

Discrete Element Modelling and Simulation of Vibratory Screens

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DEM vibratory screen simulation

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“Doing what you like is freedom. Liking what you do is happiness”

-Frank T

ABSTRACT

In Sweden about 85 million tonnes aggregate is used for road, railway and concrete every year. Crushing is the main process for producing the aggregate material in different fractions. The crushing process is divided into two sub-processes; comminution and separation. 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 play an important role, the transport of unnecessary materials can be costly and it therefore becomes 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 from the beginning for the crushing plant results in a better return on investment and better quality products.

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

The study results show some of these factors have a larger influence on screening such as a effect of motion type for different slope of deck. The elliptical motion is more efficient compared to linear motion. And also, the aperture shape in different parts of the screen deck has a different effect based on single layer material or multiple layer material in the feeding point. The result of this research needs further investigation in order to study the effect of interaction between different factors before achieving the complete screen model.

Keywords: DEM simulation, Screen efficiency, Modelling.

PUBLICATION

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Davoodi, A., 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

Paper B:

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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*, 11th International Comminution Symposium (Comminution '18). 2018: Cape Town, South Africa

CONTENTS

1	Introduction	1
1.1	Background.....	3
2	Objectives.....	5
2.1	Delimitations	5
2.2	Research Questions.....	5
3	Scientific Approach.....	7
4	Literature Review	9
4.1	Empirical Modelling.....	9
4.2	Analytical Modelling	9
4.3	Numerical Modelling.....	10
5	Research Methodology.....	13
5.1	Discrete Element Method	13
5.1.1	General	13
5.1.2	Hertz-Mindlin's Contact Model.....	14
6	Simulations And Results	17
7	Conclusions	27
7.1	General.....	27
7.2	Answering Research Questions	27
8	Future Work	31
9	References	32

APPENDED PAPERS

Paper A: DEM Modelling and Simulation of Banana Screen Classification Efficiency.

Paper B: Analysis of Screening Performance Using Discrete Element Modelling.

Paper C: The Effect of Different Aperture Shape and Material of Screen deck on Screening Efficiency.

PREFACE

This thesis was carried out at the research group Chalmers Rock Processing System at the department of Industrial and Materials Science, Chalmers University of Technology. I would like to acknowledge the contribution of the Ellen, Walter and Lennart Hesselmanns foundations, SBUF, LKAB and VINNOVA.

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Finally I would like to take this opportunity to thank my family and my friends for giving me a life outside of work and for their support, especially my wife Nazli and my son Nik for their unconditional support and all the love they bring to my life.

1 INTRODUCTION

The aim of this chapter is to

- *Provide an overview of the crushing plant.*
- *Describe the background of the screening process.*

In the mining and aggregate industry stones and rocks in different sizes are broken into smaller sizes for different purposes such as extracting the minerals in mining or for the construction of roads and buildings. In the aggregate industry the production of gravel, sand and crushed rock has increased recently which makes the process of crushing, as a main process for producing the aggregate material, more interesting.

In mining operations, the design of crushing plants, equipment and structures are critical factors in meeting production requirements while keeping capital and operational costs to a minimum. There are three main steps in designing an efficient crushing plant: process design, equipment selection, and layout. The process design and equipment selection are influenced by production requirements which include the quality of the product and the production rate.

The crushing plant consists of six different types of equipment:

1. *Feeders*: Often 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. *Conveyer belts*: Used to transport the material between different machines.
4. *Vibrations screens*: One of the common separation devices.
5. *Control system*: To control the operation from start to final products.
6. *Storage*: Stockpiles and bins, accumulate a large amount of product in the process.

Figure 1 shows an example of a comminution plant from primary crushing to final products. Two main processes in the comminution plant are crushing and classification. The crushing process is defined as a size reduction process and the classification process is defined as separating the material based on size and shape. After each crushing step the material needs to be sorted by size. One of the most common devices for separation is the vibration screen. There are many types of vibratory screens differing mostly in three design parameters, slope of deck, number of screen decks and motion type. The motion types can be specified as circular, elliptical and linear motion. Depending on the variety of sizes in the process and the requirement of the final product, the number of screen decks will be decided for each step. The number of inclinations of the screens can vary in different vibratory screens. The most common ones are single inclination, double inclination and multiple inclination (banana screen), which differ in capacity and slope of deck.

Another parameter which has some variety based on the type of operation is the type of screen deck. The types of screen deck can be categorized as wire mesh and panel deck and the selection is based on the material that the chosen screen will process. The material of the wire mesh screen deck is normally steel and the panel deck can be rubber or polyurethane.

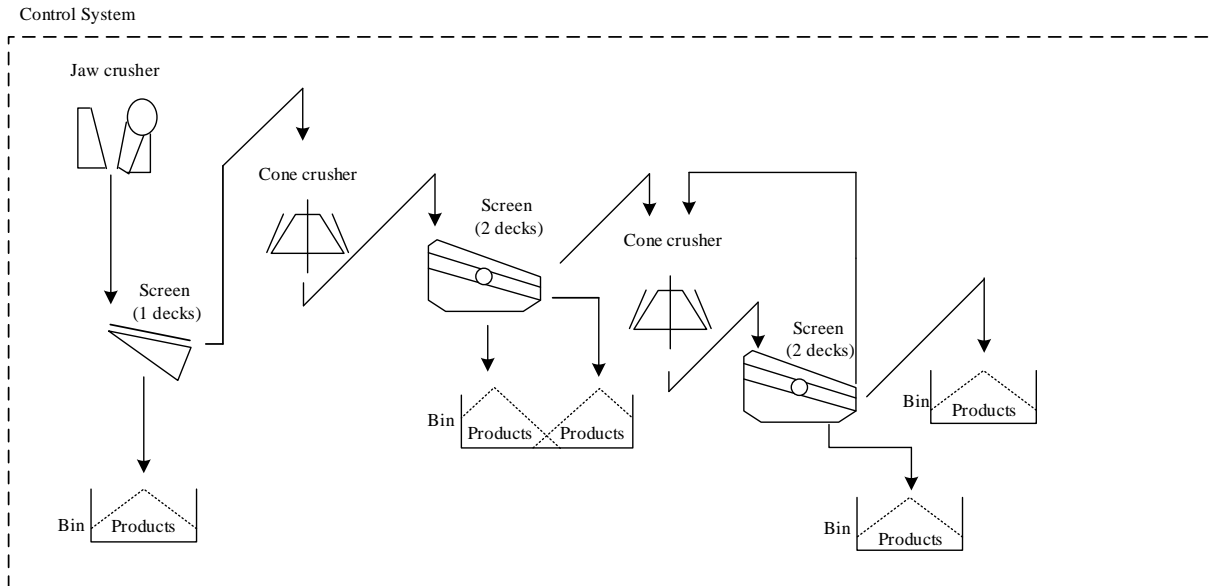


Figure 1. An example of comminution plant in an aggregates application.

1.1 Background

The comminution process is not very precise when it comes to size reduction for the end product. For size controlling a final product separation process will be needed. Depending on the size of the product and the stage of crushing, different classification processes can be used. One process which has been used for a long time is the screening process. The process of screening can be divided into two categories. One is coarse screening which is usually placed early in the process after primary crushing, the other is fine screening which is placed in the end of process for screening the final product. The basic definition of the screening process is to size control the product by using geometrical patterns. There are three different main elements which affect the screening performance see Figure 2. The screening elements are either machine based or product based, apart from material feed which is dependent on the machine capacity.

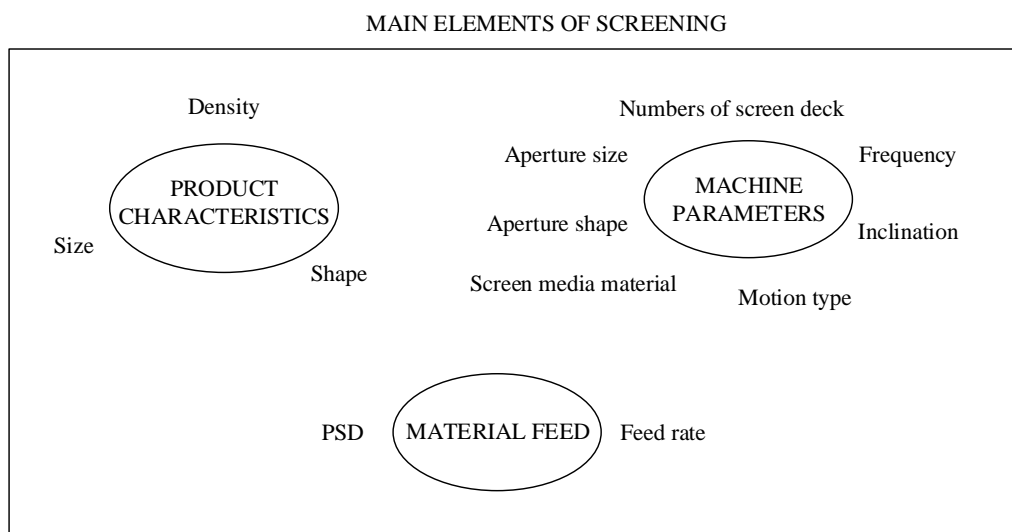


Figure 2. A map of different elements that defines the screening process.

The number of screen decks and the aperture size are dependent on particle size distribution of the material flow and the size requirement of the final products. A higher number of screen decks results in a larger diversity in size of the final product. However, the material of the screen deck is also important especially in relationship to the wear rate. Three common materials for screen media are steel, polyurethane and rubber which have different resistance to sliding abrasion and wear. Motion type and inclination are also two main parameters for screening, the most common motion types are elliptical, circular and linear motions. Some screens have only single inclination and others have several sections with different inclination, referred to as multiple inclination.

The actual screening process is comprised of three sub processes. Firstly the process of transportation which means the material being transported along the screen deck, secondly the stratification process i.e. the material being transported through the distance between other particles, and thirdly the process of the particles' passage through the aperture. All of these processes are affected by machine parameters, material characteristics and the amount of feeding material.

2 OBJECTIVES

The aims of this chapter are to:

- *Describe the aim and objective of the research.*
- *Describe the delimitation of the research.*
- *Formulate the research questions.*

The aim of this research is to study screening performance by analyzing different machine design parameters, operation parameters and material properties. The main objective of this research is to simulate the screening performance by using Discrete Element Method (DEM) to analyze screening behavior under different simulation conditions.

The theory of this research is that the screening process is affected by different parameters which change the efficiency of the screening, the quality of final products and even has an effect on the performance of the crushing plant. In order to simulate the screening performance, the Discrete Element Method (DEM) has been used to simulate different screening conditions and analyze the performance of the screening process.

2.1 Delimitations

In this research the design principle of one factor at a time (OFAT) has been considered, it means the interactions between factors cannot be estimated and also requires more simulations to achieve 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 wet screening which is complex to achieve with DEM simulations. All simulations and studies have been done for a dry screening process. DEM simulation is very time consuming due to the large amount of data gathered from interactions between all particles and also between particles and geometry, because of this some simulation has been done on a smaller scale to save simulation time.

2.2 Research Questions

By considering the aim of this research to identify the specific objectives a set of research questions has been formulated.

RQ1. Which dominating parameters in a screen will influence screening efficiency?

RQ2. How can DEM simulation be used to model screening with a good accuracy?

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

3 SCIENTIFIC APPROACH

The research approach that has been adapted in this research is a problem based approach designed by Evertsson (2000).

The first step is to identify the *problems*, which requires knowledge about the area of research. This knowledge can be achieved by doing background research and observations. The main problem that has been identified in this research is the lack of existing knowledge about particle behaviours in different process conditions which is very difficult and time consuming to ascertain by using real experiments.

The next step after defining the problem is to record information by using scientific tools, any data recorded during an experiment can be called an *observation*. In this research the observation has been done in different crushing plants in Sweden. The *modelling* phase is based on knowledge from observation and it has the ability to predict future observations. After modelling *verification* is required to confirm the truth or rational justification of a hypothesis by using experiments and simulations. Before finding any *solutions* some *implementation* should be done to improve knowledge of the characteristics and performance of components and machines (Soldinger, 2002).

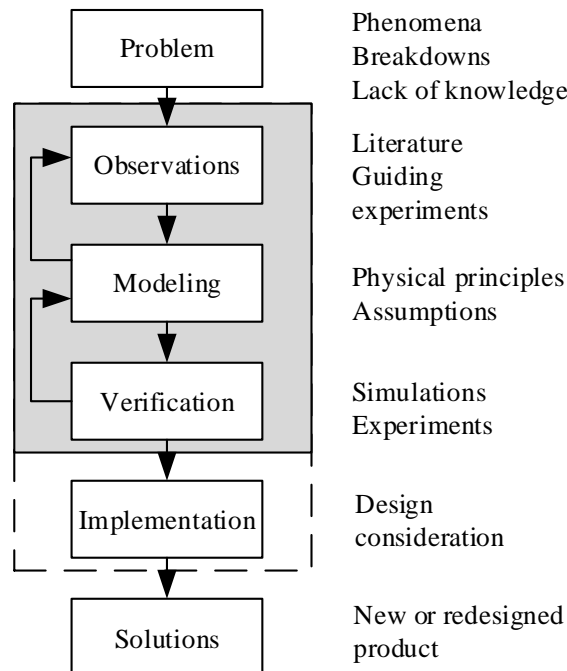


Figure 3. The applied problem oriented research model as illustrated by (Evertsson, 2000).

4 LITERATURE REVIEW

The aim of this chapter is to:

- *Overview three different screening models which are empirical, analytical and numerical type.*

4.1 Empirical Modelling

There are a number of screening calculation methods available to predict screening performance. Many studies in the past have led to the development of theoretical 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 aperture greater than 1mm (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 undersize material proportion in the feed. The factors which have an effect on the capacity of the screen are the standard conditions of the screen and the feed material. According to Karra (1979) the theoretical amount of undersize material that can be transmitted by the screen can be calculated by:

$$Q_{us} = C_A \cdot C_B \cdot C_C \cdot C_D \cdot C_E \cdot C_F \cdot G_c \cdot A_{Screen} \quad (1)$$

The factors C_A , C_B and C_C are the capacity which is defined as undersize, oversize and the amount of half size in the feed, the factor C_D is the location of screen deck. The factor C_E is the wet screening factor and C_F is the material density. The factor G_c is near-size capacity factor which has a significant effect on screening performance. If the value of Q_{us} is almost equal to the quantity of undersize in the feed this means that the screen is good or well designed.

There are some studies in which the Karra model has been adapted as a screen model. One of them, presented by Cotabarren et al. (2009), shows 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 presented the Karra model by applying it to a large-scale double-deck vibrating screen.

4.2 Analytical Modelling

According to Soldinger (2000) there are two main processes occurring during screening, one is the stratification process which is fine particles passing through the space between other particles to get contact with the screen deck. The other process is passage which is the process of particles passing through the aperture 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 of increasing the transporting distance for particles through other particles. On the other hand, by increasing the material thickness on the screen bed material, transportation velocity over the screen deck decreases which means more time for particles to pass through the aperture (Soldinger, 2000).

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

4.3 Numerical Modelling

Due to a number of different factors which have an effect on screening, this process becomes a complex process which makes it difficult to have an effective calculation screening model when designing the machine or choosing the one for the crushing plant. One of the models that has been used recently to make it easier to understand the process is a numerical model using Discrete Element Method (DEM) (Li et al., 2015). The advantage of this kind of method is the possible number of simulation runs with different process conditions which is truly time effective.

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

Some screen factors and design parameters have been studied in previous works. Dong et al. (2009) have shown that when the inclination of the discharge end is too small or too big the screening efficiency decreases because of particle velocity. This means there is an optimum inclination which is around 5° . The vibration amplitude has been studied by Dong et al. (2009). By decreasing the vibration amplitude and frequency the screening performance can be improved. The increased passing percentage of small undersized particles is mainly at the first deck at the feeding point (Dong et al., 2009). There are some other studies analysing the frequency which show the same result, that screening efficiency does not increase with an increase in vibration frequency (Chen and Tong, 2009).

There are some other screening conditions in real experiments such as airflow and wet screening which are not covered by DEM. Li et al. (2012) studied the effect of airflow velocity in terms

of grains and short straws by linking Computational Fluid Dynamics (CFD) to DEM. Similar work has been done by Fernandez et al. (2011) to analyze the effect of water flow in the wet screening process.

5 RESEARCH METHODOLOGY

5.1 Discrete Element Method

5.1.1 General

DEM is a numerical method for calculating the motion and effect of a number of small particles (Mao et al., 2004). DEM simulation consists of following the motion of every particle in the material flow and modelling each collision between combinations of particles and between particles and their environment such as walls and bins (Cleary, 2004). There is a basic calculation cycle in DEM presented by Quist (2015), shown in Figure 4.

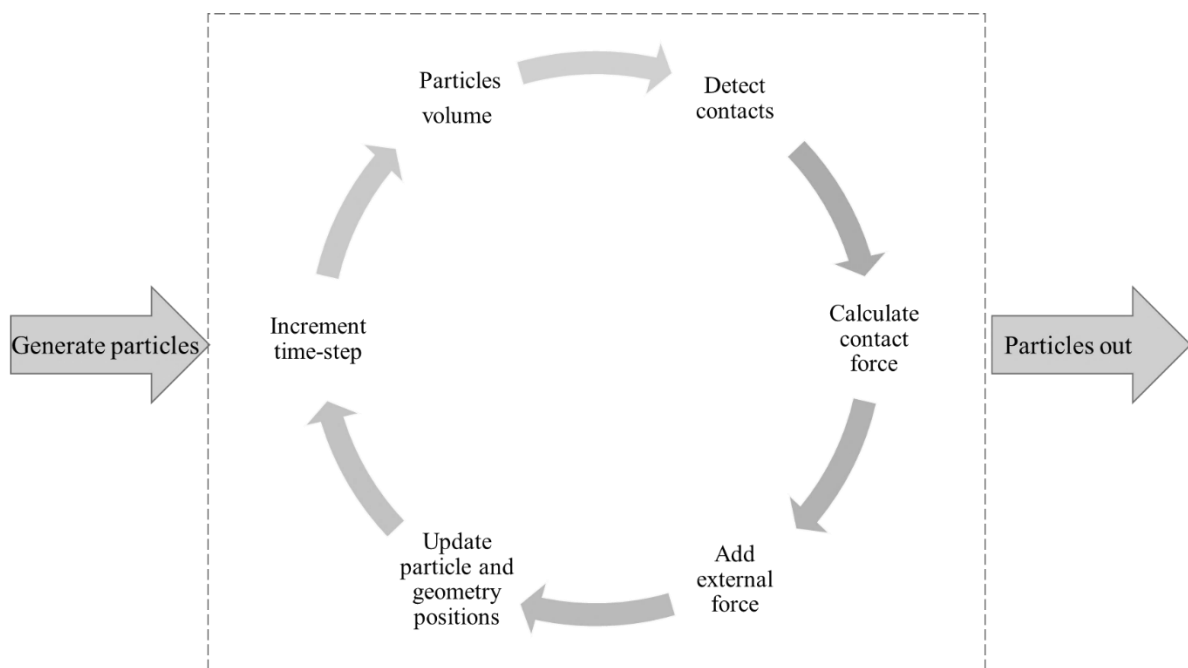


Figure 4. DEM calculation cycle by (Quist, 2015)

There are a number of factors which impact on DEM, the most important one is particle shape. Normal particle shape is spherical, which builds from one sphere, but to attain the most realistic shape as possible a combination of a number of spheres will be used. The advantage of the multi spheres particle is to have more edges which correspond better to the real shape of rock particle. One simple method which is used to create more complex particle shapes is to overlap spheres. According to Ferrellec and McDowell (2010) overlapping spheres generates a non-uniform distribution of mass inside the particle which affects the rotation of the particle in simulation. There are some other research studies regarding the effect of particle shape on the mechanical behaviour of granular materials (Jiang et al., 2009; Ng and Dobry, 1992). The studies show that

using single sphere particles is not sufficient as a granular material, on the other hand non-spherical particles give more interlocking and rotational resistance.

An illustration of a rock particle with 5 spheres is shown in Figure 5 . As long as the general shape of the particle is represented in DEM simulation the number of spheres which build the particle is not important (Pasha et al., 2016).

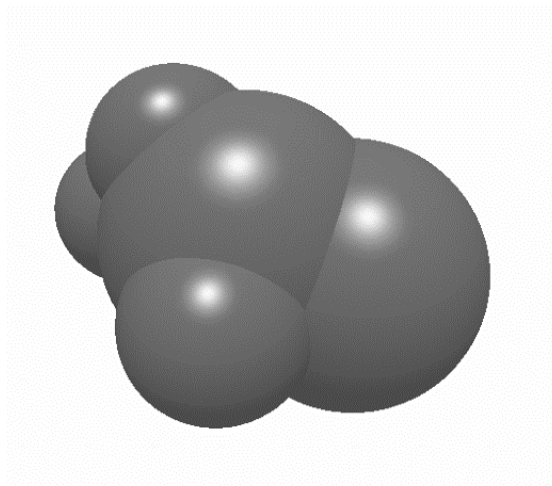


Figure 5. Illustration of rock particle with 5 spheres.

One step of the simulation process is to try to minimize the simulation time. The total computational time for simulations is a combination of multiple factors such as the number of particles in the system which means that the more particles, the more time is needed to calculate data. Also more complex particles, defined by conjoining particle, increases the number of particles in the system. One important factor is the total desired simulated time based on the time that simulation reaches steady-state. The particles are stored in simulation until the process reaches steady-state which means the total number of particles in the simulation is stable (Cleary et al., 2009).

5.1.2 Hertz-Mindlin's Contact Model

Hertz–Mindlin's contact model is a no slip model that uses a linear spring dashpot model (Just et al., 2013). Considering Hertz–Mindlin's contact model with only gravity as an external force, some input parameters for particle characteristics must be defined such as particle shape, particle density, size of particle, particle shear modulus and Poisson's ratio and also coefficient of restitution between particle-particle and particle-geometry material (Marigo and Stitt, 2015). Figure 6 shows the interaction between two particles with a frictional element between normal force and tangential force.

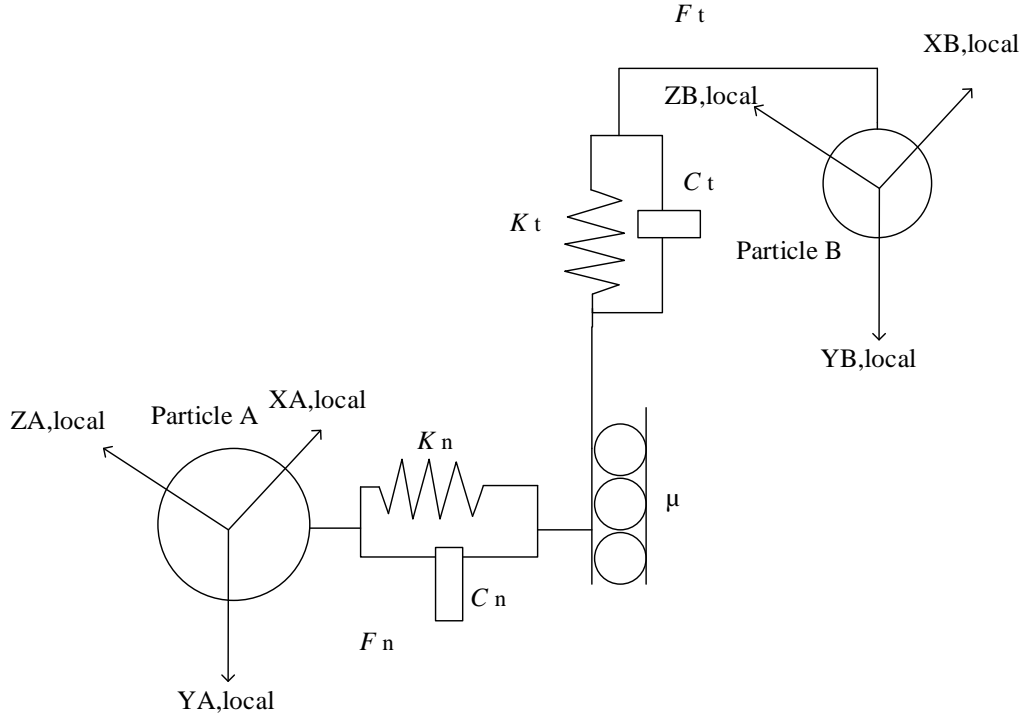


Figure 6. Graphic illustration of Hertz–Mindlin's contact model.

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. (Maw et al., 1976)

$$F_n = -K_n \Delta x + C_n V_n \quad (1)$$

- C_n Viscoelastic damping constant for normal contact.
- Δx Overlap between the two particles.
- K_n Elastic constant for normal contact.
- V_n Normal velocity of particles.

$$F_t = -K_t \Delta x + C_t V_t \quad (2)$$

- C_t Viscoelastic damping constant for normal contact.
- Δx Tangential displacement vector between the two spherical particles.
- K_t Elastic constant for tangential contact.
- V_t Tangential particle velocity.

In the Hertz–Mindlin's contact model elastic constants K_n and K_t are calculated based on material properties and are given by,

$$K_n = 2E^* \sqrt{R^* U_n} \quad (3)$$

$$K_t = 8G^* \sqrt{R^* U_n} \quad (4)$$

Where Young modulus E^* , normal overlap U_n , equivalent radius R^* , equivalent mass m^* and Viscoelastic damping constant for normal contact C are given by,

$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \quad (5)$$

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2} \quad (6)$$

$$\frac{1}{m^*} = \frac{1}{m_1} + \frac{1}{m_2} \quad (7)$$

$$C = \frac{1}{\sqrt{\ln^2(e) + \pi^2}} \quad (8)$$

6 SIMULATIONS AND RESULTS

The aims of this chapter are to:

- *Overview the highlight of each paper to understand the relation between the papers and research questions.*
- *Present the simulations results.*

To answer RQ1 different factors which have an effect on screening performance have been studied by using DEM simulations. Some of these factors are machine parameters and some of them are screening process conditions. In Paper A the focus of study is the effect of different motion type on screening performance, Paper B focuses on the effect of feed rate on screening performance and in Paper C different material for screen media and aperture size has been analysed. In paper A three different motions have been simulated. The aim of the paper is to see how elliptical and linear motion has an influence on screening. The first simulation is elliptical motion with a 6 mm amplitude. The second simulation uses elliptical motion with a 3 mm amplitude and in the third simulation, a 1 mm amplitude is used which is considered to be linear motion. The purpose of decreasing the amplitude is to approach linear motion efficiency. Figure 7 shows an illustration of different amplitudes that have been used in the simulations.

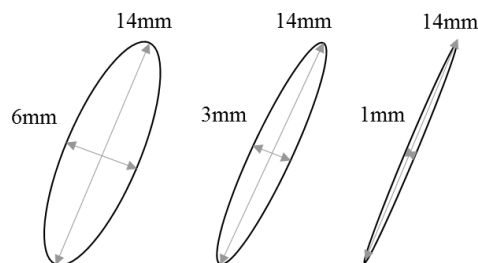


Figure 7. Amplitudes that has been used in simulation with elliptic motion. From left to right 6mm, 3mm and 1mm.

Geometric bins were generated for the simulations to make it possible to analyze the different parts of the screen during the simulations. Each section of the screen deck has one geometric bin. Figure 8 shows a schematic illustration of the bins used in the simulations.

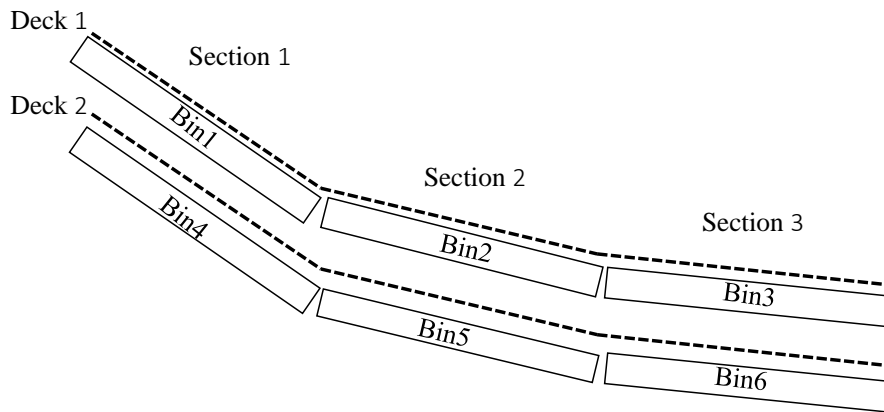


Figure 8. Schematic illustration of the geometric bins.

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

The number of particles that passed section 2 in all simulations is greater than in section 1 because the stratification became a more important effect in section 2 of deck 1. The results show that minimizing the amplitude of the elliptical motion has a negative effect on the screening efficiency. Bin 5 in section 2 has the same effect as Bin 1 and Bin 4; the effect of passage is more significant than the effect of stratification because of free fall. Because of the smaller angle of the deck in Bin 3 and 6, the material accumulates, and the process of stratification becomes more prominent. The results from Bin 3 and 6 show that an elliptical motion with a 6 mm amplitude is more efficient compared to a 3 mm and 1 mm amplitude. Figure 9 shows the images of the simulation after 12 s, illustrating that the material bed thickness in Section 3 increased by minimizing the amplitude of the elliptical motion.

The total number of particles and the scale generated in all simulations were the same for all three simulations. Better total passage efficiency was achieved by using an elliptical motion with a higher amplitude in different sections of screen. 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 10 shows the percentage of particles that passed through each section in relation to the total number of particles.

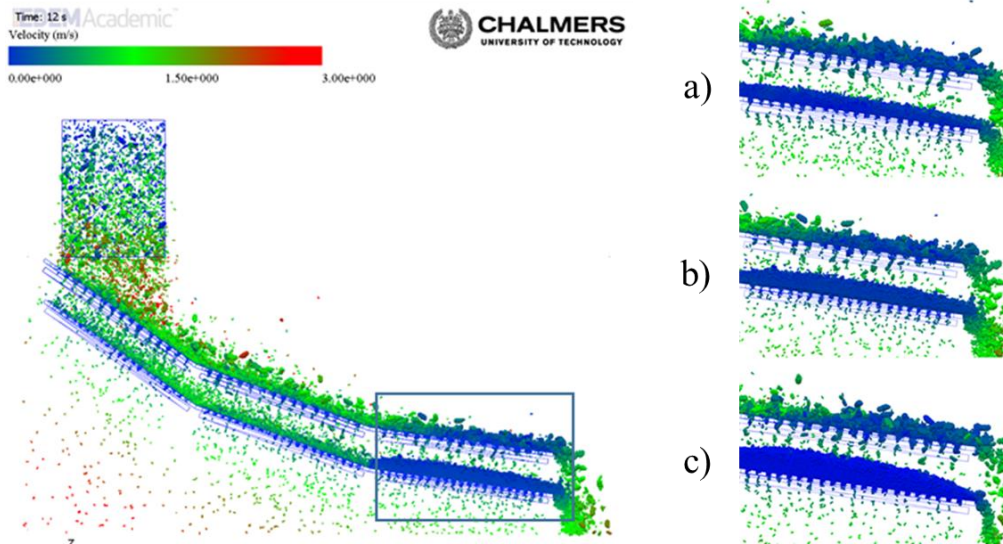


Figure 9. Illustration of simulation after 12s. a) Elliptic motion with 6mm amplitude. b) Elliptic motion with 3mm amplitude. c) Elliptic motion with 1mm amplitude.

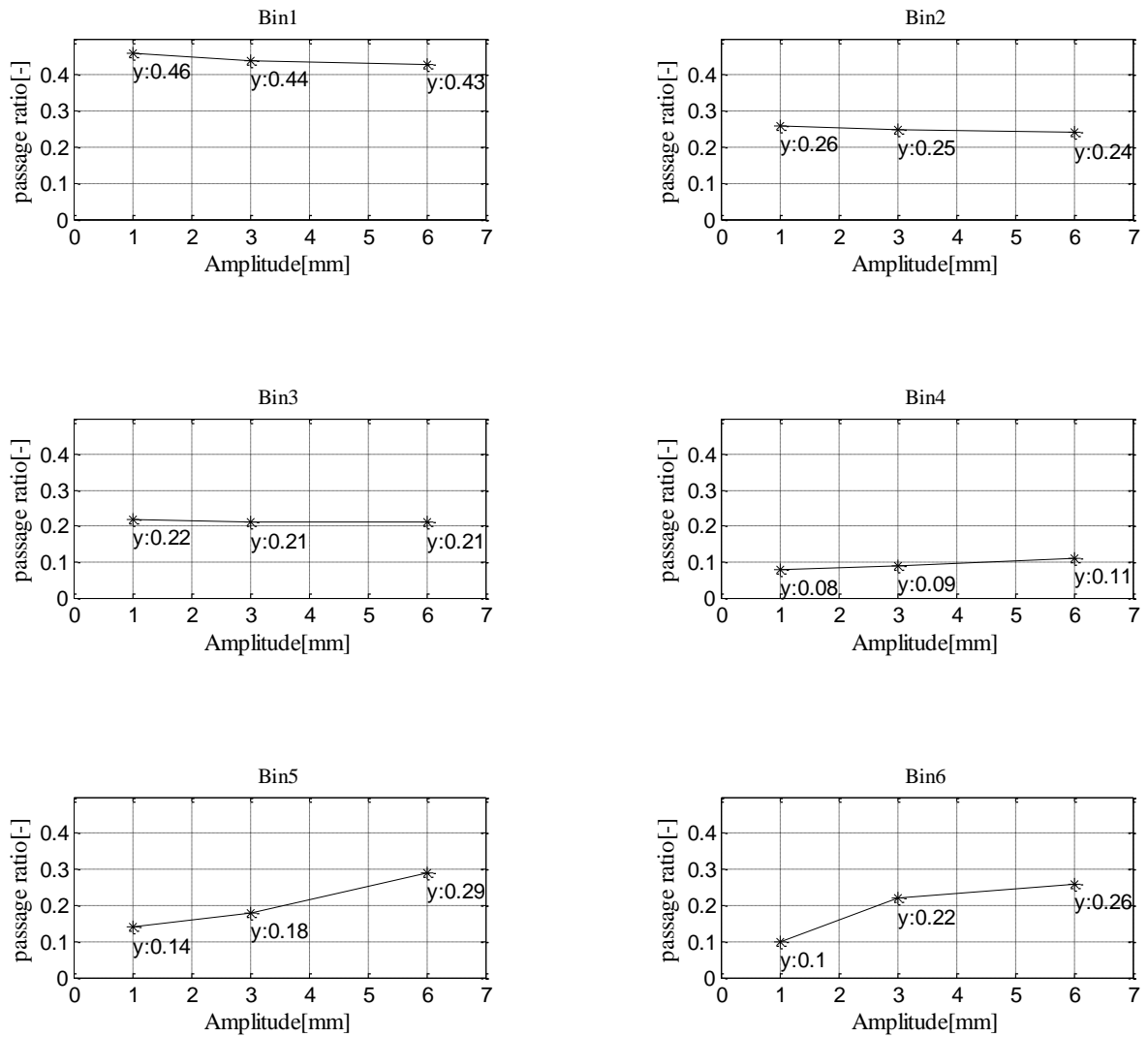


Figure 10. The ratio of particles that passed through each section.

Each screening machine has a capacity which is specified from the manufacturer but depending on the particle size distribution (PSD) this capacity will change. One way to analyze the capacity of the machine is to simulate the screening process with different feed rates. In Paper B the capacity of a screen which has been used in LKAB mine has been studied. The first step was to check the validity of simulation. A number of experiments were done and the result of these tests was used to check the validity of the simulations. The amount of undersize particles in each simulation has been compared with sieving result from the experiment. The number of undersize particles in both simulation and experiment is very comparable. Three different fractions have been studied, material under 1 mm, between 1 mm and 12.5 mm and between 12.5 mm and 25 mm, the next step was changing the feeding rate to analyse the screen capacity. Figure 11 shows how a series of collection bins were placed underneath the screen and an overflow bin was placed at the end of the screen in to collect data from passing particles.

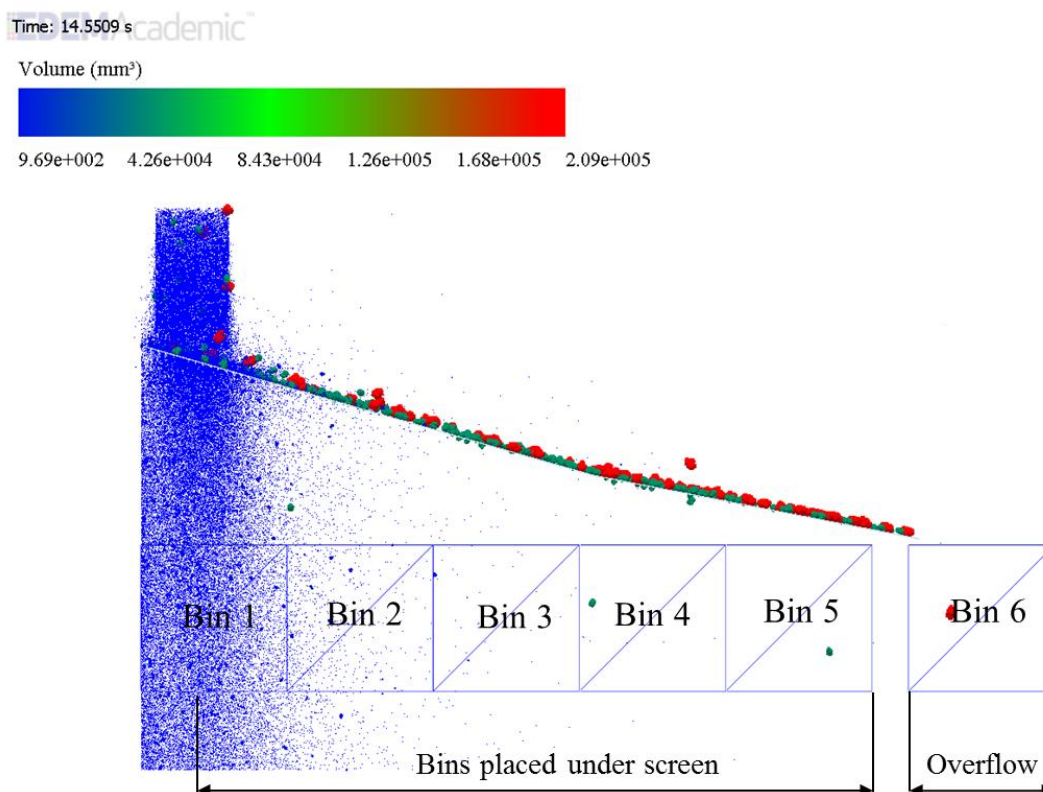


Figure 11. Overview of simulation after 14 seconds. Particles are coloured by their sizes: smaller ones are blue and largest ones are red.

The result has been analyzed in two ways. First by studying the total mass of particles that passed through each bin which is shown in Figure 12. Second by analyzing the screen performance by the number of particles over time for different feed rates.

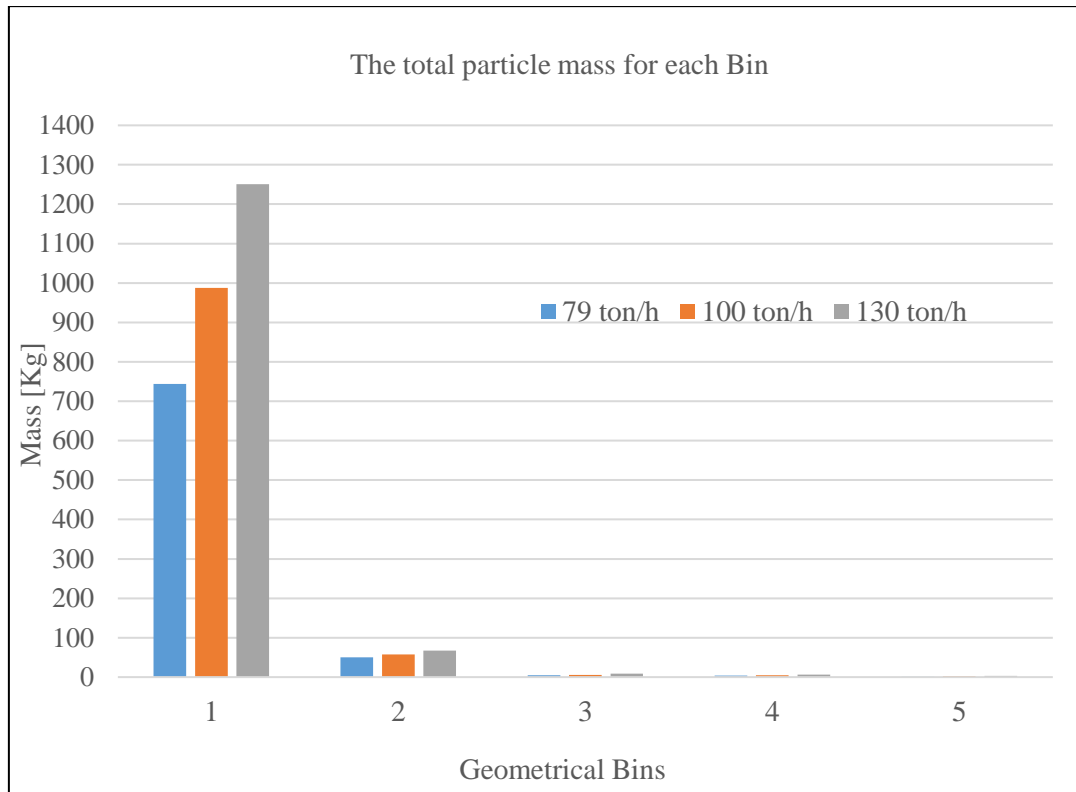


Figure 12. The total particle mass for each Bin.

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 at the feeding point to become high. Another factor that affects this process is the wide open area, in this model 35mm×35mm. The volume of particles passing through the screen deck is very high at the feeding point which is presented by Bin1. The simulation result shows that the total number of particles that pass through Bin 2 to Bin 5 for the 79 ton/h feeding rate is lower compared to the simulations with 100 ton/h and 130 ton/h. This is more noticeable in Bin 4 and Bin 5 where the increase is more than 200% in the total number of particles. In the first simulation with 79 ton/h feeding rate the particles have direct contact with screen media at the feeding point which increases the probability of passing through the screen deck. By increasing feeding rate the particle bed becomes thicker in the feeding point which affects the stratification process, in this case more particles move along the screen deck and the particle layer becomes thinner until the particles have contact with the screen deck directly.

The result from Bin 6 which is the overflow material in the simulation, shows that the total number of particles in overflow for 130 ton/h increased by around 20% compare to 79 ton/h, the important point to note is that the total number of undersize particles should not increase in the overflow material. In this simulation the average diameter of particles in Bin 6 has been studied. The average diameter difference for oversize material between 79 ton/h and 100 ton/h feed rate is about 4 mm which is very low but in 130 ton/h the average diameter is about 20 mm less than the other simulations showing that the probability of having undersize particles in this simulation is higher compared to 79 ton/h and 100 ton/h.

Paper B answers the RQ3; how can DEM simulation can be used for industry purpose? One example in paper B is to find out the optimum capacity for the machine. This can be done for different process conditions.

In Paper C the choice of material of the screen deck; steel, rubber and polyurethane, and the effect of aperture size are investigated by using DEM simulations. The effect of different materials on the number of bounces for one single particle has been analyzed. The reason for this analysis is 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 has been done by running the simulations with one single particle, the particle is big enough to not pass through the apertures. The study has been done in two different ways. First the total number of particle contacts with the screen deck by time step has been analyzed. For each screen deck material three simulations have been done with the same particle but different start positions based on the position of creating the particle. Figure 13 shows the number of particle bounces in different screen deck material. The number of contacts on the steel screen deck is slightly less compared to rubber and polyurethane.

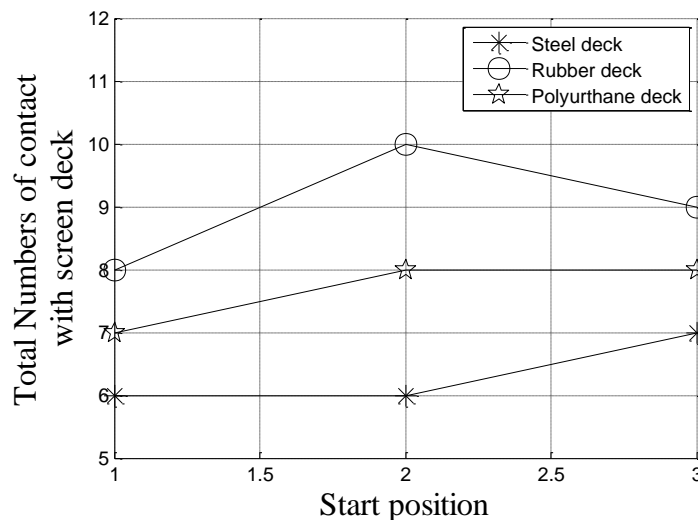


Figure 13. Numbers of bounces on different screen deck material.

However, this analysis is for a single particle and cannot directly be compared to a single layer particle because when material bed builds up the interaction between particle and particle will appear which affects the number of bounces and the amount of time for particles to travel along the screen deck.

A further analysis has been carried out to examine the numbers of particles passing through the screen at different sections along the whole screen length during a specified time period. This has been done by using geometrical bins and by recording particle coordinates when they pass through the bins in the model. Figure 14 shows a snapshot of the simulation and geometrical bins that have been used to export data from different sections of the screen.

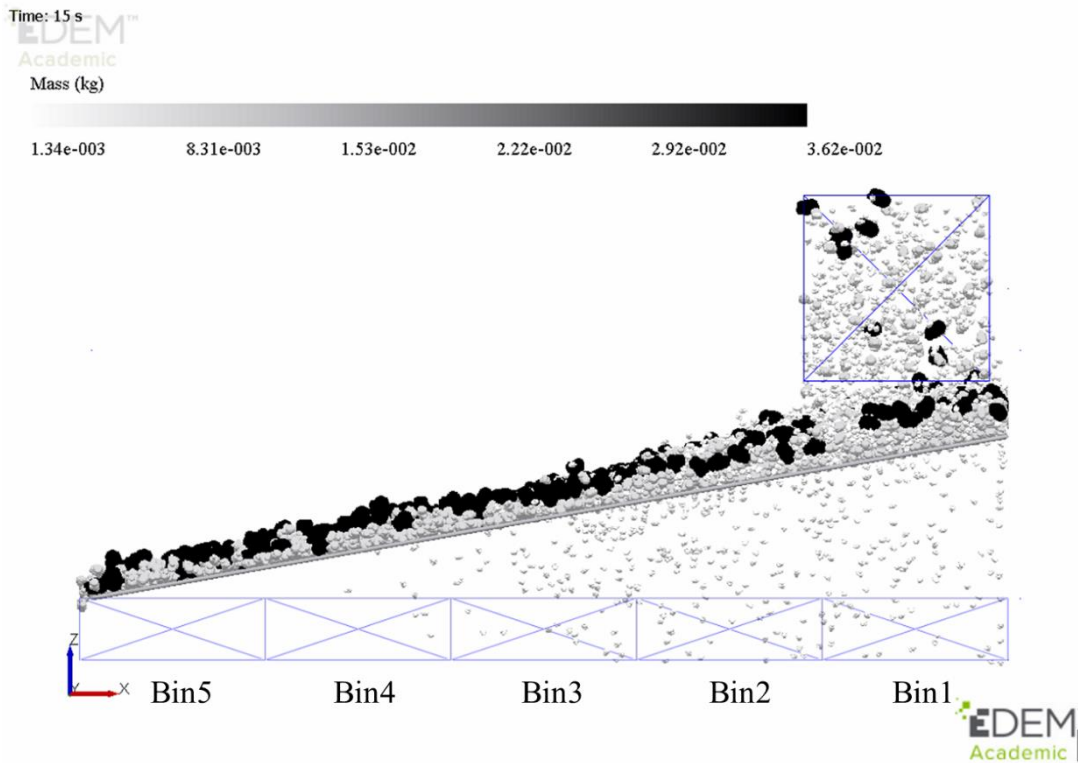


Figure 14. Snapshot of simulation after 14 s. particles coloured by mass, darker particles have more mass.

Figure 15 shows the relative number of particles passing through at different sections of the screen, at a length interval of 1500 mm, for a period of 15 s simulations. The amount of the particles passing through Bin 1 is more in the screening process with wire mesh when the feeding rate is 20 ton/h and 25 ton/h. By increasing the feed rate to 30 ton/h the number of particles in both panel and wire mesh deck in Bin1 are almost the same, when the feed rate increases to 35 ton/h and 40 ton/h the panel deck is more efficient compare to wire mesh. The reason for this is that the number of holes in the wire mesh deck is more compared to the panel deck because of thinner wire, which means the particles have more chance of passing through the deck before building up material bed. As more materials are fed onto the screen, the accumulation of particles spreads onto the whole feeding region and a material heap will form.

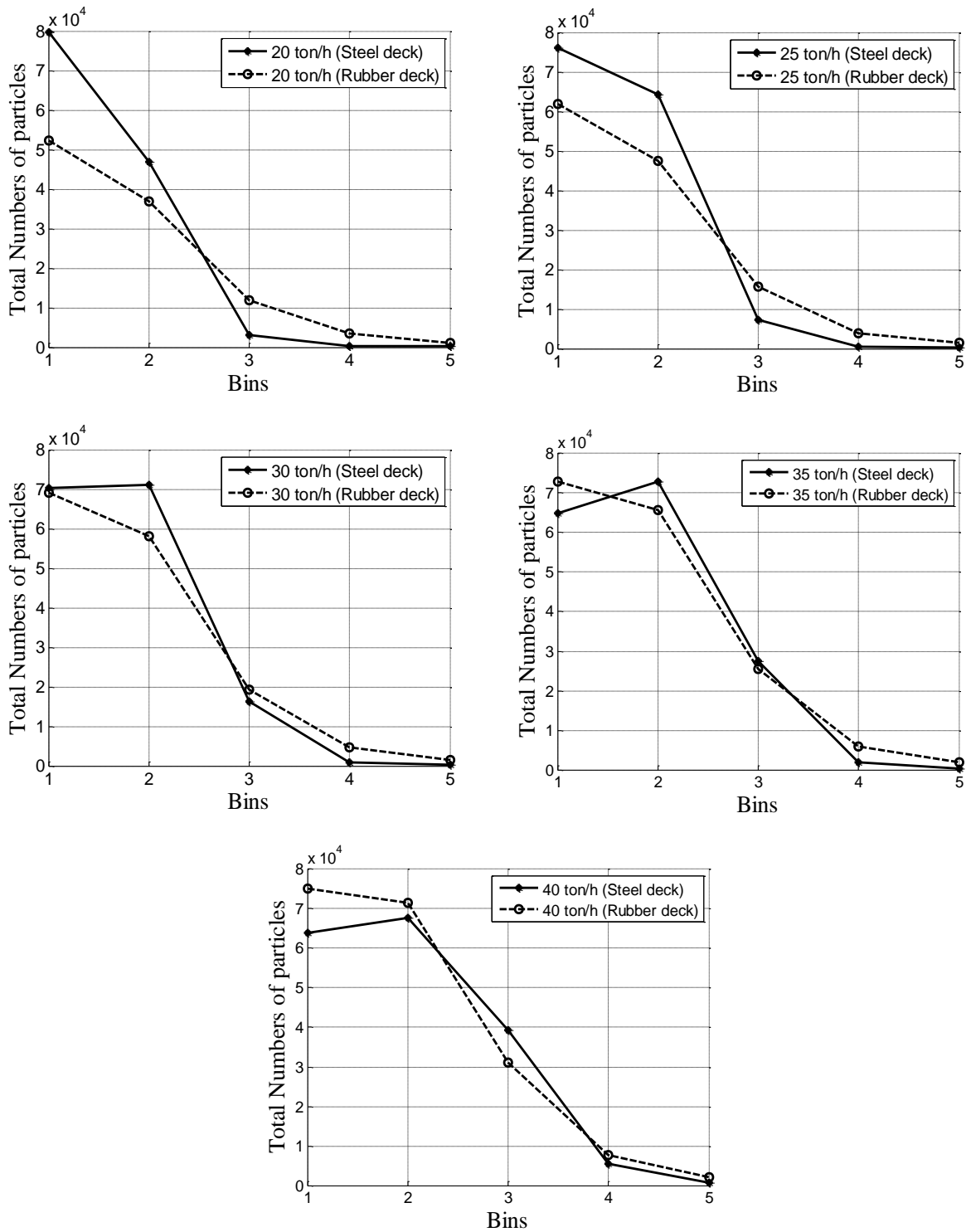


Figure 15. Analysis of screening rate along the screen.

Furthermore the velocity of particles along different screen decks has been analysed (Paper C). The average velocity for particles along the panel deck is 0.56 m/s whereas for a steel deck it is 0.68 m/s in the simulations with all feed rate. Figure 16 shows the average particle velocity in both panel and steel deck in different feed rates. By increasing the feed rate the particle velocity will decrease because the number of collisions between the particles increases due to more material on screen deck.

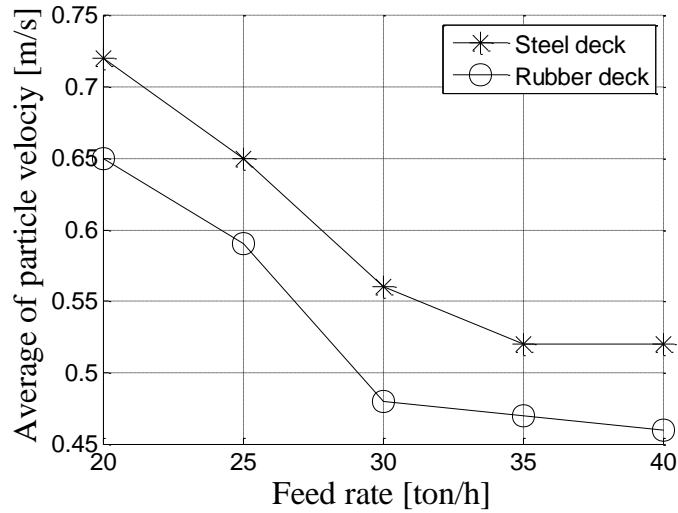


Figure 16. The average particle velocity in different feed rate.

7 CONCLUSIONS

The aim of this chapter is to:

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

7.1 General

The research result presented in this thesis is focused on improving the efficiency of the screening process in a crushing plant. The methodology that has been used to achieve the improvement was to include the most important factors which have an effect on the screening process. DEM simulations have been used to analyze different screening elements and parameters for steady-state conditions. Some of these elements are illustrated in Figure 2 in Chapter 1.

Using DEM simulations has some challenges depending on the area of application. One of the important factors is the particle shape which has significant impact on screening performance both on the passage and the stratification process. Spherical particles are too idealized to give quantitatively correct predictions compared to real experiment. However, by overlapping a number of spheres the particle attains a more realistic shape. But still for validating the simulation compared to the real screening process some simulation conditions must be calibrated for more satisfying simulation results. In the 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.

7.2 Answering Research Questions

The purpose of this thesis is to answer the stated research questions which have been presented in Chapter 2. The research questions are addressed in varying levels in different papers presented in this thesis, Table 1 shows the relationship between papers and the research questions.

Table 1. Dependency matrix for relation between the papers and research questions. The size of circle shows how strong the level of relation is.

<i>Research Question</i>	<i>Paper</i>		
	A	B	C
RQ1. Which dominating factors in a screen will influence screening efficiency?	●	●	●
RQ2. How can DEM simulation be used to model screening with a good accuracy?	●	●	●
RQ3. How can DEM simulation be used for industry purposes?			●

RQ1. Which dominating factors in a screen will influence screening efficiency?

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

Stratification:

The time of material transportation along the screen deck from feeding end to discharge end influences the stratification process. A longer transportation time increases the stratification process giving the particles more 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 the steel screen deck compared to rubber and polyurethane but the difference is not excessive and affects mostly single layer particles. (Paper C)

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

Passage:

The effect of aperture size on the passage process is dependent on the choice of panel material which are wire mesh deck or panel deck. The number of holes in a wire 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)

RQ2. How can DEM simulation be used to model screening with a good accuracy?

The DEM modelling has provided a fundamental understanding into 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, which replaces physical experiments and saves time. Some parameters are not possible to change in physical experiment due to the very high cost involved. The screening process is affected mostly by the interaction between the particles. DEM has covered different contact models that can be used for simulations and this can be validated by different methods which are based on experiments.

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

There are two types of usage for DEM at industry level. One is planning the crushing platform which helps to customize 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.

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

8 FUTURE WORK

The aim of this chapter is to:

- *Discuss the future work based on questions that have been raised during this research work. There are several lines of research arising from this work which should be pursued.*

The next step of this research is to calibrate some parameters based on real experimental testing until the result of calibration quantifies and controls errors or uncertainties within measurement processes to an acceptable level. Ideally a simulation would produce test results that exactly match the sample value, with no error at any point within the calibrated range. But this is an ideal simulation and very difficult to achieve with all of the different parameters that need to be calibrated. However, without calibration, an actual product may produce test results which differ from the sample value, with a potentially large error.

In this thesis different screening elements which have an influence on screen efficiency have been studied to find the one complete analytical model. Some elements have been excluded which should be considered as a future work such as effect of particle size distribution (PSD). The key question here is what kind of screen machine should be used for different PSD to attain the optimum screening performance.

The work that has been done in this thesis is based on one factor at a time (OFAT) analysis which cannot estimate interactions between factors. In the next phase of this research the interactions between different factors will be studied by using Design of Experiments (DOE). The four steps that should be considered for future work are shown in Figure 17.

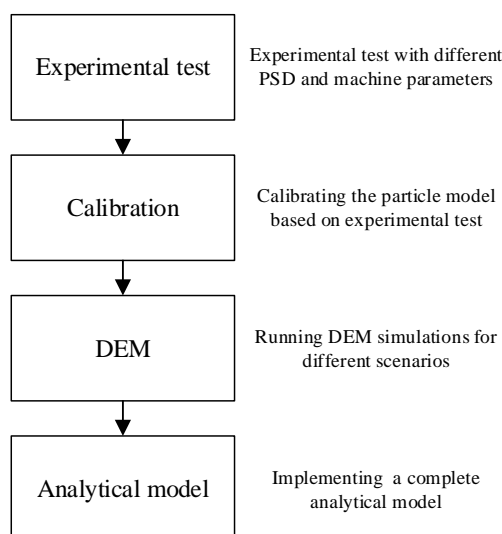


Figure 17. Future work divided into four steps.

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