sections. Bulk densities are simulated using three different feed rates. Figure 29 shows the percentage of the particles (partition number) that passed through the different sections. The low-density material had a better passage than the high-density material.

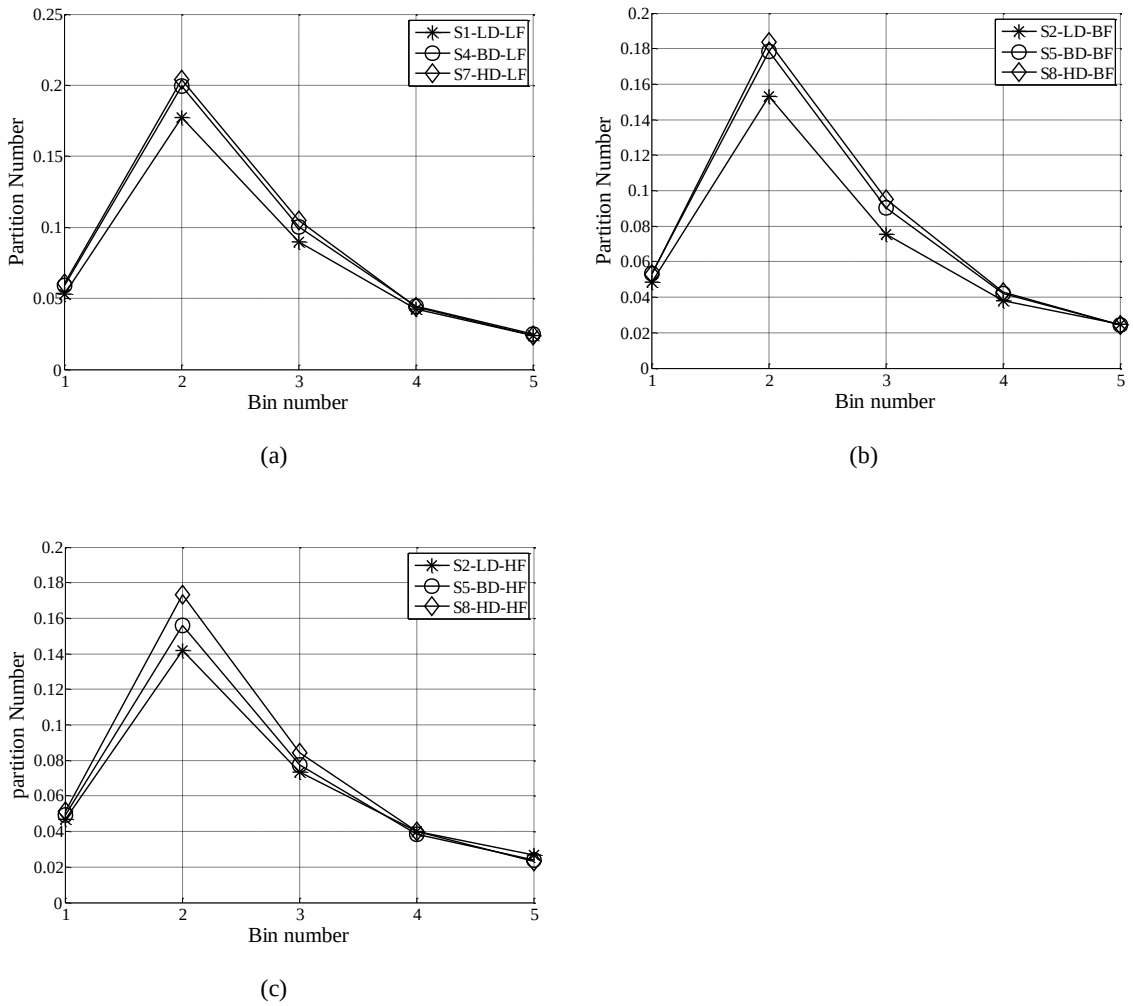
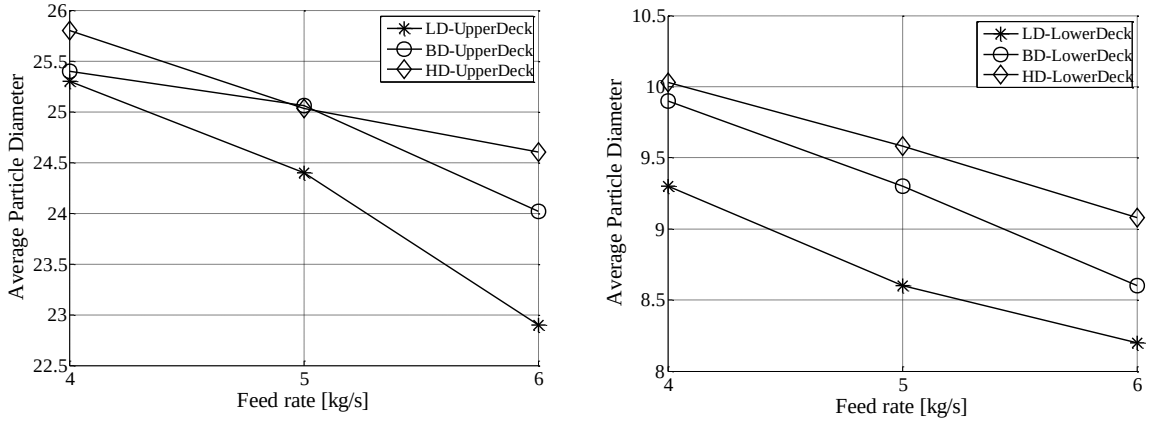



Figure 29. Passage rate in different screen sections for different densities and feed rates: (a) Low feed rate, 4 kg/s, (b) medium feed rate, 5 kg/s, and (c) high feed rate, 6 kg/s. (LD: Low-density material, BD: Between density material, and HD: High-density material

For further investigation, the material discharge was studied to compare the amounts of undersized material in the overflow for both decks. The average particle diameter in the overflow material can be seen in Figure 30. The average diameter was lower for the low-density material for both decks, which means that the simulation of the low-density material had more undersized material in the overflow than the high-density

material. However, this difference was smaller on the upper deck than the lower deck, since the upper deck had a larger aperture, and there were more chances of smaller particles passing through the screen deck.

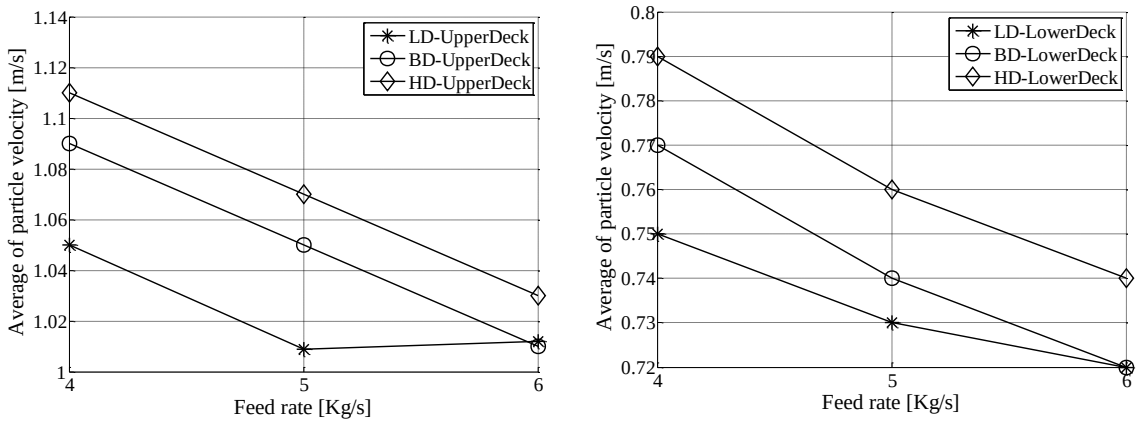
Upon increasing the feed rate, the average particle diameters decreased for both decks (Figure 30), as increasing the number of particles in the simulation resulted in a thicker bed (Figure 28) and decreased the probability that smaller particles could make contact with the screen deck.




(a) (b)

Figure 30. Average particle diameter in overflow material: (a) Upper deck, (b) Lower deck. (LD: Low-density material, BD: Between density material, and HD: High-density material)

The particle velocity during the screening process has a significant impact on the screen efficiency. The more particles that remain on the screen surface, the higher is the probability that these particles will pass through the screen deck. The average particle velocity for both screen decks is shown in Figure 31. The variation in the velocity for different material densities was not significant, and the higher-density particles had a slightly higher velocity. As Figure 31 shows, increasing the feed rate decreased the particle velocity along the screen deck as the number of collisions between the particles increased due to more material being on the screen deck.

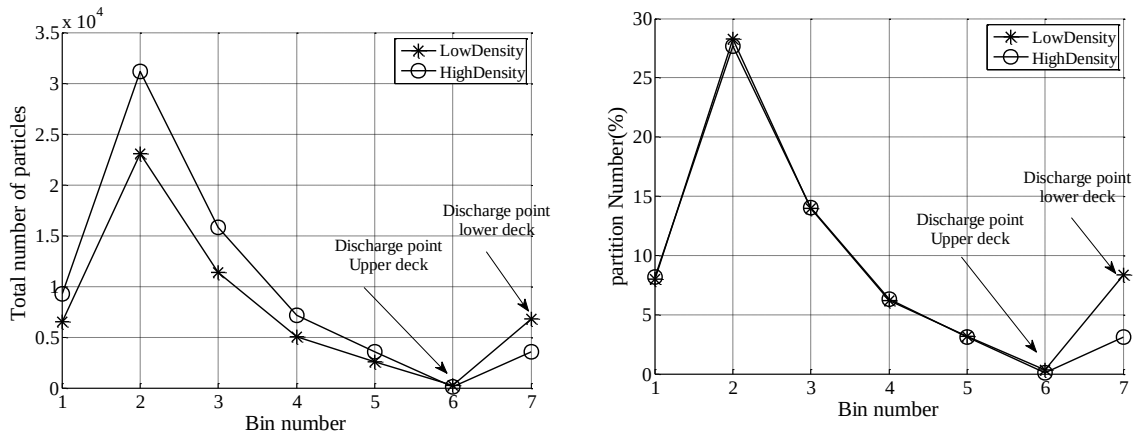



(a) (b)

Figure 31. Average particle velocity for different material densities: (a) Upper deck, (b) Lower deck. (LD: Low-density material, BD: Between density material, and HD: High-density material)

Stratification can be affected by the difference in material densities; thus, a simulation with two different material densities was performed to determine the size of the effect of the material density on the screening performance. To generate the same volume of material for different densities, numbers of particles were used in the simulation instead of generating the materials by mass. As a result, the particle factory generated different numbers of particles to achieve a specified mass.

Figure 32 shows the total number of particles that passed through the screen deck in different sections. More high-density particles passed through the screen deck than for the low-density material. As Figure 32 shows, at the discharge point of the upper deck, there was almost the same number of particles for both the high- and low-density materials. However, the total number of low-density particles was larger at the discharge point in the lower deck.



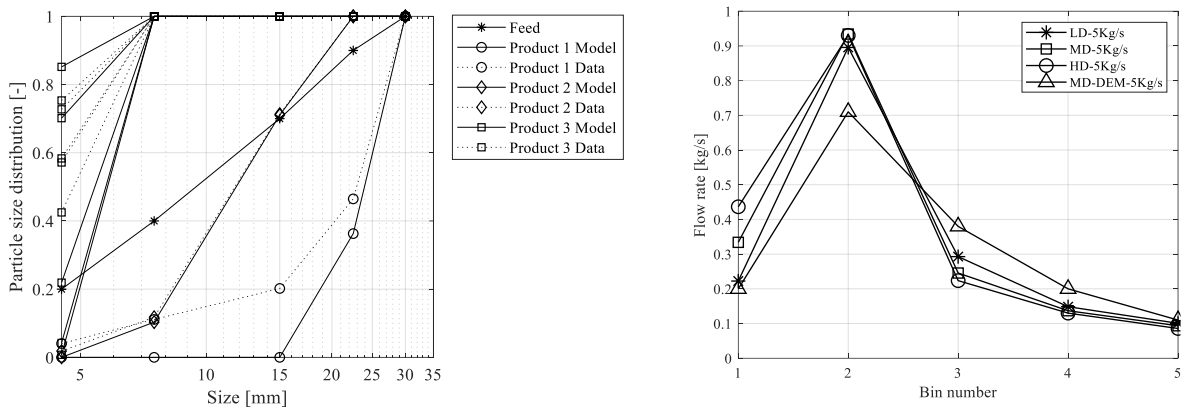

(a) (b)

Figure 32. The total number of particles passed through the screen deck in different sections with the feed for mixed particle densities: (a) The total number of particles; (b) Partition number.

The mechanistic screen model presented by Soldinger Stafhammar (1999) was used to study the theoretical passage rate along the screen deck. The factor β was calibrated to the value of 8.1, compared to 6.7 in Soldinger's original work (Soldinger, 1999). A comparison was made by changing the material density of the incoming feed and estimating the passage rate at different positions, in the same manner as used for the DEM model. The feed rate was fixed at 5 kg/s, and the size distribution was the same as the DEM simulation, to make the simulations comparable.

Figure 33(a) shows the result from the model simulation and data from DEM, where Product 1 is the coarse product, Product 2 is the medium product, and Product 3 is the fine product at different intervals. As Figure 33(a) shows, the particle size distribution for the medium and fine products was around the same range. However, in the DEM simulation results, there was a significant portion of the medium size fraction that remained in the coarse product fraction. This could be for a few reasons; first, the shape of the particles defined in both simulations was different, since the particles in the DEM simulation had a more spherical shape, and second, it could be due to the effect of friction. The friction between particles and between particles and the screen deck is different based on the different rock materials used and the screen deck material. In the case of the DEM model, this was covered by the Hertz–Mindlin contact model; in the mechanistic model, it was not explicitly formulated as an input variable.

The effect of different densities on the passage rate was studied, as can be seen in Figure 33(b). The mechanistic model and the DEM simulation showed similar trends. The simulation result showed that material with higher density had a higher chance to pass the aperture during the screening process into the first two bins.




(a) (b)

Figure 33. (a) Passage result from model simulation (product model), and DEM simulation (product data). (b) Passage rate in different screen sections by using screen model simulation.

### 5.2.4. WEAR ON SCREEN MEDIA

There are several wear tests that are mostly focused on the single-particle impact; however, a test focused on the single-particle impact cannot directly describe the continuous impact of multiple particles on targets. (Lindroos et al., 2015)

Since DEM can simulate the behaviour of multiple particles and the effect of the interaction between particles, it proved a good foundation for studying the impacts of particle and the development of wear.

After analysing the results from simulations, it can be seen that the erosion and the sliding wear rate were attributed to the combined effects of two types of factors one is material related and comprises properties like hardness and wear resistance and the other factor type is related to the material load on the deck and the comprises contact time, absorbed energy and effective stress.

In the feeding point, the velocity of a particle can be higher depending on the mass of particles, as well as the distance from the feeder to the screen deck. Also, the volume of the feed material is higher compared to other sections of the screen deck. In view of these two aspects, the wear can be substantial. The best solution can be to use a rubber or polyurethane in the feeding region to avoid erosive wear.

Three simulations were carried out for analysing the wear. The same particle size distribution (PSD) was used in all of them. The feed rate was varied to get different material loads on the screen. In the first step, the wear on the whole screen deck was studied based on the total load from the particles on the surface of the screen deck.

The three common materials used in the screen deck are steel, polyurethane, and rubber, all of which are studied in this paper. The volume of the material removed from the surface of the deck is calculated by using the Archard model, which is presented in Equation (14), where $Q$ is the volume of the material

removed from the surface, $H$ is the indentation hardness of the softer surface, $W$ is the normal load applied between the surfaces and $k$ is a wear coefficient, which provides a means of comparing the severities of different wear processes. (Andersson et al., 2011)

$$Q = \frac{kW}{H} \tag{14}$$

The load is calculated from the total mass of particles on the screen deck by using the geometrical bins, and the hardness of material H is varied based on the material of the screen.

The result presented in Figure 34 shows that the mass of the material on the screen has a linear relation to the sliding wear of the screen. The steel and the polyurethane are more sensitive to wear compared to rubber.

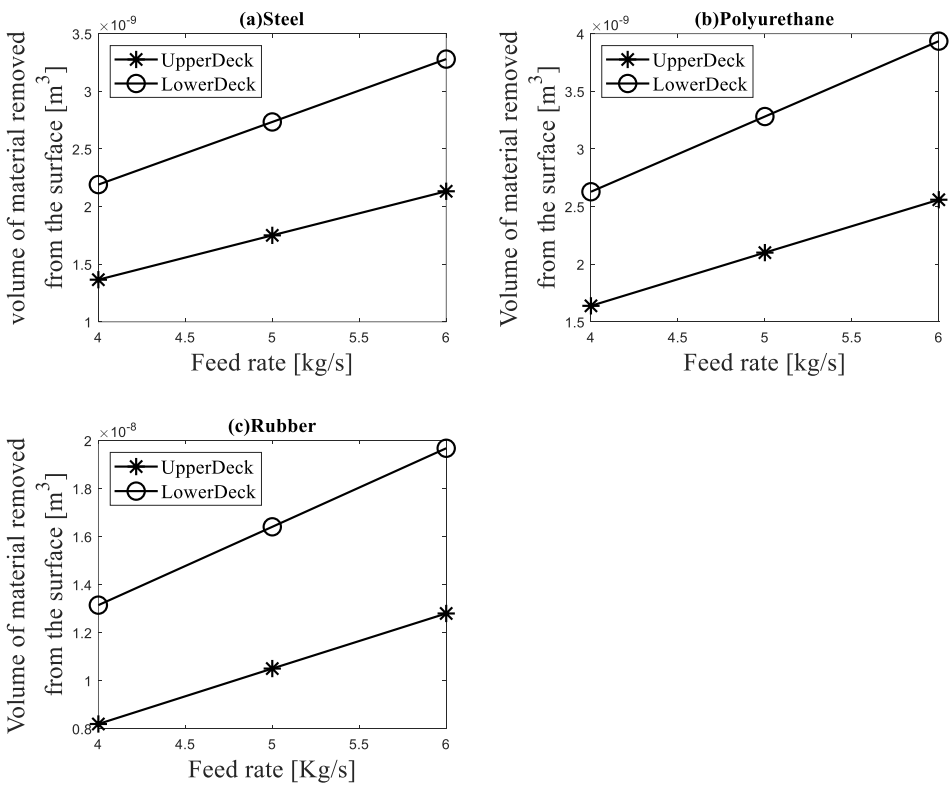



Figure 34. The volume of material removed from the surface by different feed rates: (a) steel; (b) polyurethane; and (c) rubber deck.

The mass of particles along the screen deck varies due to the materials passing through the screen deck; this makes the wear uneven along the length of the screen deck. For this reason, the screen wear is studied in four different sections on each deck, as can be seen in Figure 35. Each section is represented by one geometrical bin used for exporting the data in that region.

The amount of material is higher in section 1 and section 2 in both decks; as a result, the load on the screen deck is higher in these two sections. Figure 36 shows how the mass distribution of the material affects the screen deck wear in different sections of the deck.

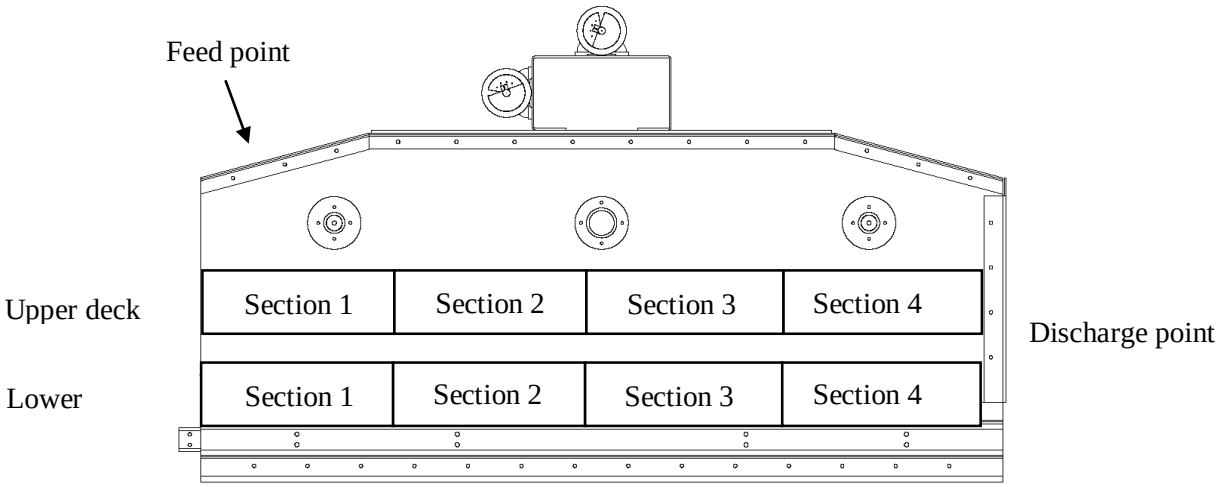



Figure 35. Schematic showing the CAD model with different sections.

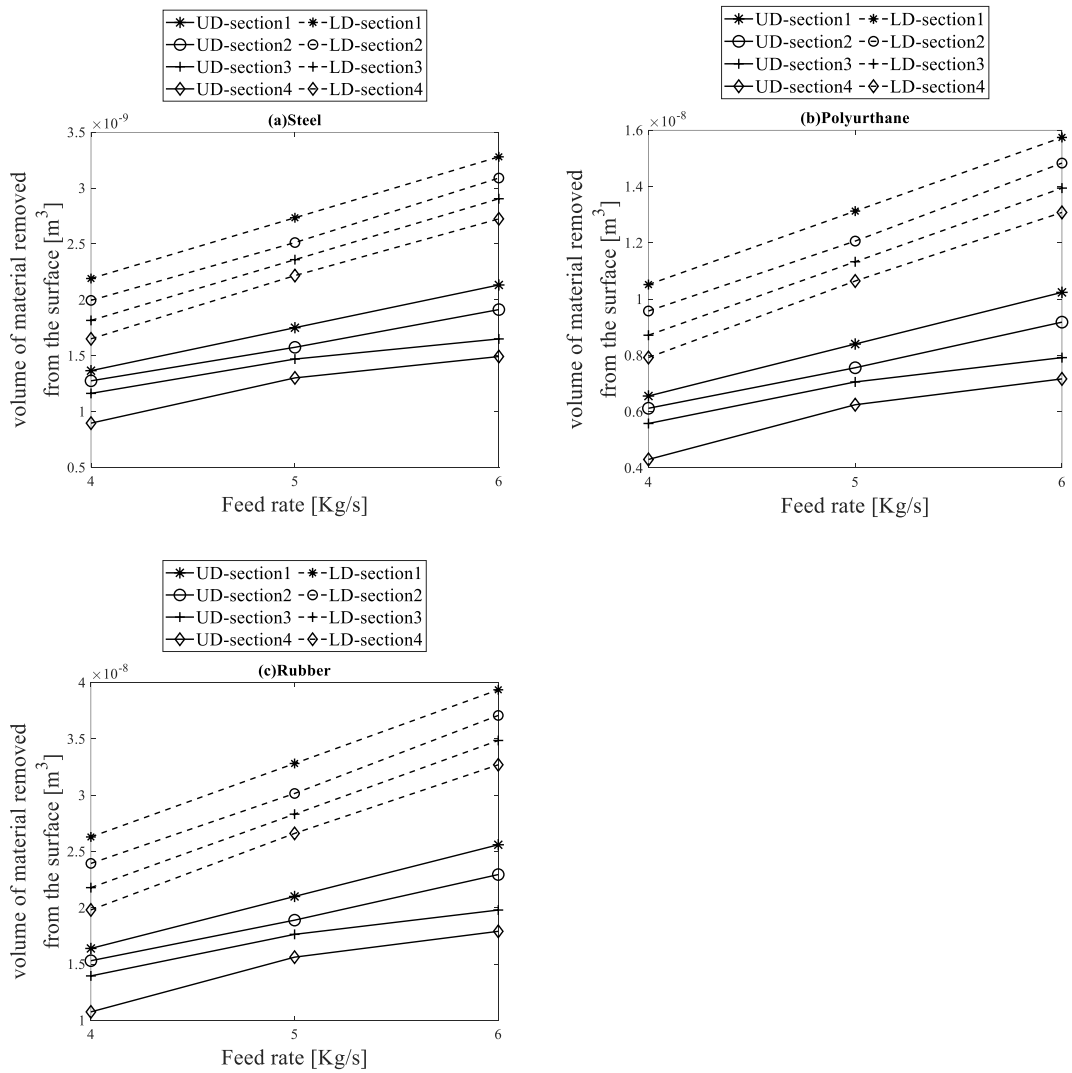



Figure 36. The volume of material removed from the surface in different sections of the screen deck by different feed rates: (a) steel; (b) polyurethane; and (c) rubber deck. (UD - upper deck, LD - lower deck)

The impact of particles hitting the surface of the screen deck is quite high in the feeding point because of their high velocity resulting from free fall. This kind of wear is very harmful, and the process of wear happens quite fast. The velocity of the particles in the feeding point varies depending on the particle mass and the distance from the feeder to the screen deck surface. A larger particle mass and longer distance give a higher particle velocity.

Other main factors that have a big impact on erosion wear are the shape of the particles and the impact angle, which is a function of the particle velocity and the screen deck motion. The impact angle can be considered when there is only one single particle striking the surface, but since there is an interaction between the particles, calculating the impact angle is more challenging. Another difference is hardness variation and contact time, which varies when there is an interaction between the particles and also variation in the particle properties.

The average velocity of the particle hitting the screen deck was calculated by using DEM and found to be around 1.3 m/s. The correlation mechanism of the erosion failure properties of various material surfaces was studied. Figure 37 shows the results for material removed by erosive wear in the feeding point area for the three different materials by using Equation (15), where $k$ is the coefficient of wear, $\rho$ is the density of the material being eroded, $U$ velocity, and $H$ hardness (Hutchings et al., 2006). As can be seen, the steel material is more sensitive to erosive wear and the polyurethane and rubber have a lower wear rate.

$$E = \frac{k\rho U^2}{2H} \tag{15}$$

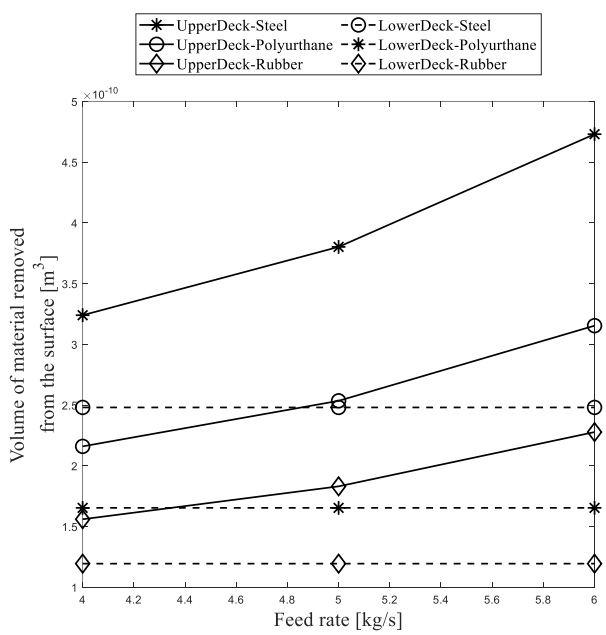



Figure 37. The volume of material removed by erosive wear in the feeding point at different feed rates.

## 5.3. VALIDATION

### 5.3.1. CAPACITY TEST VALIDATION

One factor which has a significant effect on screening performance is the size of the open area in combination with the feed rate. In the simulation reported in paper B the number of particles passing through the screen deck in the feeding point is almost 75% and therefore the PSD is significantly affected.

The geometrical bins were used to select the data from the simulations. In the first step, the simulation was validated by using the same parameters as in the experiment; in the second step, a single parameter, the feeding rate, was changed to analyse the capacity of the screen. The feed rate was increased from 79 ton/h to 100 ton/h then up to 130 ton/h.

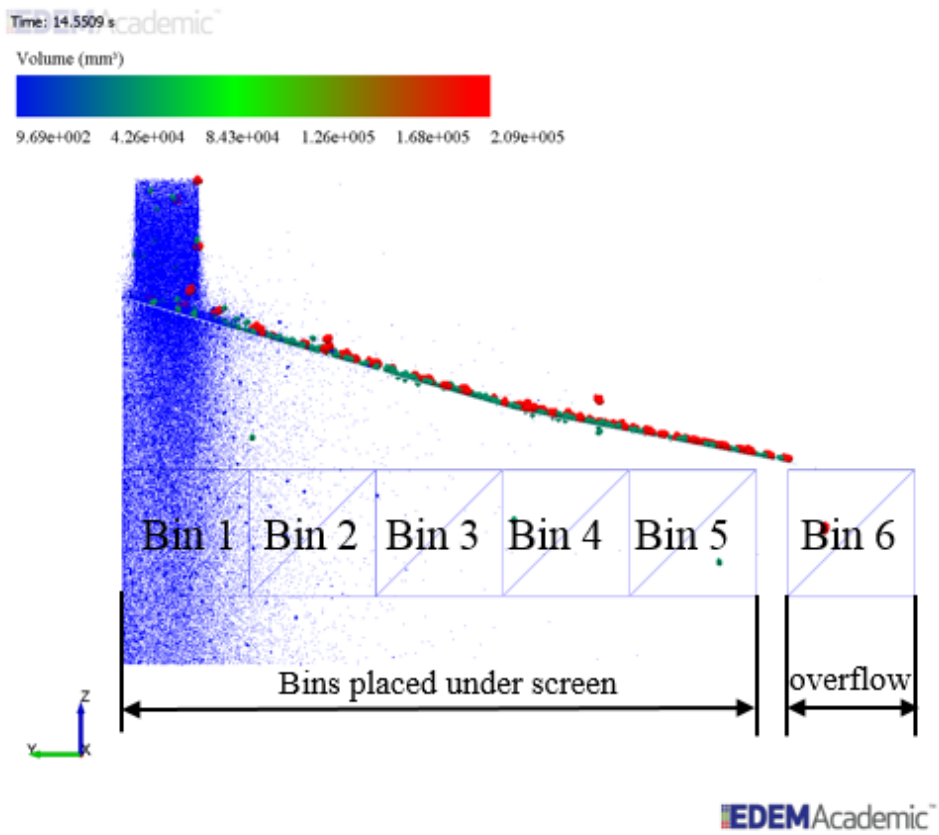



Figure 38. Overview of simulation after 14 seconds. Particles are coloured by their sizes: smaller ones are blue and the largest ones are red.

In paper B, the result was analysed in two ways, first by studying the total mass of particles that passed through each bin as shown in Figure 39, and then by analysing the screen performance by the numbers of particles over time, the results being shown in Figure 40. The graphs present each geometrical bin and the number of particles that pass through with time. The important point is that the process reaches a steady-state, which means that the number of particles in the simulation is stable. In this work, the steady-state was reached in all simulations after 8 s, which means that the simulation result was analysed after 8 s.

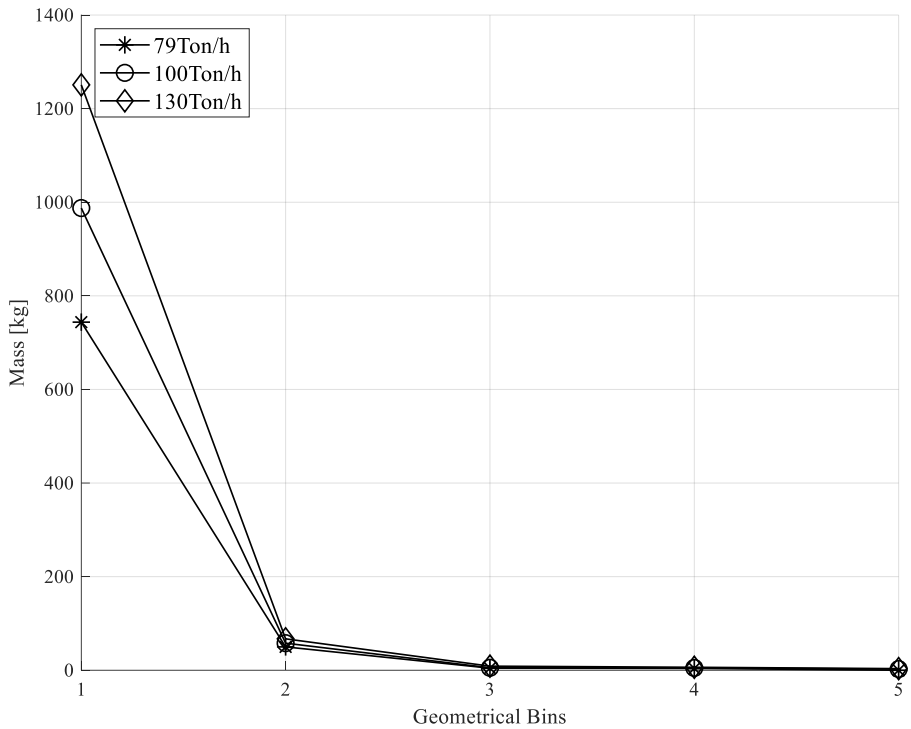



Figure 39. The total particle mass for each bin.

The particle size distribution (PSD) from the experiment shows that the percentage of the fine particles in the system is fairly high, which causes the passage probability in the feeding point to become high. Another factor that affects this process is the wide-open area, in this model 35×35 mm. In Figure 38 it can be seen that the volume of particles passing through the screen deck is very high in the feeding point for Bin 1. The simulation result shows that the total number of particles that pass through Bin 2 to Bin 5 at the rate of 79 ton/h is lower compared to the simulations with the 100 ton/h and 130 ton/h feeding rates, and this is more noticeable in Bin 4 and Bin 5, where there is an increase of more than 200% in the total number of particles. In the first simulation with a 79 ton/h feeding rate, the particles have direct contact with screen media in the feeding point, which increases the probability of passing through the screen deck. By increasing the feeding rate, the particle bed became thicker in the feeding point, which affects the stratification process, in which case more particles move along the screen deck and the particle layer becomes thinner until the particles come into direct contact with the screen deck.

The result from Bin 6, which is the overflow material in the simulation, shows that the total number of particles increased by around 20%, where the important point to note is that the total number of undersized particles did not increase in the overflow material. In this simulation, the average diameter of particles in Bin 6 was studied as shown in Table 3. The difference between the 79 ton/h and 100 ton/h rates was about 4 mm, which was very low, but at the rate of 130 ton/h, the average was about 20 mm less than the other simulations, which shows that the probability of having undersized particles in this simulation is higher compared to 79 ton/h and 100 ton/h.

Table 3. Average particle diameter for oversized material from Bin 6.

| Average of particle diameter | | |
|---|---|---|
| 79 ton/h | 100 ton/h | 130 ton/h |
| 72,0887 mm | 68,5478 mm | 55,2245 mm |

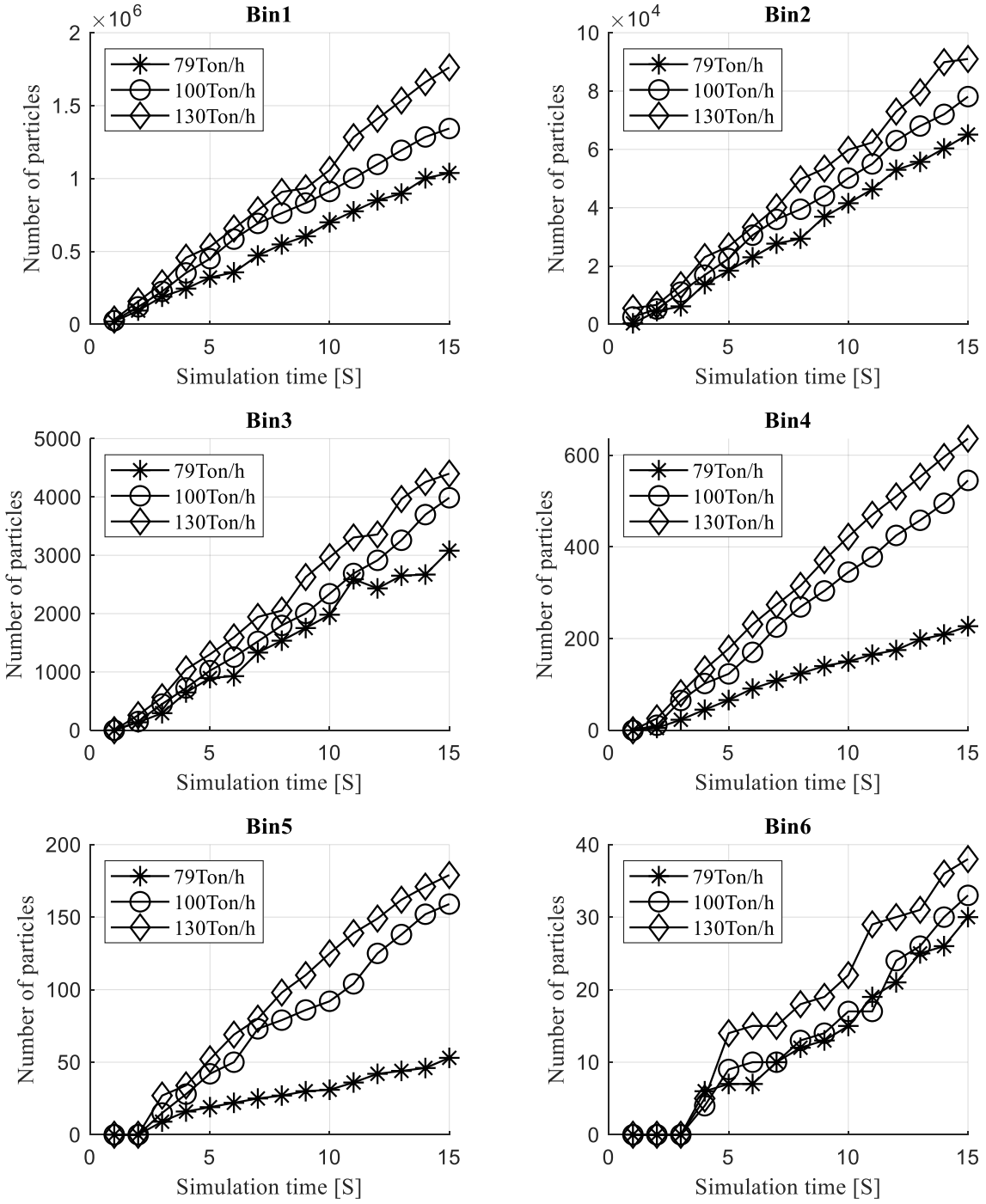



Figure 40. Screen performance by numbers of particles over time.

### 5.3.2. LABORATORY EXPERIMENTS

The aim of the laboratory experiment is to validate DEM simulations for a vibratory screen using a laboratory-scale vibratory screen. A specially designed laboratory-scale vibratory screen was designed to study different screening parameters and also to observe the screening performance.
Figure 41 shows the laboratory-scale screen model used in the experiment and schematics of the model used in the simulations.

The shape of the particles has a large influence on the efficiency of the screen in the simulations and the combination of the shape and size distribution even has more effect on screening performance.
The accuracy of the simulations is high and makes the process of study much easier and cheaper compared to the real test. The only data needed from real tests is for calibrating the simulations are the material properties shape, density and particle size distribution.

*Sieving analysis of both experiments and simulations*

In both the simulations and experiments, one factor at a time method has been used to study the particle behaviour and for comparing the simulation output with the data from experiments. Each setup was run twice. Table 4 shows the simulation and experimental setup based on different feeding velocities and strokes. For collecting data from the experiments, the screened particles were collected in boxes were placed under different sections of the lower screen deck. In the simulations, the same method was used with geometrical bins in order to export the data. Figure 41 shows the placement of bins in the simulations and experiments.

Table 4. Simulation and experimental setup.

| | Feeding velocity (m/s) | Stroke (mm) |
|---|---|---|
| Test1 | 0.2 | 7.5 |
| Test2 | 0.2 | 7.5 |
| Test3 | 0.3 | 9.5 |
| Test4 | 0.3 | 9.5 |
| Test5 | 0.2 | 9.5 |
| Test6 | 0.2 | 9.5 |
| Test7 | 0.3 | 7.5 |
| Test8 | 0.3 | 7.5 |

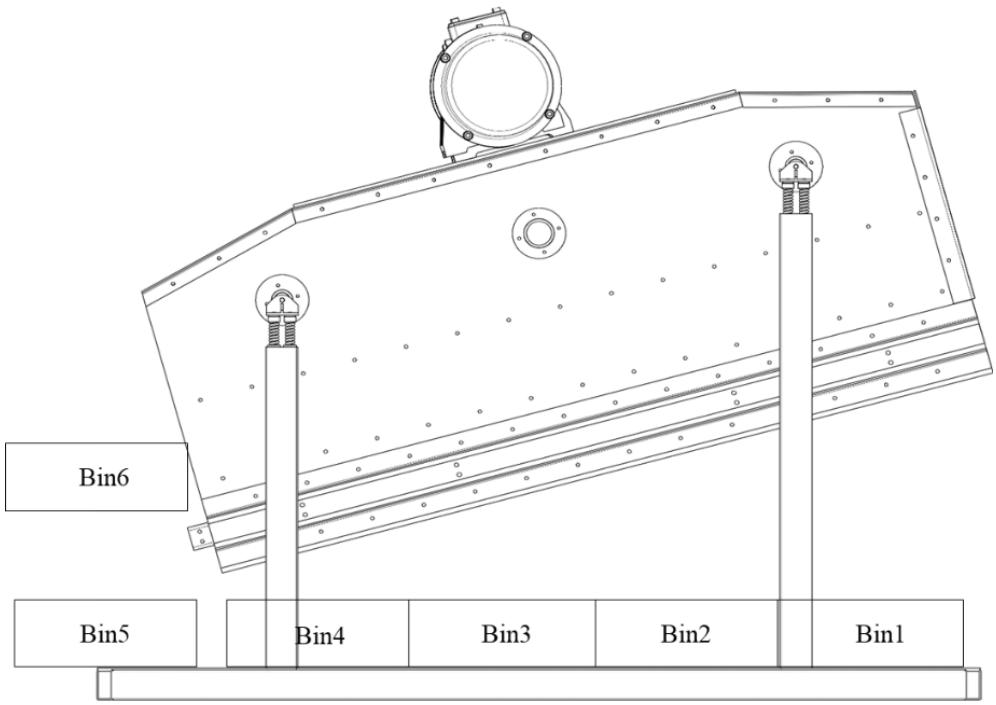



Figure 41. Placement of geometrical bins in simulations and boxes in experiments.

For studying the particle behaviour in both the simulations and experiments, the influence of different parameters were analysed, including the particle velocity along the screen deck. In the simulations, the particle velocity increases from 0.16 to 0.8 m/s. The lowest velocity is near to the feeding point and the highest is around the discharging end. The same behaviour was also observed in the experiments. The reason for this behaviour is that particles have increased interaction with each other in the feeding point because of the thicker particle bed. As soon as the small particles pass the screen deck in sections 1 and 2, the particle bed on the upper screen deck becomes thinner. The particle bed thickness in the different sections can be seen in Figure 42.

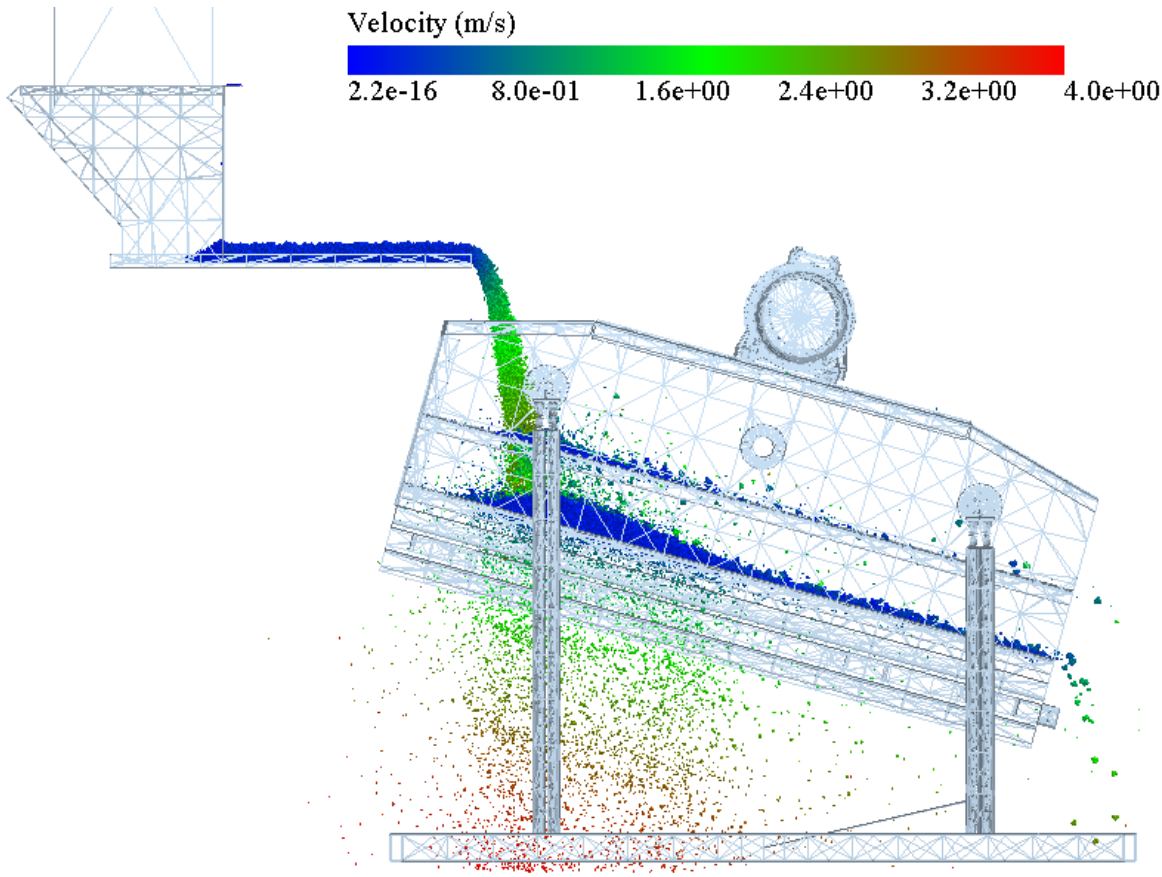



Figure 42. Simulation image after 8 s. The colour code represents the particle velocity.

Another simulation result that was studied was the PSD of the final product. Figure 43 shows the results of the sieving from different bins in all eight experiments. The effect of changing the feeding velocity and stroke is not too significant on particle behaviour. The variance in the mass of different PSDs is minimal and the reason for the small variation is the segregation of material in the hopper.

The larger amount of the finest particles below 6 mm passes through Bin1 and Bin 2 because of the freefall through the aperture in the feeding area.

As Figure 43 shows for Bin 5, there are still some undersized particles in the oversize fraction on the bottom deck that decrease the screening efficiency. The mass of 8 mm particles is ~3800 g.

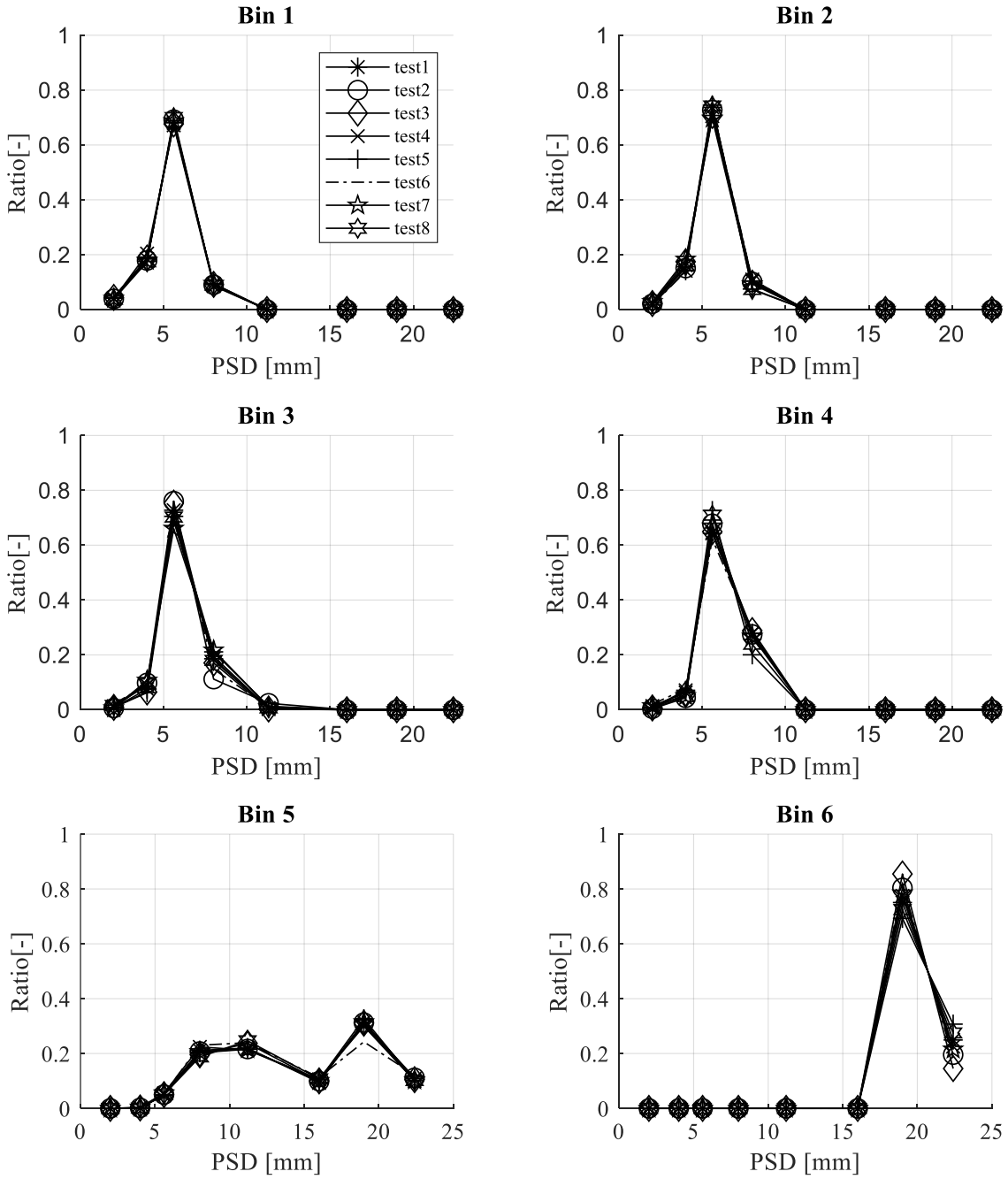



Figure 43. PSD from each Bin from laboratory experiments.

In the simulation setup, in order to obtain the same effect of material segregation, each simulation has a new start for the particle factory generator. This means that the placement of particles for each simulation is randomly varied.

Figure 44 shows the resulting PSD in different geometrical Bins from the simulation. The simulations follow almost the same curve as the experimental data. There is some variation in the different test scenarios due to some calibration issues. The most important one is the shape of the particles. In the simulations, the variation of particle shape is not much as in real experiments, which is affecting both the stratification and passage process.

The shape of the particles has a significant influence on the velocity of material flow along the screen deck, i.e., if the particles move faster along with the screen deck, then the probability of coming into contact with the aperture decreases, which negatively affects the screening efficiency.

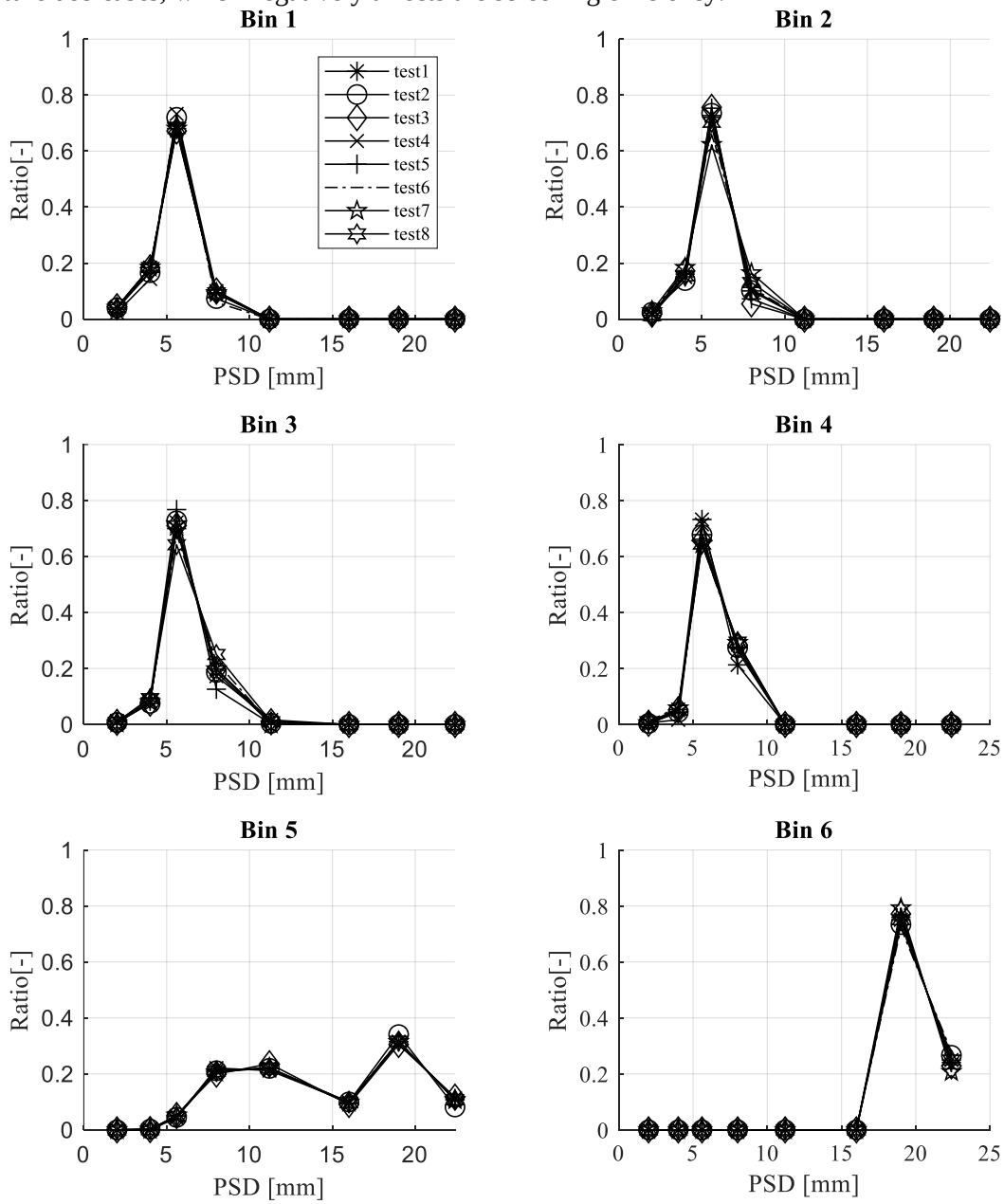



Figure 44. PSD from each Bin from DEM simulations.

Screening efficiency

The most common definition of screen efficiency is how steady-state screening produces the variation in the mass of particles falling through the screen deck along its length. This means screening that the efficiency is the ratio of undersized material in the feed that passes from the screening media to the undersize material that should pass from the screening media. This efficiency can be found from:

$$E(\%) = \frac{100(e-v)}{e(100-v)} \times 100 \tag{16}$$

where $e$ is the percentage of undersize material in the feed and $v$ is the percentage of undersized material in the overflow.

The data from the sieving analysis was studied for both simulations and experiments. The efficiency of screening was analysed by examining the amount of undersized material in the overflow.

Figure 45 shows the efficiency curves from both simulations and experiments. The results show that for both simulations and experiments, test5 and test6 are the most efficient. The reason for this is the use of more of the area of the screen deck by having a lower feed velocity, meaning that material lands closer to the feeder. Another reason is having a higher stroke, which positively helps the stratification process.

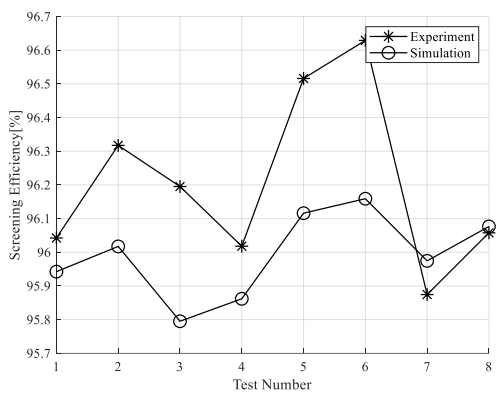



Figure 45. Efficiency curves for both simulations and experiments. (Due to the small differences between the points, the scale of the y-axis is small in order to show the difference)

In terms of validation, the efficiency of screening in both the simulations and laboratory experiments is very similar. In the simulations, the efficiency is lower compared to the experiment because of the influence of the particle shapes. These shapes are not round because of using numbers of spheres attached but they are not perfectly edgy either which causes that particle to roll faster along the screen deck instead of being stuck in the aperture.

# 6. CONCLUSIONS

*The aim of this chapter is to:*

- *Present the most important conclusions drawn in this thesis regarding the stated research questions presented in chapter 2.*

## 6.1. GENERAL

The research result presented in this thesis is focused on building knowledge and the understanding of how screening performance can be affected by different parameters. The methodology used to achieve the improvements was to include the most important factors that affect the screening process. DEM simulations were used to analyse different screening elements and parameters for steady-state conditions. Some of these elements are illustrated in Figure 6 in Chapter 3.

Using DEM simulations has some challenges depending on the area of application. One of the important factors is the particle shape, which has a significant impact on screening performance in terms of both the passage and the stratification process. Spherical particles are too idealised to give quantitatively correct predictions compared to real experiments. However, by overlapping and clustering a number of spheres the particle attains a more realistic shape. Nevertheless, for validating the simulation compared to the real screening process, some simulation conditions must be calibrated for more satisfying simulation results. In real industrial applications, the specification of material or particle properties requires calibration and measurement. While DEM has been used a lot recently at the industry level and many experimental tests have been done for validation, they have rarely been recorded and published.

## 6.2. ANSWERING RESEARCH QUESTIONS

The purpose of this thesis is to answer the stated research questions that have been presented in Chapter 2. The research questions are addressed at varying levels in the different papers presented in this thesis, Table 5 shows the relationship between the papers and the research questions.

Table 5. Dependency matrix for the relation between the papers and research questions. The size of the checkmark shows how strong the level of the relation is.

| Research Questions | Paper A | Paper B | Paper C | Paper D | Paper F | Paper G |
|---|---|---|---|---|---|---|
| RQ1. How do selected screening parameters influence the screening efficiency? | ✓ | ✓ | ✓ | ✓ | | ✓ |
| RQ2. How should DEM simulation be used to model screening with adequate accuracy? | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| RQ3. How can DEM simulation be used for industrial purposes? | | ✓ | | | ✓ | ✓ |
| RQ4. How should a vibratory screen be designed based on the parameters and process requirements? | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| RQ5. What are the limitations of using simulations compared to real experiments? | | ✓ | | | | ✓ |

*RQ1. How do selected screening parameters influence the screening efficiency?*

Different screening parameters have a different influence on screening efficiency. In this research, the motion type (Paper A), screen deck material, and aperture size (Paper B) as machine parameters studied. The theory about improving the screening efficiency is to increase the chance of a particle making contact with the screen deck, noted as a stratification process. After that contact has been achieved, the process of passage will take place.

*Stratification*

The time needed for material transportation along the screen deck from the feeding end to the discharge end influences the stratification process. A longer transportation time increases the stratification process, giving the particles a higher chance to have contact with the screen deck. One parameter which has an influence on the time of material transportation along the screen deck is the number of particle bounces on the screen deck, which is less for a steel screen deck than for a rubber or a polyurethane screen deck, but the difference is not excessive and affects mostly single-layer particles (Paper C).

Another factor that was studied is the effect of the motion type on the stratification process. A banana screen was used to study the effect of different motion on different sections by using different angels of the decks. When the slope of the deck is minimum, which is in the last section of the banana screen, elliptical motion increases the screening efficiency compared to linear motion (Paper A).

*Passage*

The effect of the aperture size on the passage process is dependent on the choice of panel material, which can be a wire mesh deck or a panel deck. The number of holes in a wire mesh screen deck is larger than a panel deck, which has a larger effect, especially in the feeding point before building up the particle bed (Paper C). The wear on screen media also affects the passage process negatively, by changing the size open area (Paper E).

*RQ2. How should DEM simulation be used to model screening with adequate accuracy?*

DEM modelling can provide a fundamental understanding of the particle separation process at a discrete particle level. It displays advantages as a tool for the study of different screening processes. It can easily and accurately simulate screening operations in accordance with actual conditions as a substitute for physical experiments and saves time and its a lot more controllable and observable compare to real experiment. Some parameters cannot be changed in the physical experiment due to the very high cost involved or because is not possible to study the actual effect of varying the parameter. The screening process is affected mostly by the interaction between the particles. The DEM cover different contact models that can be used for simulations and this can be validated by different methods that are based on experiments (Paper F). The observation of the screening process and the data from feed material and machine parameters are the key steps for having the acceptable accuracy for simulations.

*RQ3. How can DEM simulation be used for industrial purposes?*

There are two types of usage for DEM at the industry level. One is planning the crushing platform, which helps to select or customise the optimum machine for the process. A key application of DEM is the possibility to model equipment of complex geometry and the complex kinematics for these geometries. Another usage is to change the machine parameters to improve the design of current machines operating in the process (Paper B).

Using DEM for industry purposes has some challenges. One of them is calibration and, as previously mentioned, some parameters have a huge impact on the screening process, so the calibration of these parameters is important to achieve satisfactory results. The material properties such as particle shape, density, and rolling friction are examples of parameters that need calibration depending on the required accuracy.

*RQ4. How should a vibratory screen be designed based on the parameters and process requirements?*

The interaction between the machine parameters makes the design of the screen more difficult. The design of the vibratory screen should be considered based on the expected quality of the product and the screening efficiency. The most important step is to choose the machine type, such as a banana screen or horizontal screen, as this has a direct relation to the feed rate and the capacity of the machine. Furthermore, particle characteristics such as size, shape, and density have a strong influence on the design of the screen mainly in terms of choosing the screen deck media (Paper A, Paper C and Paper D).

*RQ5. What are the limitations of using simulations compared to real experiments?*

One limitation is wet screening, which is not covered by DEM, and another limitation is the duration of the simulation, as more particles in the system require a longer calculation time, which will increase the simulation time.

Other important factors are the characteristics of the particles like their shape and size, which change some of the data for simulation such as the rolling friction coefficient. The calibration of each material type is a complex and time-consuming process and also very important to make the simulation more accurate. The variation in the shape of particles in the real experiment is often larger than in simulations and therefore it is almost impossible to completely calibrate the shape.

# 7. FUTURE WORK

*The aim of this chapter is to:*

*Discuss future work based on questions that have been raised during this research work.*

The screening process is a complex process due to the number of machine and process parameters that affect screening efficiency. The screening performance and efficiency are not only affected by individual factors but also by the interaction between factors. In future studies, the interaction between different elements can be studied to improve the screening efficiency by using Design of Experiments (DoE).

In order to create the screening model to improve the efficiency of the screen, both machine and process parameters must be analyzed by using simulations and data from experiments.

In future work a wider range of values and parameters can be investigated such as:

- Different PSD and particle shapes by studying the influence of the flakiness index of particles on screening efficiency.
- The particles moisture negatively affects the screening process, the particles stick together and that increase the particle size and decreasing the screening efficiency. Another effect is the particle cover or blocks the aperture which is minimizing the hole size.
- The aperture shape is one of the parameters that can also be studied to improve screening efficiency.

The future goal should be a predictive screening model that can be implemented in a different type of situations. It should help to understand how different parameters and conditions affect the screening process both for the design of the screen, when selecting the screens and when the screens are operated.

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